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12 **Abstract (Purpose, method, results, conclusions)**

The basal aquifer underlying the Pearl Harbor-Honolulu Basin comprises the principal source of water supply for municipal demands of greater Honolulu and the demands of irrigated agriculture. Declining freshwater head and increasing chlorinity of coastal well water have led to recent groundwater development controls in the area. Determination of the sustainable (safe) yield of the basin requires a spatially and temporally detailed estimate of the recharge. The water balance of the basin was computed for 258 discrete zones at a monthly interval over the 1946 to 1975 (360 months) period. Results of the analysis include estimates of monthly precipitation, fog drip, sugarcane irrigation, urban lawn sprinkling, runoff, evapotranspiration, and groundwater recharge for each zone. The average recharge rate of the critical Pearl Harbor region was found to be 11.74 m^3/s (268 mgd), of which 2.98 m^3/s (68 mgd) is derived from the return of applied irrigation water. Results indicate that the groundwater resources of the basin are sufficient to support a population increase of approximately 450,000, should sugarcane and pineapple cultivation be discontinued.

2540 Dole Street, Holmes Hall 283 • Honolulu, Hawaii • U.S.A.

WATER BALANCE OF THE PEARL HARBOR-HONOLULU BASIN, HAWAI'I, 1946-1975

Thomas W. Giambelluca

Technical Report No. 151

May 1983

Research Project Technical Completion Report
for
The Water Balance of the Pearl Harbor-Honolulu Basin, 1946-1975
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WATER RESOURCES RESEARCH CENTER
University of Hawaii at Manoa
Honolulu, Hawaii 96822

AUTHOR:

Dr. Thomas W. Giambelluca
Assistant Researcher
Water Resources Research Center
University of Hawaii at Manoa

$15.00/copy
Checks payable to: Research Corporation, University of Hawaii

Mail to: University of Hawaii at Manoa
Water Resources Research Center
2540 Dole St., Holmes Hall 283
Honolulu, Hawaii 96822

Tel.: (808) 948-7847 or -7848

ABSTRACT

The basal aquifer underlying the Pearl Harbor-Honolulu Basin comprises the principal source of water supply for municipal demands of greater Honolulu and the demands of irrigated agriculture. Declining freshwater head and increasing chlorinity of coastal well water have led to recent groundwater development controls in the area. Determination of the sustainable (safe) yield of the basin requires a spatially and temporally detailed estimate of the recharge. The water balance of the basin was computed for 258 discrete zones at a monthly interval over the period 1946 to 1975 (360 months). Results of the analysis include estimates of monthly precipitation, fog drip, sugarcane irrigation, urban lawn sprinkling, runoff, evapotranspiration, and groundwater recharge for each zone. The average recharge rate of the critical Pearl Harbor region was found to be 11.74 m^3/s *(268 mgd), of which 2.98* m^3/s *(68 mgd) is derived from the return of applied irrigation water. Results indicate that the groundwater resources of the basin are sufficient to support a population increase of approximately 450,000, should sugarcane and pineapple cultivation be discontinued.*

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INTRODUCTION

The Hawaiian Islands, like most oceanic islands, are beset with special water problems. Despite abundant rainfall, the most urgent water problem facing Hawai'i is that of supply. Geographical isolation and a growing population increase the potential for water shortage, particularly on O'ahu.

The water resources of O'ahu, largely derived from groundwater, stimulated the cultivation of large areas through irrigation. More recently, the water supply has sustained rapid urban and residential development. The groundwater body underlying Honolulu and all of southern O'ahu has played a key role in this growth. It has been called the "most productive and important aquifer in the State of Hawaii" (Mink 1980). However, the growth stimulated by the abundance of water, now threatens to overburden the capacity of that resource.

A century of groundwater development in the Pearl Harbor-Honolulu basin, and particularly the increasing withdrawals of the last two decades, have reduced the original volume of storage in the aquifer by about 40% (Mink 1980). Concurrently, the water table has declined by more than 4.57 m (15 ft) in some areas, and saltwater encroachment has closed many wells along the coast. Estimates of sustainable yield—the maximum rate of water withdrawal which will not impair the long-term productivity of the resource—range from 10.95 to 13.42 m^3/s (250-300 mgd), while demand has reached 12.70 m^3/s (290 mgd) (State Water Commission 1979). In response to this, the Hawaii State Department of Land and Natural Resources has designated the region for special regulation (Cox 1981). New groundwater development in the Pearl Harbor area is under a virtual moratorium as a more precise estimate of the basin's sustainable yield is awaited.

O'ahu's principal groundwater resource consists of a basal, lens-shaped body of fresh water floating on and displacing the underlying seawater in the aquifer. This phenomenon was first described by W. Badon Ghyben in 1888 and by Alexander Herzberg in 1901; thus, such systems now bear their names (Wentworth 1947). To model the behavior and to ultimately determine the sustainable yield of a Ghyben-Herzberg lens in which the amount of water in storage is not constant—as in southern O'ahu, the input, "recharge", must be known. Many years of research have led to great advances in the understanding of southern O'ahu's groundwater. Efforts at analytical (Mink 1980) and numerical (Liu, Lau, and Mink 1981; Eyre 1980) modeling of the complex dynamics of the basal lens in southern O'ahu have been successful. However, recharge, the input requirement for the models, is still not known with certainty. The many estimates vary widely in value, and each exists only in the form of mean annual or mean monthly values.

Objectives

This investigation was made in response to the growing concern about possible overdraft of the Pearl Harbor-Honolulu aquifer. The investigation has resulted in a complete and detailed quantitative description of the water exchanges which occur at the surface and within the soils of the region. The study area is shown in Figure 1. Because of the importance of

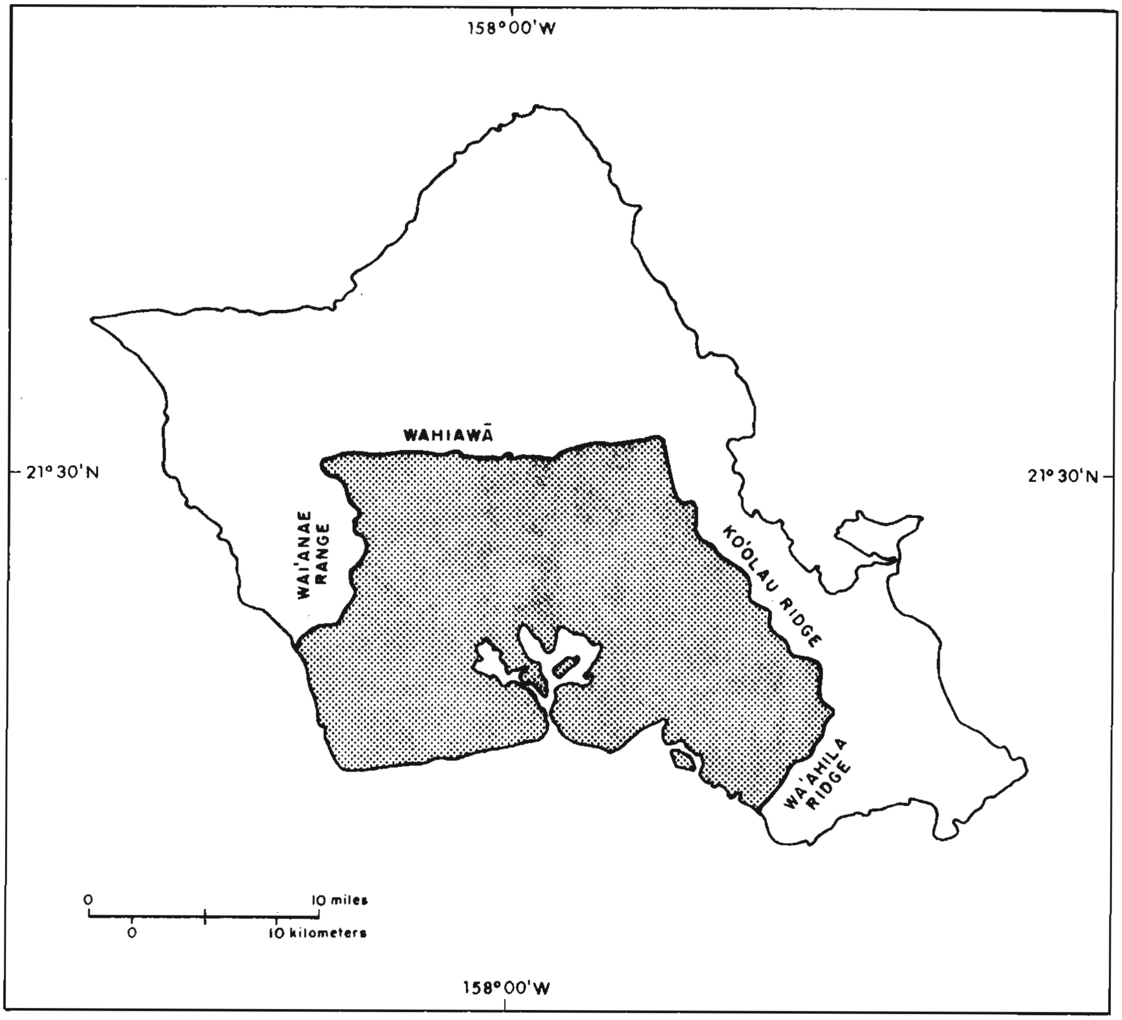


Figure 1. Pearl Harbor-Honolulu basin study area, O'ahu, Hawai'i

the sustainable yield problem in southern O'ahu, estimation of groundwater recharge was the primary focus of the study. The research was designed to include the effects of spatial heterogeneity and to examine interannual variation, problems lacking attention in previous studies.

Evaluation of the water balance for each month of the study period (1946-1975) has enabled the determination of the average rate, spatial distribution, and temporal variation of each of the components of the water balance: precipitation, irrigation, runoff, evapotranspiration, and groundwater recharge.

This study of the water balance of southern O'ahu was initiated for the following reasons:

1. The urgent need for water resource evaluation
2. The need for an accurate historical record of the recharge to be used as input to analytical and numerical models of groundwater yield
3. The existence of a more complete data base than was available for previous studies

4. The availability of greatly improved estimates of evapotranspiration in high rainfall areas (Ekern 1982).

Literature Review

Water research on O'ahu began with studies of geology and groundwater occurrence. Notable among early investigations are those by Palmer (1927, 1946), Stearns and Vaksvik (1935), and Stearns and Macdonald (1940). Wentworth (1942, 1946, 1947, 1951) continued the earlier geological surveys and initiated study of the structure and dynamics of the basal groundwater lens. More recently, Visher and Mink (1964), Dale (1967), Soroos and Ewart (1979), Mink (1980), and Liu, Lau, and Mink (1981) have studied the historical records of draft, head level, and salinity, and estimated storage losses from the aquifers of southern O'ahu.

Studies of water balance and its components are numerous. Average annual water budgets for the region were computed by Wentworth (1951), by Mink (1980) for a 1964 USGS study reported in a Board of Water Supply publication, and by Broadbent (1980). Mink also calculated the average annual water balance of the irrigated areas (Engineering-Science, Inc. 1972) and updated his earlier water balance estimates (Mink 1980). The average monthly water balance of a portion of the Honolulu area was estimated by Todd and Meyer (1971), and revised by Ekern (Cox et al. 1971). Comparisons among the results of various studies are made difficult by differences in boundary definitions. A summary of previous water balance estimates appears in Table 1 with some adjustments to account for different boundary configurations.

TABLE 1. SUMMARY OF PREVIOUS WATER BALANCE STUDIES, PEARL HARBOR AND HONOLULU NON-CAPROCK AREAS, O'AHU, HAWAI'I

Investigator	Precipitation (mgd)	Runoff (mgd)	Evapotrans. (mgd)	Precip. Rechg. (mgd)	Irrig. Return (mgd)	Total Rechg. (mgd)
			PEARL HARBOR NON-CAPROCK AREA			
Voorhees (1929)	448*	--	---	---	--	---
Wentworth (1951)	409*	98	100	211	--	---
Hawaii Water Authority (1959)	509	--	---	---	--	---
Mink (1964, 1980)	428	61	154	213	45	258
Dale (1967): 1931-1932	400	--	---	210	40	250
1964-1965	400	--	---	220	30	250
Hirashima (1971)	---	65*	---	---	--	---
Takasaki (1978)	425	70	105	250	--	---
State Water Commission (1979)	425	65	---	---	--	---
			HONOLULU BASALTIC AREA			
Kunesh (1929)	126†	34†	---	---	--	--
Wentworth (1951)	---	33†	---	---	--	--
Mink (1980)	---	--	---	---	--	60

NOTE: mgd × 0.043 81 = m^3/s.
*Adjusted by Mink (1980) to represent non-caprock portion of Pearl Harbor region.
†Adjusted to represent basaltic area of Honolulu region.

Related studies include water balance studies of other areas of Hawai'i (Caskey 1968; Kaneshiro and Peterson 1977; Juvik, Singleton, and Clarke 1978*b*), and a great deal of research on each hydrological component.

Average annual rainfall volume has been estimated for the region by Voorhees (1929) and by the Hawaii Water Authority (1959). Statistical analysis of rainfall and rainfall patterns over O'ahu has been done by Solot (1950), Stidd and Leopold (1951), Landsberg (1951), Yeh, Wallen, and Carson (1951), Mink (1960, 1962), Cheng and Lau (1973), Meisner (1976, 1978), and Schroeder (1976).

Runoff, stream flow, and related topics were investigated by Rice (1917), Mink (1962), Anderson, Duffy, and Yamamoto (1966), Wu (1967, 1969), Wang, Wu, and Lau (1970), Wood (1971), Hirashima (1971), Lopez (1975), Phamwon (1976), Fok, Murabayashi, and Phamwon (1977), Mink (R.M. Towill 1978), Murabayashi and Fok (1979), Cooley and Lane (1980), and Shade (1981).

Evapotranspiration and evaporation from various surfaces and crops in Hawai'i have been studied by Campbell, Chang, and Cox (1960), Chang (1961), Chang et al. (1967), and Ekern (1964, 1965*b*, 1965*c*, 1966*a*, 1966*b*, 1972, 1977). The results of a field investigation of evapotranspiration along two transects into the high rainfall areas of the Ko'olau Range recently conducted by Ekern (1983) greatly improved evapotranspiration estimates for the region.

All previous studies have failed to treat adequately two aspects of the water balance of the basin.

1. Spatial heterogeneity effects of the basin

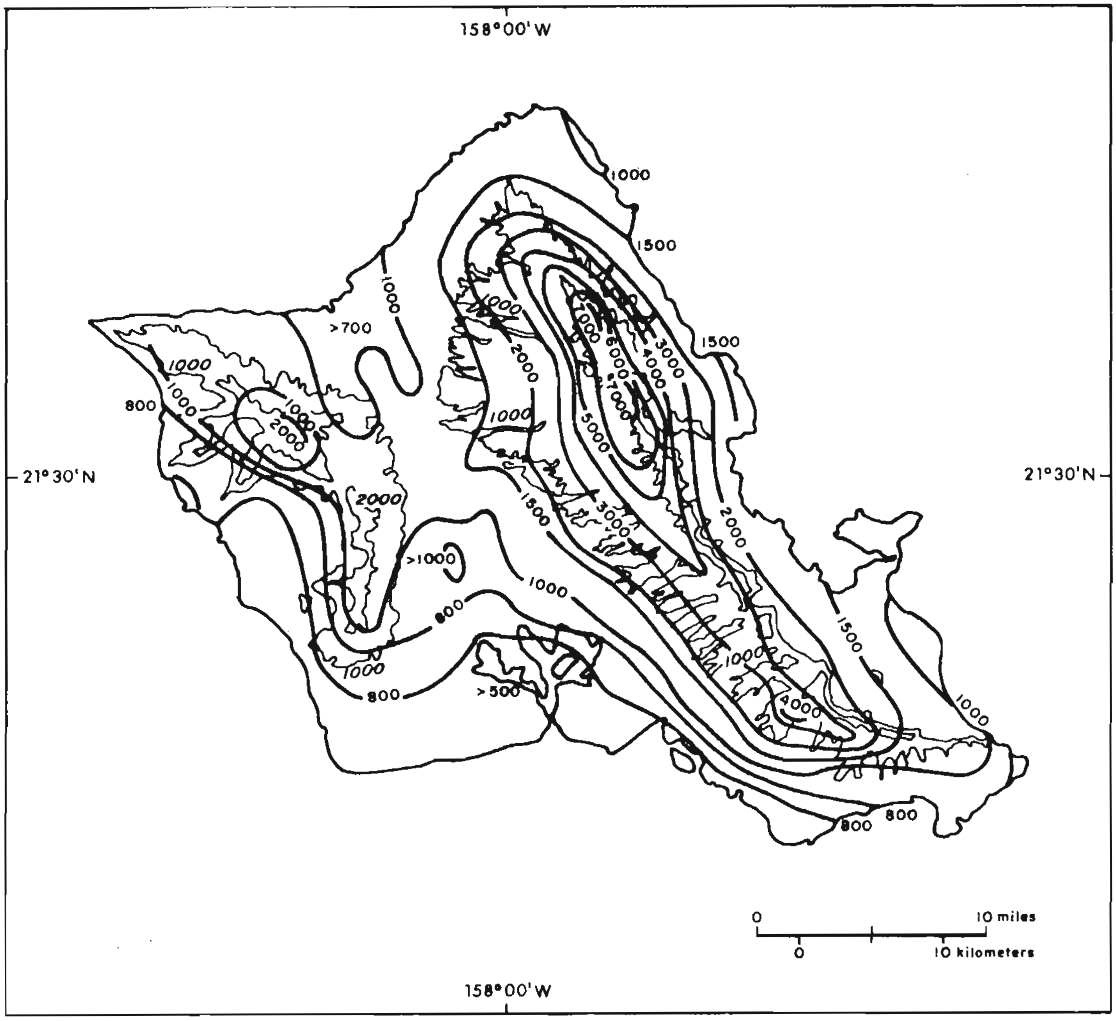
   A common practice in past studies has been to compute separately each term in the balance equation as a lumped parameter representing the entire basin. The implicit assumption of this single-cell approach is that each element is independent of the others or may be treated as though it were homogeneously distributed over the basin. The components of the water balance of southern O'ahu are neither independent nor homogeneously distributed. Dealing with them as bulk values contributes to the uncertainty of the results. The present study deals with the effects of spatial heterogeneity by evaluating separately the water balance for each of 258 homogeneous subareas.

2. Temporal variability of the water balance

   Most hydrological studies give great importance to the question of temporal variability. Water balance studies of southern O'ahu, however, invariably employ time-averaged values in the computations. The results are in the form of annual or, at best, monthly averages. The interannual variability is either ignored or described qualitatively. The problem of temporal variability is addressed in this study by computing the water balance for each month over the 30-yr study period (1946-1975).

Physical Setting

CLIMATE. O'ahu lies within the best of northeast trade winds, which



SOURCE: Adapted from Meisner and Schroeder map (DOWALD 1982).

Figure 2. Median annual precipitation, O'ahu, Hawai'i

are part of the circulation associated with the North Pacific anticyclone. The trade winds prevail over 90% of the time during summer and about half the time in winter (Blumenstock and Price 1967).

The rainfall pattern on O'ahu shows the dominance of the tradewind circulation and topographic effects (Fig. 2). Two mechanisms are responsible for most of the rainfall on O'ahu. The principal rain-producer is the orographic lifting of the trade winds along the slopes of the Ko'olau and Wai'anae ranges. About 1.016 mm (40 in.) of rain falls annually on the open ocean surrounding O'ahu (Reed 1980, Table 1). The effect of topography on rainfall is illustrated by median annual totals of greater than 6 858 mm (270 in.) received on the Ko'olau Range. In the absence of trade winds, cyclonic circulation may occur during which widespread storm rainfall is common. Cyclonic rainfall is less influenced by the topography and tends to be more uniformly distributed. This type of rainfall is generally a winter phenomenon and is often associated with the presence of a subtropical cyclone, known locally as a "Kona storm" (Blumenstock and Price 1967). Rainfall may be very intense, occasionally resulting in widespread flooding (Ramage 1962). The Kona cyclone has a frequency of about three to four annual occurrences, yet accounts for more than half the rainfall received in the drier areas of Hawai'i (Simpson 1952).

The rainfall pattern in the study area is characterized by a maximum slightly leeward of the Ko'olau crest. Mink (1960) has shown that the pattern of rainfall on the leeward Ko'olau slopes is related to distance from the crest according to a geometric progression. A secondary maximum is observed along the Wai'anae summit where median annual rainfall exceeds 2 032 mm (80 in.).

Seasonal variation in rainfall is pronounced in drier areas, exhibiting a maximum during the winter months. In the mountains, rainfall is relatively constant throughout the year. As a result, the gradient is greater in summer than in winter.

LAND USE. The patterns of land use in southern O'ahu have undergone rapid changes during the last two decades. Most of the change resulted from the growth of the residential and commercial districts of Honolulu and satellite communities. In many areas, this growth has displaced agriculture. However, according to Mink (1980), the net decline in agricultural acreage due to urbanization is only about 20.235×10^6 m² (5000 acres) because of a compensating expansion into formerly uncultivated areas. The Land Study Bureau has made two detailed land-use surveys of O'ahu (Nelson 1963; Sahara et al. 1972). Dale (1967) investigated changes in land use in the Pearl Harbor area, particularly the displacement of sugarcane land by residential development, and its impact on groundwater.

According to a land-use survey conducted for the present study, the southern O'ahu study area had the following breakdown as of 1975: forest/vacant/grazing land, 46.5%; sugarcane, 15.5%; pineapple, 6.4%; and urban/part urban, 31.0%.

SOILS. The variety of climate and landform conditions under which soils develop in Hawai'i and differences in parent material result in a very diverse soil geography. About 30 different soil series have been identified within the study area by the most recent soil survey (Foote et al. 1972). Ruhe et al. (1965) showed that variations in the properties of soils in the 'Ewa-Waipahu area are attributable to differences in origin and age of the soils.

Because of the low quartz content of Hawaiian volcanic parent material, the percentage of sand and silt-sized particles is generally low (Foote et al. 1972) and the dominant soils of southern O'ahu are clays. Significant percentages of silt-sized particles derived from aeolian dust occur in older soils of high rainfall areas (Jackson et al. 1971). Oxisol order soils, red clays formed in semiarid to moderately wet areas, are prevalent throughout the Schofield Plateau. Most soils in this region, such as the Wahiawa silty clay (Tropeptic Eutrustox), have a water-stable aggregated structure, which imparts hydrologic characteristics of much more coarsely textured soils (Sharma and Uehara 1968; Ekern 1966*b*). Consequently, infiltration and drainage are rapid.

Land use has a considerable impact on the hydrological properties of some Hawaiian soils. Trouse and Humbert (1959), for instance, showed that the aggregated clays are easily compacted by heavy tillage and harvesting equipment used in sugarcane cultivation. Wood (1971) found that soils under forest cover had higher porosity and rates of infiltration, and lower bulk density than similar soils under pineapple, sugarcane, or pasture. Urbanization has also been shown to reduce infiltration rates of these soils (Murabayashi and Fok 1979).

HYDROGEOLOGY. The surface relief of O'ahu is dominated by two roughly parallel mountain ridges, the summits of which form portions of the study area boundary. The Ko'olau Range runs the length of O'ahu's windward side. Oriented northwest-southeast, the Ko'olaus are approximately perpendicular to the prevailing trade winds. A series of narrow stream valleys separated by steep-sloped ridges run transverse to the main ridge along the leeward Ko'olau slope. The summit elevation varies from 361.5 m (1186 ft) at Nu'uanu Pali to a maximum of 960.1 m (3150 ft) at Kōnāhuanui.

The Wai'anae Range is parallel to the Ko'olaus in its northern part and is oriented north-south at its southern end. Its highest point along the study area border is 953.1 m (3127 ft) at Pu'u Kaua. The landward slopes are steep near the crest, giving way to moderately sloping colluvial fans at lower elevations.

The Schofield Plateau lies between the mountain ranges, and is bisected by the drainage divide which forms the northern boundary of the study area. From this divide the plateau slopes gently southward into the coastal plain.

About 25 streams drain the Pearl Harbor-Honolulu basin (Wentworth 1951). Most of these originate in the Ko'olaus and flow generally southwestward to the Honolulu shoreline and into Pearl Harbor. Only two streams discharge intermittently into Pearl Harbor from the Wai'anae Range.

The island of O'ahu consists of the eroded remnants of two shield volcanoes. The Wai'anae and Ko'olau volcanoes are two peaks of more than 50 large undersea volcanoes, which extend more than 3.2×10^6 m (2000 miles) along the floor of the Pacific. The volcanoes of the Hawaiian archipelago are increasingly younger toward the southeast, evidence of tectonic movement of the Pacific Plate over a "zone of melting" in the earth's mantle (Dalrymple, Silver, and Jackson 1973). The volcanoes are built by an accumulation of thin layers of lava poured out successively. Hawaiian eruptions generally occur as gentle flows of very fluid lavas that produce shield volcanoes with 3- to 10-degree slopes (Stearns and Vaksvik 1935).

The Wai'anae shield formed between about 3.3 and 2.7 million years ago; the younger Ko'olau between about 2.6 and 2.2 million years ago (McDougall 1964). The surface of the Schofield Plateau formed as the lavas of the Ko'olau volcano banked against the slopes of the Wai'anae (MacDonald and Abbott 1970). The present topography of the island bears evidence of extensive stream erosion that is particularly advanced along the windward Ko'olaus due to the high rainfall of the region. Although much drier, the leeward Wai'anae slope is dissected by large stream valleys due to its long period of erosion.

The deposition of sediment eroded from the domes forms the flat coastal plain along southern O'ahu. Variations of world climate and isostatic adjustments of the island led to large fluctuations of sea level. Low stands of the sea served to accelerate erosion of deep stream valleys, while high stands led to increased deposition on lowlands and coral formation and marine sedimentation on the now exposed coastal plain (Visher and Mink 1964; Ruhe et al. 1965).

Superimposed upon the massive shield landforms are smaller features of more recent volcanism. The Honolulu volcanic series, which occurred with the last million years (Funkhouser, Barnes, and Naughton 1968), is evidenced by numerous cinder cones, tuff cones, and lava flows on the southeastern O'ahu landscape.

The lavas of the Wai'anae and Ko'olau domes form the bulk of the island, including the important groundwater aquifers. The domes were built of rapid successions of lava flows with little erosion taking place between events. The vesicular magma and the nature of the eruptions produced basalt of high permeability (Palmer 1946). The aquifer underlying the Pearl Harbor-Honolulu basin is composed of such rock.

Vents through which volcanic eruptions occurred often consisted of linear openings or rifts in existing rock formations. Magma which cooled in rifts, such as those of the Ko'olau and Wai'anae volcanoes, formed dikes of dense impermeable rock. In some areas along the crests of the Ko'olau and Wai'anae ranges and possibly under the Schofield Plateau, dikes form compartments enclosing permeable flow lava. The occurrence of high level groundwater in some areas is due to the impoundment of water by these dike compartments (Stearns and Macdonald 1940).

The coastal plain of southern O'ahu is composed of sedimentary rock originating from terrestrial alluvium, marine sediment, and coral formations. This body of rock forms a wedge lying on the surface of the Ko'olau lavas, and is called the caprock. Sedimentary deposits also extend inland along valley floors where they may exist to depths of 304.8 m (1000 ft) as ancient valley fills. The caprock is composed of materials with a range of permeabilities. Taken as a whole, however, the caprock is much less permeable than underlying and adjacent basalt (Palmer 1946).

Groundwater in O'ahu is derived from rainfall and occurs in high-level compartments, deep basal aquifers, and—in small amounts—in shallow limestone aquifers in the caprock. High-level groundwater is that which is confined within dike complexes or perched on beds of ash, soil, or alluvium (Stearns and Vaksvik 1935).

The basal groundwater consists of a lens-shaped body of fresh water floating on sea water within the aquifer. Fresh water in the saturated zone flows gradually seaward and is maintained by the constant influx of downward percolating rain water. By virtue of its lower density, the fresh water floats on and displaces the underlying salt water, reaching a depth below sea level of approximately 40 times the freshwater head above sea level. The separation of fresh and salt water is not distinct. Due to fluctuations in recharge and discharge and the tidal influences, the basal water is forced to oscillate. Some mixing results from this motion. Salinity is found to grade from fresh to sea water concentration over a certain depth dependent on the amount of mixing. The region of intermediate salinity is called the transition zone.

A fortunate circumstance with regard to the water resources of O'ahu is the existence of the caprock whose relative impermeability effectively slows the seaward flow of fresh water and inhibits the encroachment of sea water. As a result, the freshwater storage capacity is increased. Groundwater trapped beneath the caprock is under hydraulic pressure which provides coastal areas with an artesian water supply.

The basal groundwater body underlying the study area may be considered virtually continuous (Mink 1980). However, it has long been recognized that in the Honolulu area the groundwater is compartmented into isopiestic areas by several less permeable formations consisting of ancient valley fills (Palmer 1927). Although some lateral flow occurs across these boundaries, discontinuities of groundwater head are observed.

Generally, the aquifer is recharged in the rainy mountain regions, and the flow within the saturated zone is seaward. Under predevelopment conditions, discharge consisted of springflow along the landward edges of and through leaks in the caprock.

Water Use

WATER RESOURCE DEVELOPMENT. Irrigation has long dominated water use in Hawai'i. Ancient Hawaiians were the first to use irrigation, raising taro in ditch-fed paddies. But not until the late 19th century, when sugarcane became the primary irrigated crop, were large quantities of water extracted from the ground for irrigation. As of 1975 agriculture accounted for about 51% of the water used in the Pearl Harbor-Honolulu area (State Water Commission 1979).

Municipal water demand has shown rapid growth over the last two decades. For O'ahu as a whole, municipal use has grown from about 2.63 m^3/s (60 mgd) in 1955 (Hawaii Water Authority 1959) to about 7.67 m^3/s (175 mgd) in 1975 (State Water Commission 1979). While agricultural use is projected to remain constant, municipal demand is expected to increase by 70% by the end of the century.

The water resources of southern O'ahu are diverse. Water sources include streams and springs, used mainly for irrigation; dike-confined water tapped by high-level tunnels; and basal artesian and non-artesian groundwater developed by wells and inclined shafts.

The basal groundwater has been the principal source of water for Honolulu since the end of the last century. The first successful well was completed at Honouliuli in 1879. Before the turn of the century, 249 wells had been drilled in the Pearl Harbor-Honolulu area (Wentworth 1951). Hundreds of additional wells have been drilled since then. Construction of shafts and tunnels began in the 1930s (Cox 1981).

Draft from the Pearl Harbor area rose rapidly from 0.88 to 7.23 m^3/s (20-165 mgd) between 1901 and 1912. During the next 50 years, the rate of withdrawal fluctuated about an average of 7.0 m^3/s (160 mgd) (Visher and

Mink 1964). This stability was a result of the dominance of agriculture in water use during the period. However, beginning in the 1940s with the construction of Hālawa Shaft and accelerating after the advent of statehood, nonagricultural consumption became significant. During the 1970s plantation draft in the Pearl Harbor region was down to 5.91 m^3/s (135 mgd) (Mink 1980), while total draft had reached 10.51 m^3/s (240 mgd) (State Water Commission 1979).

BASAL LENS. The water table fluctuates in response to recharge variation. In addition, a long-term trend in groundwater head in Pearl Harbor is apparent (Fig. 3). In Pearl Harbor the average annual head had decreased 3.05 m (10 ft) over the 70 years preceeding 1979 (State Water Commission 1979). Today the trend continues.

Also continuing is the steady landward encroachment of salt water (Soroos and Ewart 1979) — a problem encountered very early in groundwater development on O'ahu. Shortly after pumping reached significant levels, chloride concentrations began to rise in coastal wells. This led to the abandonment of many wells and subsequent devleopment was confined to areas farther inland. Observations of increased salinity apparently indicate landward and upward movement of sea water and a general increase in thickness of the transition zone (Visher and Mink 1964).

A considerable decline in freshwater storage is implied by the head decrease and the rise of salinity in the Pearl Harbor-Honolulu area. The extent of the loss is the subject of debate. Because of the freshwater-saltwater density differential, a 0.30 m (1 ft) head loss corresponds to a 12.19-m (40-ft) rise of the lower boundary of fresh water if equilibrium is maintained. Under such conditions, storage changes implied by the observed head fluctuations are unreasonably large. Wentworth (1942, 1951) developed the concept of "bottom storage" to account for this apparent discrepancy. According to this theory, the movement of the lower margin of fresh water is slow to respond to head variation. The 40:1 ratio cannot be maintained during rapid withdrawal or recharge due to the resistance of the medium. On this basis Wentworth concluded that measured head changes were not indicative of equivalent storage fluctuations. Mink (1980) used the terms "operating head" and "storage head" to distinguish between the effects of pump drawdown and actual storage loss.

Long-term trends, however, certainly indicate storage changes involving movement of the bottom margin of the lens. The simultaneous rise in salinity in many wells is consistent with this conclusion. Mink (1980) estimated that 40% of the original volume in storage has been depleted.

Concern has grown in recent years over the effects of continued withdrawal from the basal groundwater in southern O'ahu. Local declines in water quality in springs and wells have long been problems. However, the overall shrinkage in the extent and volume of the basal lens and, particularly, the thickening of the transition zone, are problems of a larger scope. Water resource planners have long sought to determine the basin's sustainable yield. Many estimates of the sustainable or "safe" yield of the Pearl Harbor-Honolulu basin and various portions of the basin have been made. Present draft is well within the range of uncertainty of existing estimates. The need of more precise knowledge of the true yield limits for the basin is urgent. According to the State Water Commission (1979, p. 2), "the Pearl

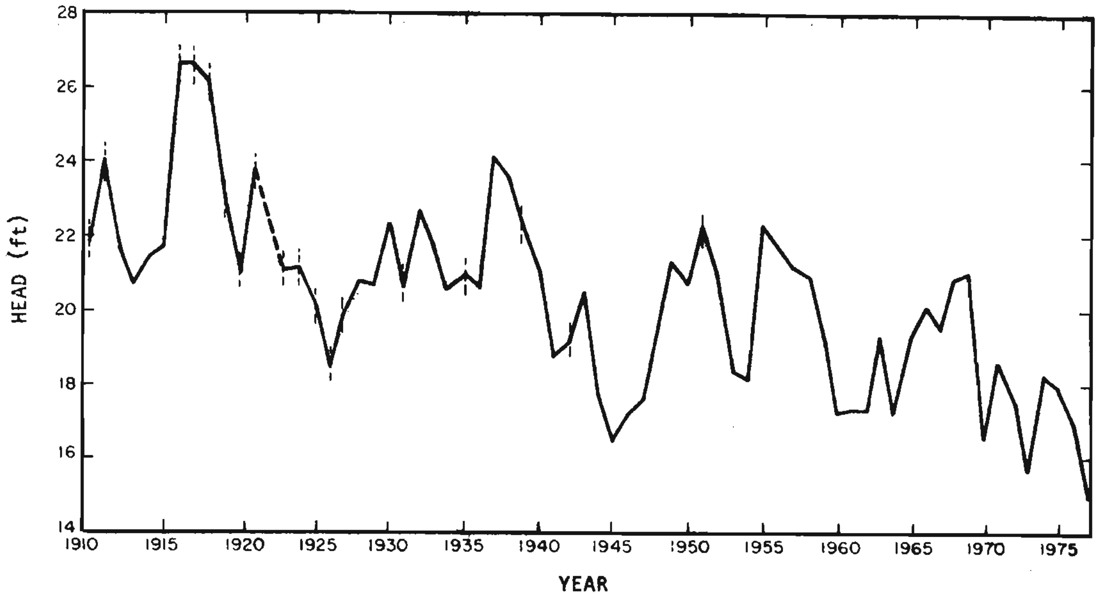


Figure 3. Height of water table, well 2300-10 near Waipahu, Pearl Harbor region, O'ahu, Hawai'i

Harbor ground water reservoir is approaching the limits of feasible development...." However, the Commission noted that "the range of uncertainty in sustainable yield of basal ground water is particularly large" (State Water Commission 1979, p. 1).

Water Balance

SUSTAINABLE YIELD. To assess the limitations of the southern O'ahu groundwater resource and to address the question of sustainable yield, intensive effort has gone into the development of groundwater models to describe the complex behavior of the basal lens. Recent research has produced highly sophisticated analytical (Mink 1980) and numerical (Eyre 1980; Liu, Lau and Mink 1981) groundwater models. Both models require recharge and pumpage estimates. A detailed time series history of groundwater withdrawal has been compiled (Mink 1980; Soroos and Ewart 1979; Dale 1967) and used as model input data. Recharge, however, although highly space- and time-dependent, was until now available only in the form of a long-term average rate representing the entire basin. Eyre (1980), Mink (1980), and Liu, Lau, and Mink (1981) were forced to use a single, estimated recharge rate in their attempts to model the sequence of storage and head fluctuations during the period of groundwater development.

Plainly, the solution of the important Pearl Harbor-Honolulu basin's sustainable yield question awaits an accurate estimate of the recharge in high spatial and temporal resolution. The most practical method of determining the recharge is by the calculation of the soil-plant system water balance.

An important component of the recharge in southern O'ahu is irrigation return flow. A large proportion of water applied to sugarcane percolates beyond the root zone and eventually enters the basal groundwater system. The amount and distribution of this flow is important not only for water quantity evaluation, but for water quality assessment as well, since irrigation return may be contaminated with fertilizers, pesticides, and herbicides.

OTHER APPLICATIONS. While recharge is of great interest to groundwater hydrology, the remaining components of the water balance are important in other areas of study.

The climate of Hawai'i is characterized by spatial and seasonal variability, primarily fluctuations in available water. The regional distribution of soil moisture and its temporal variability are of particular importance to agriculture, especially where irrigation must augment precipitation. Actual evapotranspiration is a measure of energy and moisture availability, and provides a climatic index of potential plant productivity, both cultivated and natural. An understanding of the variability of the water balance is essential in planning for and minimizing the effects of recurrent flooding and drought. In urban land-use planning, consideration of potential water problems has high priority. Thus, an understanding of the water balance and the effects of land-use changes on runoff and recharge is a prerequisite to intelligent decision-making.

Methodology

Water balance is defined in this report as the exchange of moisture that occurs at the surface, through the vegetation, and within the root zone of the soil. The soil-plant system is the appropriate site for evaluating the water balance because (1) it is here that moisture input (precipitation + irrigation) is partitioned into output water masses (runoff, evapotranspiration, and groundwater recharge), and (2) the elements of the water balance are most conveniently measured or estimated at the earth-atmosphere interface.

MODEL. The water balance of the Pearl Harbor-Honolulu basin was evaluated using the balance equation,

$$P + IRR = RO + ET + SM + RCHG \,, \qquad (1)$$

where

P = precipitation
IRR = irrigation
RO = runoff
ET = evapotranspiration
SM = change in soil-moisture storage
RCHG = groundwater recharge.

The plant-soil system for which this equation applies is bounded at the top by the upper surface of the vegetative canopy, and below by the bottom of the root zone of the soil. Each term represents an input to or output from the system. Each term of the equation was evaluated based on direct measurement, estimation from physical or empirical relationships, or by inference through the balancing procedure. The actual balancing was computed by a form of Thornthwaite's "bookkeeping method" (Thornthwaite and Mather 1955). The bookkeeping procedure is used to monitor the quantity of water stored in the soil. The relative soil moisture content determines, in large measure, the partitioning of water input into runoff, evapotranspiration, and recharge. Descriptions of data and techniques of estimation of each element are discussed in detail in later sections.

SPATIAL CONSIDERATIONS. The Pearl Harbor-Honolulu basin study area (Fig. 1) is delimited by natural topographic boundaries: the Ko'olau crest, the drainage divide of the Schofield Plateau, the Wai'anae crest, and the southern coastline of O'ahu. The aquifers underlying the basin are hydraulically connected (Mink 1980) and should be considered as a continuous unit.

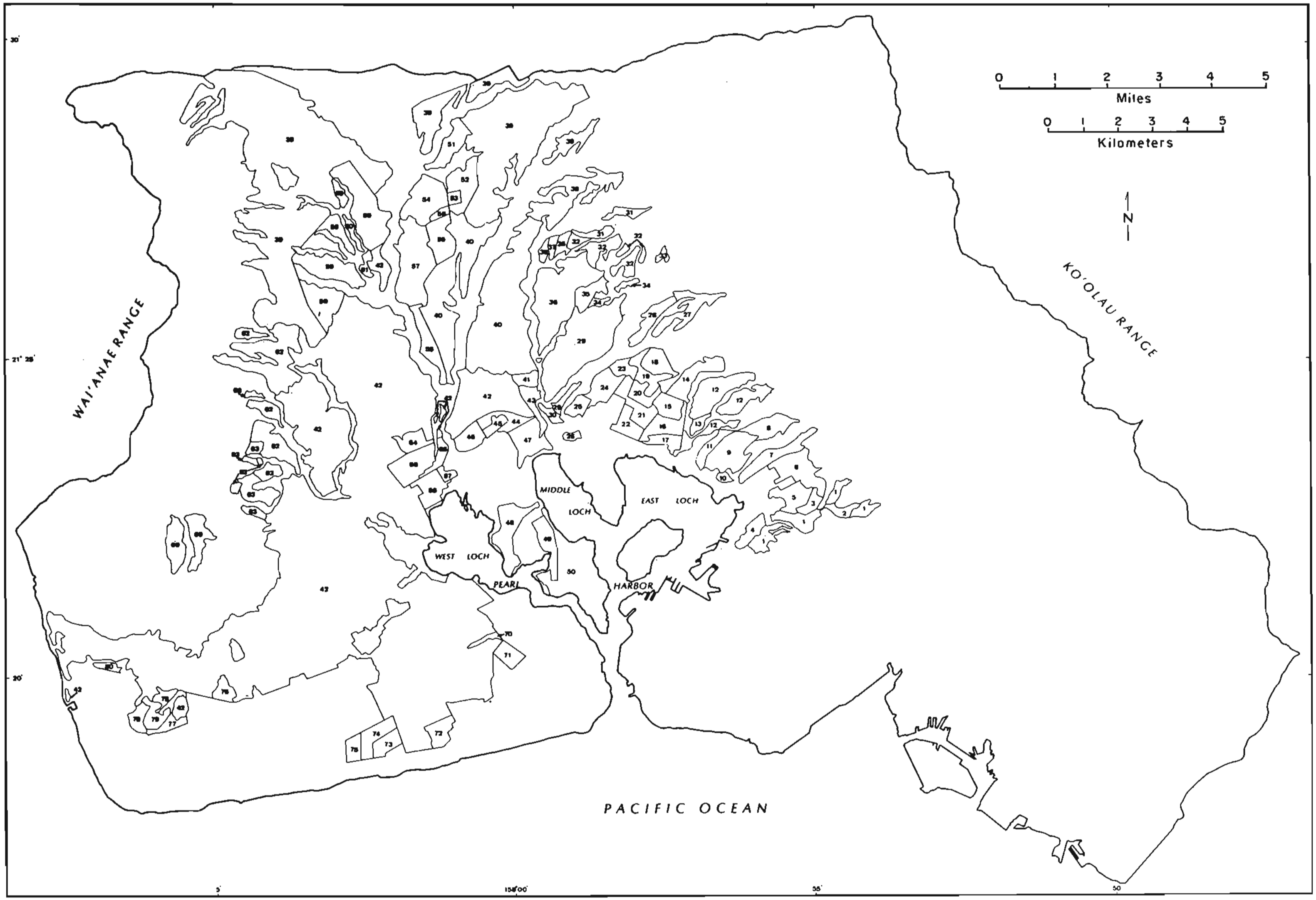
The elements of the water balance have space-dependent distributions in the region. The use of areal averages in such a heterogeneous field can produce substantial error in the balancing operation. Therefore, the basin must be subdivided into units of a scale in which the distribution of each element can be considered homogeneous.

Certain real discontinuities exist in the spatial distributions of the water balance elements. Irrigation is the most notable example. Adjacent fields on the 'Ewa Plain (one vacant land, the other irrigated sugarcane) may receive respectively 635 and 4 445 mm (25 and 175 in.) of total annual water input (precipitation + irrigation). Such a situation is impossible to model accurately without recognizing a boundary between the irrigated and nonirrigated fields. Pineapple cultivation introduces another discontinuity. Evapotranspiration of the pineapple plant is suppressed by the unusual physiology of the plant. Total evaporative flux from a pineapple field may be only 25% of that from an adjacent area of natural vegetation (this topic will be discussed in greater detail in the Evapotranspiration section). In terms of water balance, real discontinuities exist along the borders of all sugarcane- and pineapple-growing areas.

Because the sugarcane- and pineapple-growing areas of southern O'ahu have been in a nearly constant state of flux, a very complex maze of irrigation and evapotranspiration-suppression discontinuities exists for the 30-yr study period. A detailed investigation of the sequence of regional distribution of sugarcane and pineapple fields within the study area was conducted to determine the boundaries of the irrigated and evapotranspiration-suppressed areas during each year (1946-1975). The result of the investigation is shown in Figure 4. Each numbered zone represents an area in which sugarcane or pineapple cultivation occurred during a period which differs from adjacent areas. Table 2 lists the cropping history of each numbered zone.

Irrigation data exist as volumetric totals whose areal distribution could be estimated only by generalizing the irrigation system into five large regions (explained in detail in the Precipitation and Irrigation section). Figure 5 shows the boundaries of the five irrigation zones used in the irrigation analysis.

Another real boundary occurs in the upper Ko'olau Range where the land surface is frequently shrouded in clouds. The cloud base remains relatively constant in Hawai'i at about the 610-m (2000-ft) elevation. Above this elevation, cloud droplets intercepted by vegetation drip to the surface and contribute a significant amount of precipitation. A sharp evaporation dis-



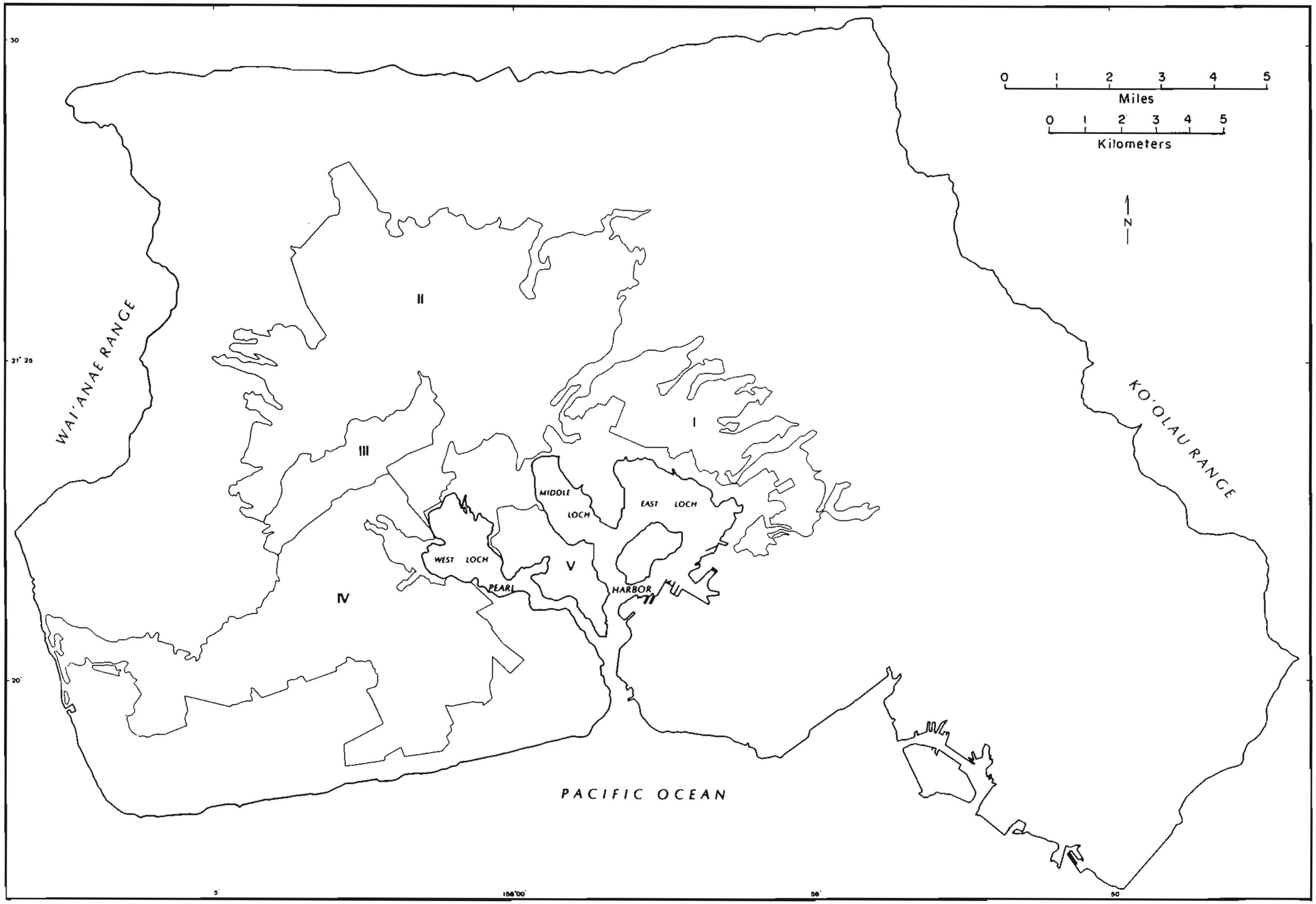
NOTE: Index numbers refer to Table 2.

Figure 4. Sugarcane and pineapple growing areas of southern O'ahu, 1946-1975

TABLE 2. SUGARCANE AND PINEAPPLE CULTIVATION PERIODS, 1946-1975, PEARL HARBOR-HONOLULU BASIN

Map Key*	Sugar- cane	Pine- apple	Map Key	Sugar- cane	Pine- apple
1	1946-61	....	40	1946-51	1952-75
2	1946-56	....	41	1946-64	....
3	1946-63	....	42	1946-75	....
4	1946-61	....	43	1946-65	....
5	1946-59	....	44	1946-69	....
6	1946-48	....	45	1946-55	....
7	1946-58	....	46	1946-72	....
8	1946-65	....	47	1946-64	....
9	1946-60	....	48	1946-75	....
10	1946-64	....	49	1964-75	....
11	1946-66	....	50	1946-75	....
12	1946-70	....	51	....	1946-75
13	1946-68	....	52	....	1946-68
14	1946-69	....	53	....	1946-64
15	1946-68	....	54	....	1946-65
16	1946-68	....	55	1948-51	1952-65
17	1946-68	....	56	1948-74	....
18	1946-70	....	57	1948-75	....
19	1946-64	....	58	1946-51;	1952-61
20	1946-66	....		1962-75	....
21	1946-56	....	59	1968-75	1946-67
22	1946-51	....	60	....	1946-65
23	1946-63	....	61	1961-75	....
24	1946-64	....	62	1961-75	1946-60
25	1946-58	....	63	1963-75	....
26	1946-66	....	64	1946-68	....
27	....	1946-65	65	1946-60	....
28	....	1946-65	66	1946-64	....
29	1946-75	....	67	1946-56	....
30	1946-68	....	68	1946-52	....
31	1963-75	1946-62	69	....	1946-70
32	1961-75	1946-60	70	1964-75	....
33	....	1946-68	71	1965-75	....
34	1952-75	1946-60	72	1962-75	....
35	1946-51;	1952-55	73	1967-75	....
	1956-75	....	74	1963-75	....
36	1946-50;	1951-64	75	1967-75	....
	1965-75	....	76	1947-75	....
37	1946-51;	1952-60	77	1964-75	....
	1961-75	....	78	1968-75	....
38	1946-51	1952-60	79	1949-75	....
39	....	1946-75	80	1968-75	....

*See Figure 4.



NOTE: See Table 8.

Figure 5. Irrigation distribution zones

continuity has also been observed at the cloud base elevation (Ekern 1982).

The principal goal of this study is to provide recharge data for groundwater modeling. The geology of the basin determines the fate of percolating water. Areas underlain by caprock do not contribute recharge to the basal lens. The deep sedimentary (alluvial and colluvial) formations which fill ancient valleys have quite different hydrologic properties from the basaltic aquifer. Although percolation into these formations contributes to the basal groundwater recharge, the rate of movement is retarded by the higher conductive resistance and the recharge of these areas should be considered separately. Thus, three important hydrologic areas are recognized within the study area: (1) basaltic intake, (2) alluvial and colluvial, and (3) caprock. In some previous studies, areas (1) and (2) are lumped together as the "non-caprock" area.

The mean cloud base level was assumed to be at the 610-m level. The hydrogeologic boundaries were determined based on the work of Wentworth (1951). Figure 6 delineates the basaltic, alluvial and colluvial, and caprock areas, as well as the area above the mean cloud base level.

Runoff is measured as streamflow. The water passing a gage represents the integrated runoff contribution of the entire drainage basin upstream of the gage. Thus, the topographic divides become practical discontinuities with regard to runoff data. Drainage boundaries for gaged basins have been determined and delineated on maps by the U.S. Geological Survey (maps available at the USGS Honolulu office). Figure 7 is a map of the drainage basins corresponding to each gage whose data were used in this study.

A rational subdivision of the study area was made by superimposing each set of boundaries described above (Figs. 4-7). Areal units of various sizes resulted. Several large areas remained which violated the premise of climatic and surface homogeneity. These zones were further divided using median annual rainfall isohyets (Fig. 2). In some cases lines which do not represent real boundaries but which were necessary to subdivide a too-large zone were drawn. Very small areas produced by the overlaying process were incorporated into larger units. The result (Fig. 8) is the water balance base map used in this study. Each zone is considered to be homogeneous with respect to each element of the water balance. The 258 spatial units depicted on the map will be referred to subsequently as wb-zones (water balance-zones). The area of each wb-zone was determined by planimetry and is listed in a report by Giambelluca (1983, Table 70).

LAND-USE CLASSIFICATION. To estimate sugarcane irrigation, urban irrigation (lawn sprinkling), runoff, evapotranspiration, and recharge, determination of the land use for each wb-zone was required. Since land use was constantly changing during the study period, a time series of the land use in each wb-zone was determined. The categories of the land-use classification are listed in Table 3. The land use of each wb-zone during each year of the study period is shown in the Giambelluca (1983, Table 70) report.

TEMPORAL CONSIDERATIONS. The water balance was computed for the 1946 through 1975 period by using a monthly interval. The 30 yr (360 mo) study period was selected to assure that a wide range of climatic variation would be included. As such, the water balances of the dry and the wet periods of

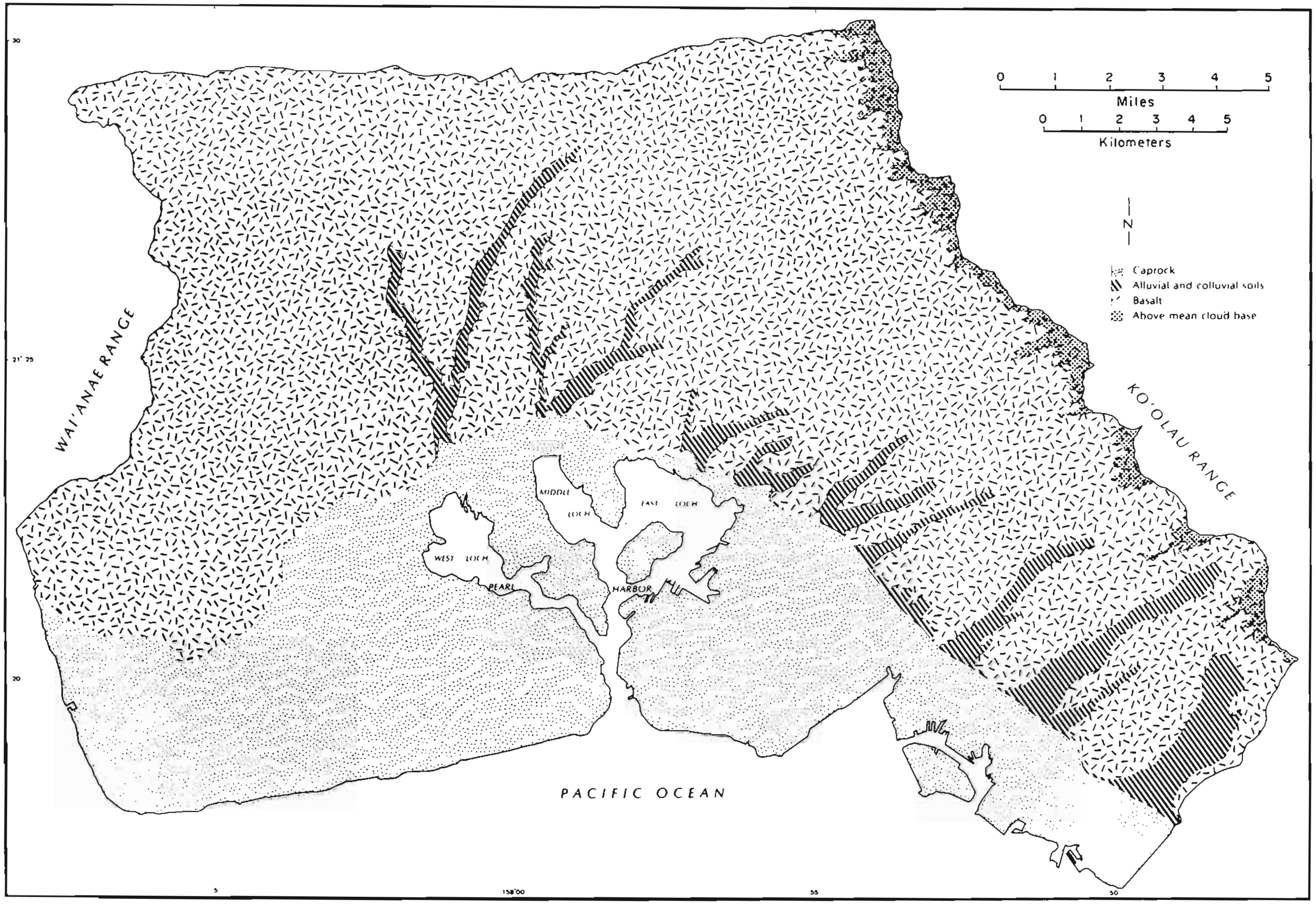


Figure 6. Hydrogeologic areas of caprock, alluvial and colluvial, basalt, and area above mean cloud base level (610 m)

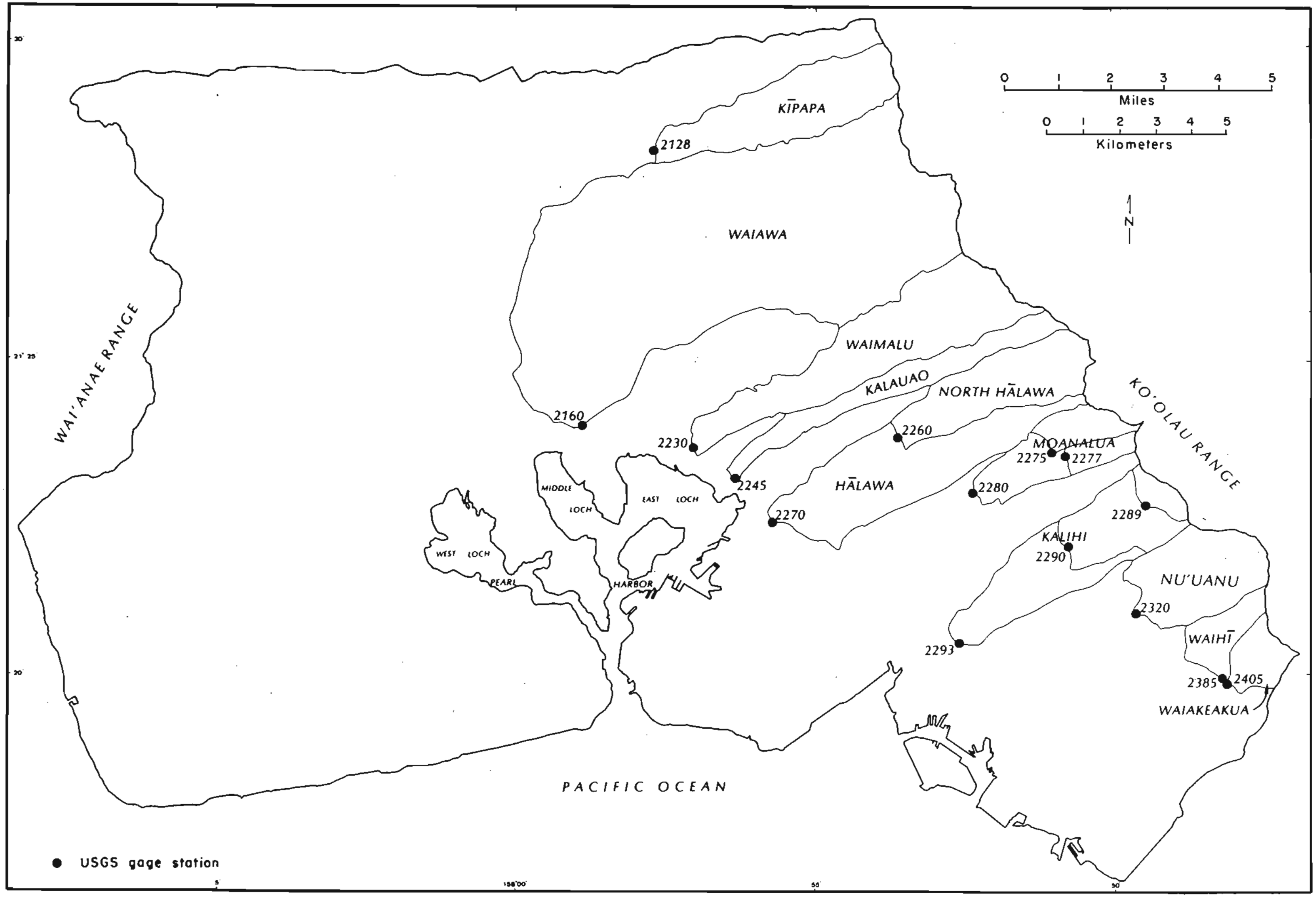


Figure 7. Gaged drainage basins whose stream flow data were selected for runoff analysis

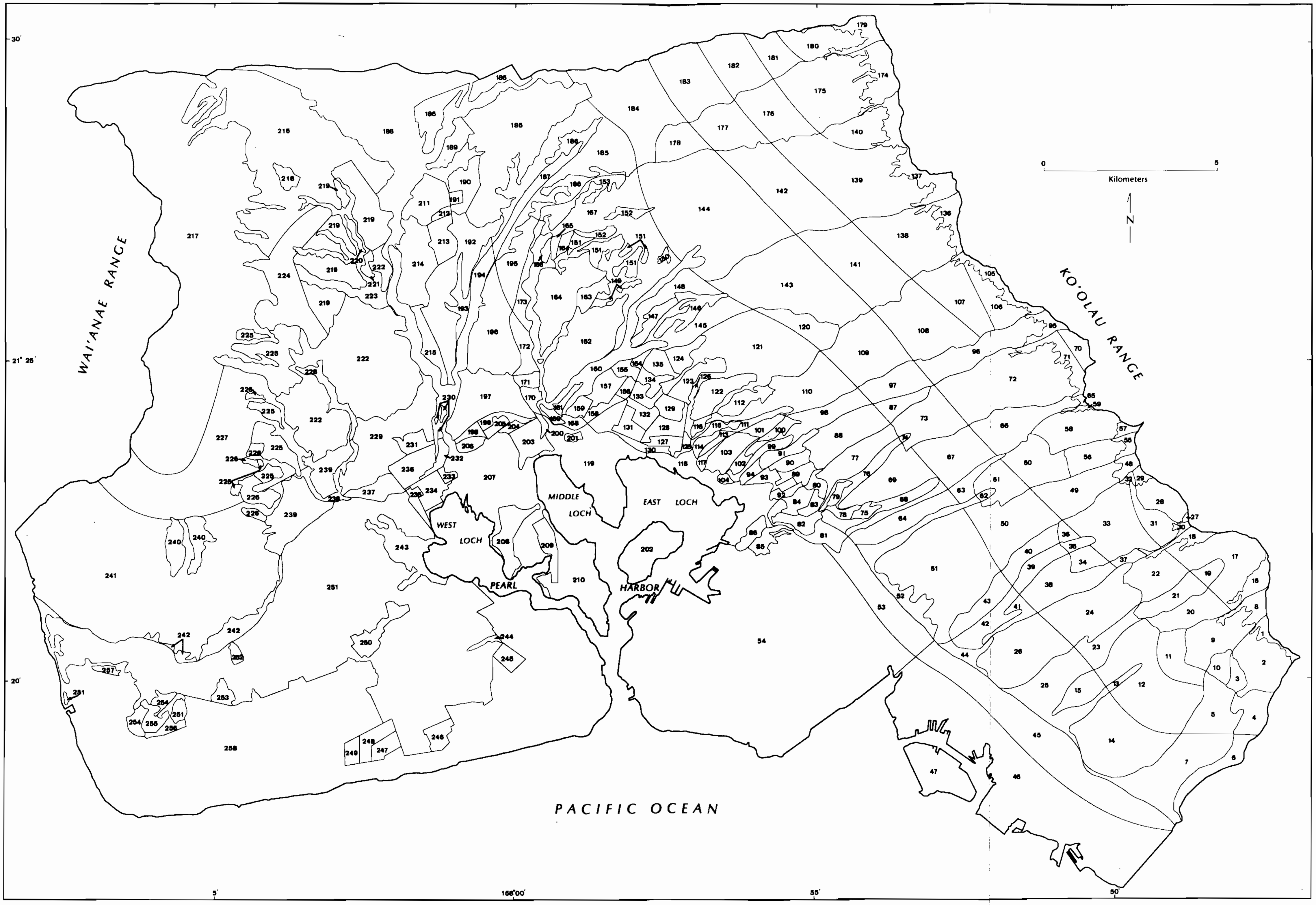


Figure 8. Water balance base map, Pearl Harbor—Honolulu basin, O'ahu, Hawai'i

TABLE 3. LAND-USE CATEGORIES, PEARL HARBOR-HONOLULU BASIN, O'AHU, HAWAI'I

Category	Land-Use Category	% Pervious
1	Sugarcane	100
2	Pineapple	100
3	Urban—Low density	80
4	Urban—Medium density	50
5	Urban—High density	15
6	Mixed (Urban—Medium density; Vacant)	75
7	Mixed (Urban—High, Medium density)	32.5
8	Mixed (Urban—High density; Vacant)	57.5
9	Parks and Golf Courses	100
10	Vacant, Forest, or Pasture	100

various lengths were computed. The length of the study period allows the results to be used to establish the long-term normal water balance in terms of central tendency measures, and its variability in terms of measures of dispersion. Between 1946 and 1975, substantial land-use changes have affected the region. The effects of these changes are apparent in the water balance time series for which implications of future development may be estimated.

The monthly time interval was primarily selected in response to data availability. Although shorter interval observations (weekly or daily) are made at some stations, a greater abundance of monthly totals has been compiled, especially for infrequently read, remote gages. Computer-readable data of monthly precipitation up to 1975 have been compiled; however, an update of this data base to 1981 is currently in progress and was not available for this study. The choices of the study period and the computational interval were based in part on practical considerations, especially the limitations imposed by computer costs and availability of machine-readable data.

SUMMARY. The water balance model was applied individually to 258 wb-zones to compute a 360 mo time series of each water balance element. This research structure facilitates the evaluation of long-term normals and variability, as well as the identification of trends, especially those resulting from anthropogenic impacts on the landscape. The results may be directly applied to the solution of the sustainable yield question, by providing a temporally and spatially detailed quantitative description of groundwater recharge. The important irrigation return-flow component may be identified independently of any irrigation efficiency assumption. Areal totals for any number of different interest regions may be easily computed by summation of the values in the appropriate wb-zones.

PRECIPITATION

The key element of the water balance is rainfall precipitation, the source of all fresh water on the island. Rainfall is the input term in the hydrological cycle. All other elements of the cycle are in some way dependent on precipitation, the only completely independent element. Real and estimated irrigation, runoff, evapotranspiration, and recharge each rely on precipitation.

Rainfall Network

Because of the great spatial diversity of rainfall on O'ahu, a dense network of gages is necessary for proper monitoring. The rain gage network on the island is undoubtedly one of the most dense in the world (Meisner 1978, p. 5). Within the study area, 100 gages were in operation as of 1975, a density of 0.45 gages/mile^2. This figure is misleading, however, since even with this number of gages, rainfall is inadequately monitored in some areas. While the average gage density is high, the distribution is uneven and favors areas of lesser importance with regard to groundwater recharge. A large portion of the network is mainly operated for irrigation management purposes by sugar growers. The bulk of the gages are therefore concentrated on gently sloping, lower and middle elevation, agricultural land. Remote mountain areas are sparsely monitored. Unfortunately for the purposes of this study, the mountains are precisely the areas of greatest concern and the areas requiring the densest rain gage network. The rainfall maxima occur here as well as the steepest gradients.

The computation of the water balance requires an estimate of precipitation for each wb-zone during each month of the study period. Since the distribution of gages is insufficient to provide a measurement site within each wb-zone, a method is required for the estimation of wb-zone precipitation from the existing network.

Precipitation Model

The scale of the problem (258 wb-zones × 360 mo) and the scarcity of data in the remote areas preclude the use of standard point-to-area techniques, such as the Thiessen polygon or isohyetal methods. A precipitation model for this study was required which would

1. Utilize all available relevant data, giving more weight to stations in closer proximity
2. Permit interpolation and/or extrapolation according to known rainfall patterns
3. Be adaptable to automatic computation.

A technique used by the U.S. Weather Bureau for estimating missing precipitation measurements (Paulhus and Kohler 1952) fulfills these requirements. The model, called the normal-ratio method, uses the measurements taken at three nearby stations. These values are extrapolated to the station whose observation is missing by multiplying by the ratio of the normal at the station of interest to the normal of the nearby station. Each of the three stations provides an estimate of the precipitation at the missing station. The final value is determined as the average of the three estimates.

The normal ratio method may be represented as

$$P_X = [(N_X/N_1)\ P_1 + (N_X/N_2)\ P_2 + (N_X/N_3)\ P_3]/3 \qquad (2)$$

where

P_X = precipitation at point of interest
N_X = normal precipitation at point of interest
N_1 = normal precipitation at station 1
N_2 = normal precipitation at station 2
N_3 = normal precipitation at station 3
P_1 = precipitation recorded at station 1
P_2 = precipitation recorded at station 2
P_3 = precipitation recorded at station 3.

Because the estimation is linked to the normals at each location, the known spatial pattern is preserved. This amounts to an analytical, and thereby computer-adaptable, interpolation/extrapolation scheme. The chief assumption of the approach is that the gradient between an estimator station and the point of interest, represented by the ratio of the respective normals, remains constant. In other words, high spatial correlation of rainfall is implied.

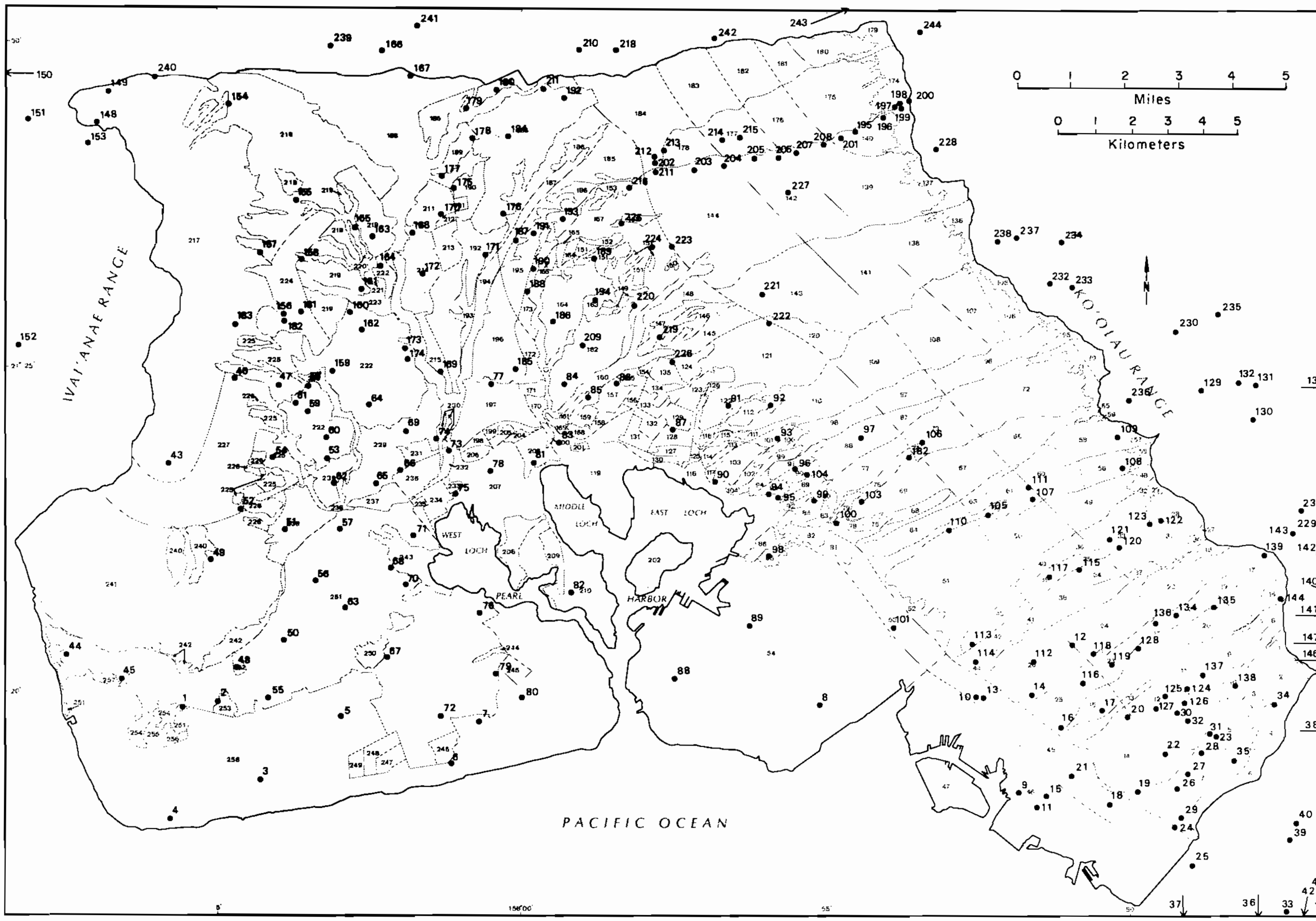
The high spatial correlation of monthly precipitation in the study area has been illustrated by Giambelluca (1983, Fig. 11). The pattern of correlation indicates that stations in close proximity are very well related, and isopleths are oval-shaped and elongated along the normal isohyet. That is, a high correlation between rainfall measurements occurs at greater inter-station distances if the stations have similar normals. Similar results were found by Schroeder (1978) for daily rainfall in Hawai'i. Using contingency index analysis, he showed that high index values were indicated between nearby stations, especially for stations within the same range of normal rainfall.

Rainfall on O'ahu is dominantly orographic in character (Stidd and Leopold 1951). Because of this, the long-term normal pattern strongly resembles shorter-term distributions. The ratio between normals at two points therefore provides a good estimate of the rainfall gradient during any particular month.

Estimation of wb-zone rainfall by the normal ratio method would be expected to be reasonably accurate if index (estimator) stations are near the wb-zone and within approximately the same rainfall belt.

DATA. Hawaiian rainfall data were originally compiled by Taliaferro (1959) and later updated by Meisner (1976) whose data was made available by the Department of Meteorology, University of Hawaii at Manoa. From the Meisner data, records of 244 stations were selected (Fig. 9). A list of the stations and their respective periods of record are listed by Giambelluca (1983, Table 71). Only stations which measured rainfall for a significant period between January 1946 and December 1975 were selected for this study. A few stations which were in close proximity to other stations with similar or longer periods of record were deleted.

INDEX STATIONS. Each wb-zone was assigned six index stations from



NOTE: For station list see Giambelluca (1983, Table 71).

Figure 9. Locations of selected rain gages, southern O'ahu, Hawai'i

which rainfall estimates for that zone were made. Although the model seeks only three stations, a pool of six was necessary because many observations were missing in the data base. Each six-station pool had a priority sequence, such that the nearest or otherwise most preferable stations were sought first. Each month, the three stations with the highest priority were sought to make the estimate. If any of the first three stations had a missing value in a particular month, one or more lower priority stations in the pool was used. For any particular month, no more than three stations were used. In some instances, when several stations were missing observations in the same month, less than three stations were used.

In addition to assigning a priority to each index station in a pool, stations which were clearly more representative of a particular wb-zone than other stations were given additional weight. A simple method of weighting was accomplished by assigning the station to more than one position in the six-station pool of a wb-zone. For instance, if one station was located near the center of a wb-zone and the next nearest station was at a considerable distance away, it was preferable to use only the near station, or at least weight that station's contribution to the rainfall estimate more heavily than the contributions of the more distant stations. To accomplish this, the within-zone station was assigned as the first and second, or the first, second, and third stations in the six-station pool. By assigning a station as both the first and second pool station, its contribution to the estimate was always double that of any other station. If the same station was assigned as the first three pool stations, it provided the sole index for that zone except when data were missing. Lower priority stations were consulted only when this key station was missing an observation.

Based on the pattern of spatial correlation of rainfall, index stations (Giambelluca 1983, Table 72) were chosen according to proximity and similarity in annual normal rainfall to the wb-zone.

NORMALS. In the original version of the normal-ratio method, annual means were used as the normal ratios. In this study, medians will be used rather than means. Several investigations have shown the median to be more representative of the normal monthly rainfall in Hawai'i (Meisner 1978; Landsberg 1951). For estimating monthly precipitation, annual normals can be used only if the gradients between stations remain constant throughout the year. This is not the case for Hawai'i. With the seasonal fluctuation in tradewind frequency and the concentration of cold front occurrence and other mid-latitude type weather patterns in the winter months, a distinct seasonal pattern exists in rainfall gradients. Stidd and Leopold (1951) pointed this out while showing that for each island the mean of any month is a function of the annual mean.

For this study, median rainfall for each month was regressed against annual median rainfall by using data of the stations in and near the study area (Table 4). The coefficients allow monthly medians to be estimated with good accuracy—indicated by the high r^2 values—for any point in the study area whose annual median is known.

The use of these coefficients for dry areas (<635 mm [25 in.] annual median) was found to yield negative values during the summer months. The

TABLE 4. RESULTS OF REGRESSIONS OF MEDIAN MONTHLY VS. MEDIAN ANNUAL RAINFALL, SOUTHERN O'AHU, HAWAI'I

MONTH	MONTHLY = a + b (ANN.)		r^2	SE	N
	a	b			
January	2.44	0.060	0.775	1.17	194
February	0.99	0.059	0.935	0.57	194
March	-0.25	0.091	0.955	0.72	194
April	-1.46	0.095	0.970	0.60	194
May	-1.57	0.079	0.972	0.49	194
June	-1.76	0.071	0.950	0.59	194
July	-2.15	0.093	0.966	0.63	194
August	-2.10	0.089	0.950	0.74	194
September	-1.22	0.066	0.969	0.43	194
October	-0.46	0.072	0.956	0.56	194
November	0.01	0.088	0.922	0.93	194
December	0.97	0.082	0.922	0.86	194

NOTE: SE = standard error of estimate; N = number of cases.

regression was therefore carried out separately using only stations with annual medians of 635 mm (25 in.) or less (Table 5).

To obtain an estimate of median precipitation for any month in a wb-zone, only the median annual precipitation (Fig. 2) for that zone was needed. The median annual rainfall of each wb-zone was determined using this map (Giambelluca 1983, Table 73). Mass balancing computations usually associated with means were not invalidated by the use of medians, since median rainfall was used only for the purpose of defining interpoint gradients.

COMPUTATIONS. The precipitation model employing the normal-ratio method was carried out by computer (program coded in FORTRAN) for each wb-

TABLE 5. RESULTS OF REGRESSIONS OF MEDIAN MONTHLY VS. MEDIAN ANNUAL RAINFALL FOR DRY STATIONS, SOUTHERN O'AHU, HAWAI'I

MONTH	MONTHLY = a + b (ANN.)		r^2	SE	N
	a	b			
January	-3.27	0.296	0.266	0.93	28
February	0.73	0.058	0.093	0.35	28
March	-1.04	0.121	0.432	0.26	28
April	-1.49	0.102	0.577	0.17	28
May	-0.42	0.044	0.350	0.11	28
June	-0.19	0.017	0.141	0.08	28
July	-0.54	0.038	0.410	0.09	28
August	-0.06	0.017	0.039	0.16	28
September	-0.14	0.028	0.137	0.13	28
October	-1.20	0.102	0.465	0.24	28
November	-3.88	0.259	0.364	0.65	28
December	1.13	0.057	0.076	0.38	28

NOTE: Dry stations characterized by <635 mm (25 in.).
NOTE: SE = standard error of estimate; N = number of cases.

zone by month. The computation proceeded as follows:

1. Median precipitation for each month was computed for the wb-zone from the annual median rainfall (Giambelluca 1983, Table 73) by using the regression coefficients listed in Tables 4 and 5
2. From the wb-zone's index station pool (Giambelluca 1983, Table 72), the records for up to three stations were sought in order of station priority
3. For each index station, the ratio for the particular month was calculated
4. The product of the normal ratio and the rainfall measurement at the index station for that month was computed for each index station, where each of these products comprised one estimate of the wb-zone precipitation for that month
5. One to three estimates thus computed were averaged for the monthly zone precipitation
6. The procedure was repeated for each of the 360 months of the study period, then the process began again for the next zone.

Results

The computations resulted in the creation of 258 12-by-30 matrices of monthly wb-zone precipitation. This output dataset is stored on magnetic tape as dataset ZONE.PRECIP.DATA (App. B). Regional precipitation averages are summarized in Appendix Tables A.1 through A.4. Monthly and annual 30-yr averages are shown for various portions of the study area. The three hydrogeologic divisions, caprock, alluvial/colluvial, and basalt intake areas are represented. Averages are expressed in terms of depth (in.) and volume (mgd). The annual average precipitation for the entire 570.069×10^6 m² (220.1 miles²) study area is 1 556.77 mm (61.29 in.) or 28.53 m³/s (651.13 mgd). The results are also summarized in the form of annual totals (App. Tables A.5-A.8) to illustrate year-to-year variations. Table 6 shows the present results in comparison with previous studies.

TABLE 6. COMPARISON OF PRECIPITATION ESTIMATES, PEARL HARBOR AND HONOLULU REGIONS, O'AHU, HAWAI'I

INVESTIGATOR	PRECIPITATION Pearl Harbor Non-Caprock	Total	Honolulu Basalt
	(mgd)		
Voorhees (1929)	448*	492	---
Wentworth (1951)	409*	---	126†
Hawaii Water Authority (1959)	509	---	---
Mink (1964)	428	---	---
Dale (1967)	400	---	---
Takasaki (1978)	425	---	---
State Water Commission (1979)	425	---	---
Mink (1980)	425	---	---
This study	427	478	118

NOTE: mgd × 0.043 81 = m³/s.
*Adjusted by Mink (1980) to represent non-caprock portion of Pearl Harbor region.
†Adjusted to represent basaltic area.

ERROR ESTIMATE. To test the model, the method was applied to points where rainfall is measured, i.e., rain-gage sites. Seven stations were selected representing various portions of the study area and including a wide range of normal precipitation. For each of these stations, a pool of six index stations was selected and precipitation was estimated based on the records of these stations by using the normal-ratio method.

Comparison of the estimated and measured precipitation shows very good agreement for all seven stations. Shown in Table 7 are the results of correlations of model vs. actual precipitation at each location. The r^2 values are uniformly high, indicating strong relationships. The last column shows the average distance of the first three index stations. The standard error of the estimate did not exceed 30% except for station 863.10, whose primary predictor stations were at an average distance of 2 253 m (1.40 mile). Most wb-zones are within 1 609 m (1 mile) of their first three index stations. This error is of the same order of magnitude as measurement errors for rain gages and is considered acceptable for the purposes of this study. Scattergrams of estimated vs. measured monthly precipitation (Giambelluca 1983, Fig. 13) show a strong clustering along a 1:1 line, indicating that the model is properly calibrated.

TABLE 7. CORRELATION OF MEASURED VS. ESTIMATED (NORMAL-RATIO METHOD) MONTHLY RAINFALL, O'AHU, HAWAI'I

Map Key*	State Key No.	Station Name	r^2	Std. Error† (in.)	Std. Error† (%)	N‡	Dist.§ (mile)
1	700.00	Waimānalo ('Ewa)	0.970	0.483	26.3	360	1.124
18	704.00	Makiki	0.952	0.686	21.5	360	0.706
63	740.00	Reservoir 5	0.968	0.517	25.5	360	0.939
134	782.00	Lower Laukaha	0.937	1.453	14.5	360	0.517
137	784.00	Pauoa Flats	0.910	2.006	14.8	360	1.124
218	833.00	Ko'olau Dam	0.887	1.839	17.7	360	0.812
240	863.10	Area BB	0.794	1.710	43.9	360	1.403

NOTE: in. × 25.4 = mm.
*See Fig. 9 for rain gage sites.
†Standard error of estimate.
‡Number of cases.
§Average distance to first 3 estimator stations.

FOG DRIP. Interception of cloud droplets by vegetation contributes significant quantities of moisture to the soil in cloud-shrouded areas of the Hawaiian Islands (Ekern 1983; Juvik and Ekern 1978; McKnight and Juvik 1975). A water balance study of an area of West Maui (Caskey 1968) found evidence that fog drip may contribute a large portion of moisture input to elevated land areas. In a recent field study by Ekern (1983), the quantity of fog drip on leeward Ko'olau slopes where light winds prevail was found to remain relatively constant at about 152.4 mm (6 in.) per year for areas above the 609.6 m (2000 ft) cloud base level.

INTERCEPTION. Not all of the precipitation measured by a rain gage reaches the soil surface and becomes available for runoff, evapotranspiration, and groundwater recharge. Part of it is caught by vegetation and forest litter and evaporated during and after a storm. This water is termed interception.

For the purposes of this study, interception loss was not computed explicitly because of the uncertainty regarding its magnitude. Evaporation rate adjustments made for computing the evapotranspiration of various vegetation surfaces (see Evaporation section) were assumed to adequately account for interception loss as a part of total evapotranspiration.

IRRIGATION

Sugarcane Irrigation

In areas under sugarcane cultivation, most of the total water available at the surface is supplied by irrigation. Sugarcane is grown year-round, and is usually harvested after about a 22 to 24 mo crop cycle on O'ahu. Because of the large evaporative demands of Hawai'i's climate and the high permeability of the aggregated Oxisol order silty clay soils, sugarcane requires up to 5 080.0 mm (200 in.) per year of irrigation in some areas. This water is an especially important component of the water balance over the non-caprock portion since a large portion percolates beyond the root zone and eventually recharges the groundwater.

Several methods of irrigation have been used in southern O'ahu during the three decades of the study period. The dominant method throughout was furrow irrigation, in which water is applied directly to the soil via a system of gravity fed ditches, troughs, and in-field furrows (Hawaiian Sugar Planters' Association [various years]). During the 1960s, various types of overhead sprinkler irrigation systems were introduced into portions of the plantation fields (Hall 1965). Later, drip irrigation systems were installed in many areas (Fukunaga 1978).

Overhead systems were introduced to improve irrigation efficiency (the ratio of water use by the crop to total water applied). Furrow irrigation is inherently inefficient because large amounts of water must be applied at the upper edge of the field to assure that adequate quantities reach the lower portions (Vaziri and Reynolds 1968; Dougherty 1961). Because of high soil infiltration capacities, much of the applied water percolates beyond the root zone, especially at the upper edge of the fields. Irrigation efficiency of the furrow method is believed to range between 30 and 70% (Fukunaga 1978). Overhead irrigation systems are capable of more uniform distribution of water. However, such systems proved difficult to maintain in the field,* and their use apparently peaked in the mid-1960s and gradually declined as acreage was converted back to furrow irrigation or the new drip technology. Areas under drip systems have markedly increased in the last several years; however, drip irrigation was primarily introduced after 1975, the end of the study period. Since irrigation efficiency of the drip method may be as high as 80 to 95% (Fukunaga 1978), it is important to be aware of the effects of recent conversion to drip irrigation when interpreting the results of this study.

The sources of water used for sugarcane irrigation on southern O'ahu are (1) water pumped from the basal aquifer, (2) water imported from wind-

*Y. Morita 1982: personal communication.

ward O'ahu streams and Ko'olau dike compartments via the Waiāhole Ditch-Tunnel system, (3) water diverted from leeward Ko'olau streams, and (4) water pumped from shallow caprock aquifers. In many local groundwater studies, irrigation water derived from groundwater is treated separately from other irrigation sources. The portion of water which percolates beyond the root zone, return irrigation, is subtracted to obtain a net groundwater loss by plant use. In this study, irrigation is not differentiated by source. The recharge which results is due to the combination of irrigation from various sources and precipitation. Subsequent assessment of the hydrologic budget of the groundwater basin requires that pumpage be accounted for as an output term.

Data

The sugarcane plantations within the study area, Oahu Sugar Company and Ewa Plantation Company (since 1970 part of Oahu Sugar), kept records of the amounts of water pumped from wells and imported by ditch or diverted from streams to be used for irrigation. These data are kept on file at the U.S. Geological Survey, Honolulu office, where they were made available for this study. The data are in the form of volumetric quantities and the particular sources are identified. Monthly volumes are tabulated for each pump and ditch.

Records of pumped groundwater are derived from electrical usage of the pumps. At the time of installation of each pump, calibration constants were determined, relating water pumpage to power consumption. Some local hydrologists suspect that, as the pumps aged, efficiency declined and estimated of water extraction obtained from the electrical usage were gradually inflated.* Lower water table levels also require additional energy to raise the same water quantity. The amount of calibration drift associated with machinery deterioration and water table decline is open to speculation. Recently, the Hawaii State Department of Land and Natural Resources initiated action to require that flow meters be installed on all pumps. Data from these meters are not yet available. Evidence of errors in existing pumpage data are discussed later in this section.

Analysis

To estimate the spatial distribution of irrigation water volumes and to obtain the depth of irrigation for a particular location, the location and extent of irrigated lands were first determined. Because of continuous changes in land use, an assessment was made for each year of the study period. The results were presented in the Introduction section (Figure 4, Table 2). The study area was subdivided into wb-zones, partly because of the need to locate irrigated areas on a time-independent basis.

The determination of the locations and changes in irrigated areas throughout the study period was made by comparing various maps and aerial photographs made at different times. The primary sources of information were the Pineapple Research Institue (1940), Hawaiian Pineapple Company (1952), Land Study Bureau (Nelson 1963; Sahara et al. 1972), Hawaii State Department of Agriculture (1975), U.S. Geological Survey (1968), Dale (1967), and Oahu Sugar Company plantation maps for various years. Because maps were not available for each of the 30 years of study, other sources of informa-

*P. Eyre 1982: personal communication.

tion (pumpage data, sugarcane acreages reported in plantation reports) were occasionally used. The occurrence of a particular land-use shift, into or out of sugarcane, could often only be narrowed to a 2- to 3-yr range. In such cases, an estimate was based on the best available information.

Sugar plantation irrigation network maps from Oahu Sugar Company were used to determine the areas of distribution for each irrigation volume total. The maps depict the field which are irrigated by each pump and ditch. However, because of the manifold system interconnecting various pumps and ditches, the irrigation system could only be separated into five zones. For each of these zones (see Fig. 5), corresponding monthly irrigation totals were obtained by combining the data of a group of wells and ditch systems. Table 8 lists the well and ditch grouping.

TABLE 8. WELL PUMPS AND DITCHES SUPPLYING WATER TO IRRIGATION ZONES, O'AHU, HAWAI'I

Irrig. Zone*	Well Pumps and Ditches
I	'Aiea section pumps 1-6, 16, 21; McCandless Tunnel
II	Waipahu section pumps 3, 4, 6, 6B, 8, 9, 17A, 17B; Kīpapa Ditch; Waikakalaua Ditch; Waiawa Ditch; Waiawa Intake; Waiāhole Ditch
III	Waipahu section pumps 1, 2, 5
IV	'Ewa section pumps (all)
V	Mill water; pump 7

*See Fig. 5.

The average depth of applied water for each irrigation zone during each month was computed by dividing the water volume by area irrigated and making appropriate unit conversion. The irrigated area for each year was computed by summing all wb-zones in sugarcane that year. Because the wb-zone boundaries were generalized, sugarcane areas in this study include nonirrigated areas, such as roads and small gulches.

To obtain the depth of irrigation for an individual wb-zone, an adjustment was made to allow for differing irrigation requirements within an irrigation zone. Irrigation management practices presumably attempt to provide water where needed. Because of the size of the irrigation zones, large differences in wb-zone precipitation may occur within a single irrigation zone. Therefore, a simple model was developed to simulate irrigation distribution within each irrigation zone. The model assigns irrigation to wb-zones each month according to the amount of rainfall received that month. The basic assumption of the model is that irrigation is applied so that the total water input depth (precipitation + irrigation) is constant over the entire irrigation zone in any month. Greater depths of irrigation were assigned to drier areas. No provision was made for differences in evaporative demand, assumed constant over each irrigation zone. When extreme differences in rainfall were observed, a constant total water depth could not be maintained over the irrigation zone. In such cases, precipitation alone in some wb-zones exceeds precipitation plus irrigation elsewhere.

Average depths of applied water for each irrigation zone were examined for evidence of possible calibration drift error. To account for variations in irrigation requirements because of rainfall fluctuations, total water input (precipitation + irrigation) was computed. Figure 10 shows average annual total water input for each irrigation zone. As suspected, higher quantities of water input are indicated in later years in zones using only pumped groundwater (irrigation zones III, IV, V). While zone IV indicates a gradual increase, zones III and IV exhibit sudden increases to higher levels, followed by a decline— a pattern not consistent with the theory of calibration drift.

Possible alternative explanations for the observed changes in total water input to the fields are as follows.

1. Irrigation management is based on supply, since even at highest rates of application the crop may be underirrigated (in terms of potential yield). As such, total available water has increased (new wells, more Waiāhole Ditch water) as total sugarcane acreage has declined. Thus, observed increases in depths of applied water are real and reflect increased water availability.

2. Irrigation practices have undergone changes over the years. Introduction of different irrigation techniques, such as overhead sprinkling, coincide with the observed peaks in Figure 10 which may indicate greater water usage accompanied this technology shift. Also, the criteria for scheduling irrigations have changed as a result of continuous experimental research by the HSPA and others regarding optimum water-yield relationships . Soil moisture estimation techniques have also varied (evaporation pan, gypsum block, tensiometer).

Evidence is insufficient to warrant adjustment of power consumption-based irrigation estimates. Although some figures appear to be too high and may be erroneous, no reliable means of adjustment is available. The possible alternative explanations appear plausible. Therefore, pump estimates were used in this study without adjustment.

The results of the irrigation analysis consist of 12-mo-by-30-yr matrices of irrigation depths for each wb-zone within any of the five sugarcane irrigation zones (Fig. 5). These matrices are stored on magnetic tape as dataset ZONE.IRR.DATA (App. B).

Urban Lawn Sprinkling

In dry suburban residential environments, such as portions of leeward O'ahu, irrigation of lawns and gardens provides a significant portion of the water input to the soil. Quantitative assessments of lawn sprinkling on O'ahu have been a factor in economic analyses of municipal water consumption (Yamauchi 1981; Oh and Yamauchi 1974). In these studies a regular pattern of seasonal water use fluctuation was observed with usage peaking during the summer. The month-to-month fluctuation was attributed mainly to variations in outdoor use of municipal water in response to seasonal rainfall by

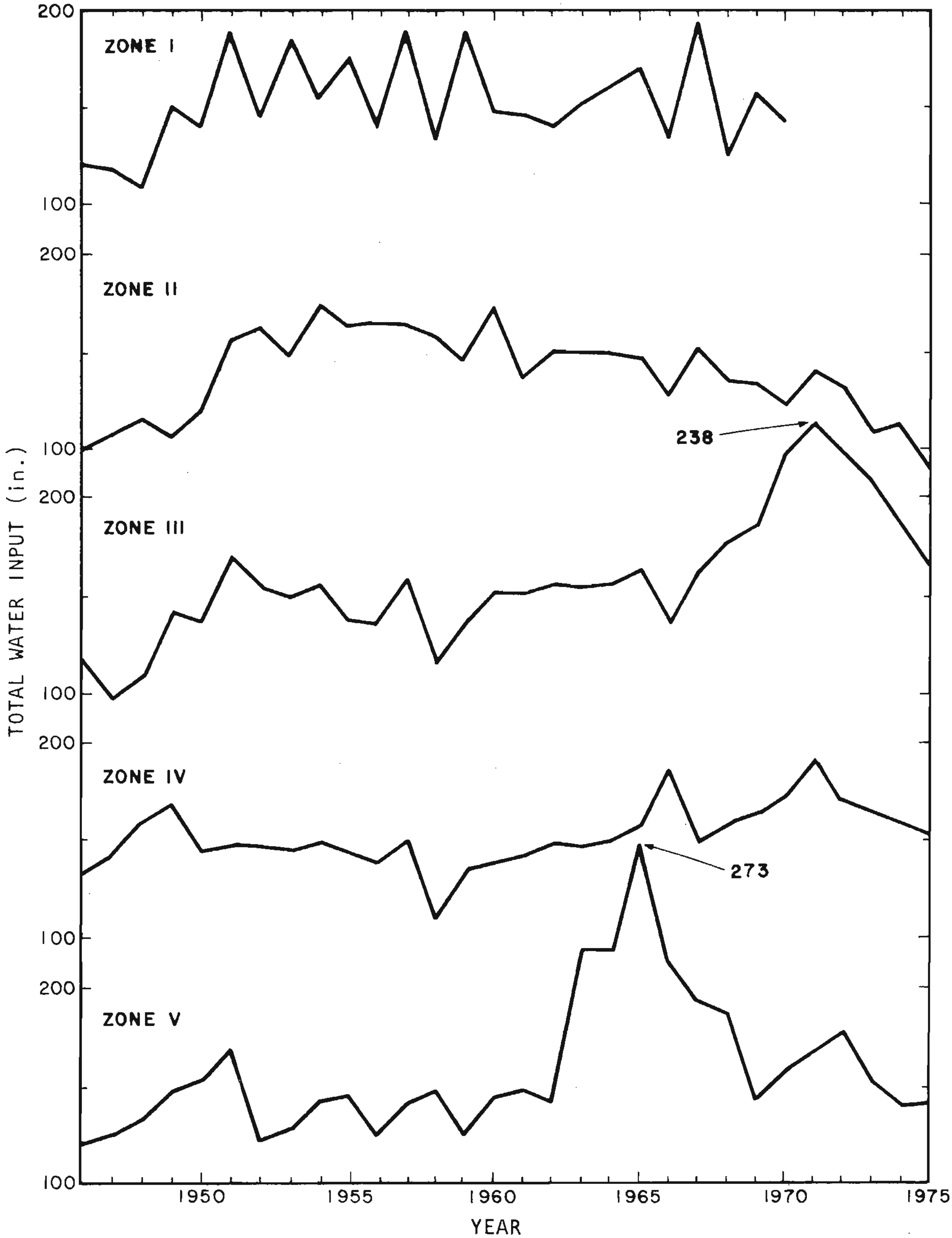


Figure 10. Annual total water input (precipitation + irrigation) by irrigation zone, 1946-1975, Pearl Harbor-Honolulu basin

Yamauchi (1981, p. 177). Oh and Yamauchi (1974, Table 5) presented a monthly index of water consumption, which they termed the "ratio-to-moving average seasonal index" for the July 1960 to June 1961 period. The pattern is clearly represented by the following monthly averages: January 86.5, February 88.1, March 89.6, April 95.0, May 97.7, June 109.2, July 116.4, August 115.3, September 116.4, October 101.7, November 94.3, and December 88.9. Also presented were equations representing trends in maximum and minimum daily water consumption (Oh and Yamauchi 1974, App. K). By assuming that the lowest observed water use represents a period of no lawn sprinkling (an extended rainy period), these relations together with the seasonal index values provide a means to estimating monthly urban irrigation.

Using this approach, the volume of water used for lawn sprinkling in southern O'ahu was computed for each month between January 1961 and December 1970. The area over which this irrigation occurred was estimated based on the land-use assessment (Giambelluca 1983, Table 70). For each year, the pervious portions of the low- and medium-density residential areas were integrated. Average depths of lawn sprinkling were then computed using these area estimates (Table 9). The seasonal fluctuation accounts for much of the variability and year-to-year changes do not appear to represent a trend; therefore, the monthly averages were used in the water balance. The appropriate quantity of monthly irrigation was added to soil moisture of pervious portions of residential wb-zones only (LU3*, 75%; LU4, 50%; LU6, 25%; LU7, 25%; LU9, 100%). While it is acknowledged that spatial variations in lawn sprinkling occur because of the rainfall pattern, no provision was made for such variation in this study.

TABLE 9. MONTHLY AND ANNUAL URBAN IRRIGATION DEPTHS BASED ON SEASONAL FLUCTUATION OF MUNICIPAL WATER USAGE, 1961-1970, O'AHU, HAWAI'I

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual (in.)
	(in.)												
1961	0.15	0.21	0.34	1.16	0.90	1.74	1.44	1.67	2.03	1.02	0.48	0.27	11.42
1962	0.70	0.49	0.16	0.38	0.68	1.42	1.92	1.94	1.99	1.21	1.22	1.02	13.13
1963	0.45	0.00	0.22	0.24	0.21	1.21	2.22	2.04	2.05	1.10	0.87	0.76	11.37
1964	0.31	0.48	0.51	0.76	0.49	1.72	2.16	1.77	2.07	1.11	0.88	0.31	12.58
1965	0.31	0.37	0.64	0.88	0.97	0.55	1.87	1.70	2.13	1.13	0.56	0.30	11.41
1966	0.28	0.33	0.17	0.78	1.09	1.34	2.22	2.23	2.20	1.58	0.44	0.35	13.00
1967	0.36	0.38	0.31	0.43	0.84	1.52	2.10	1.99	1.63	1.31	0.87	0.28	12.01
1968	0.15	0.12	0.18	0.58	1.28	2.14	2.77	2.66	1.74	0.89	0.56	0.02	13.09
1969	0.00	0.26	0.74	0.95	1.38	1.97	2.10	1.79	1.49	1.17	0.61	0.29	12.76
1970	0.00	0.54	1.05	1.31	1.42	1.97	2.10	2.13	1.69	1.10	0.50	0.16	13.98
Avg.	0.27	0.32	0.43	0.75	0.93	1.56	2.09	1.99	1.90	1.16	0.70	0.38	12.48

NOTE: in. × 25.4 = mm.

*Land-use categories (see Table 3).

RUNOFF

For the purposes of this study, runoff includes all surface flow except that which originates in the basal groundwater body. Thus, direct storm runoff, interflow, and high-level spring flow are included in one term. Conservation of mass requirements are thereby satisfied for the water balance of the soil system. Streamflow may be equated with runoff if no diversions (such as for irrigation), additions (such as sewage effluent), or seepage through the streambed occur, and no basal groundwater leaks into the stream. Where diversion, addition, seepage, or basal groundwater flow take place, streamflow data must be adjusted to represent runoff.

Data

The records of 15 stream gages, covering a total drainage area of 168.195×10^6 m^2 (64.94 $miles^2$) or about 30% of the study area, serve as the runoff data base. Table 10 lists the gages. Figure 7 shows the boundaries of each gaged drainage basin. The U.S. Geological Survey (1979) monitored the gages and published the data. The coverage provided is nearly complete along the important leeward Ko'olau region of the study area. Elsewhere, few data are available.

Although a long record of stream discharge is available for Waikele Stream at Waipahu (USGS gage 2130), the data were not included for two reasons. First, the measurements are affected by nonrunoff inflow, including base flow, and sewage effluent, which enter the stream above the gage (Hirashima 1971, p. 13). Thus, a significant portion of the measured dis-

TABLE 10. GAGED DRAINAGE BASINS, O'AHU, HAWAI'I

Basin	Stream	USGS Gage No.	Wb-Zones	Drainage Area ($mile^2$)	Period
1	Waiakeakua	2405	1-3	1.06	1946-1975
2	Waihī	2385	8-10	1.14	1946-1975
3	Nu'uanu	2320	16-22	3.35	1946-1960
4	Kalihi	2289	27-29	0.60	1966-1971
5	Kalihi	2290	30-36	2.01*	1961-1971
6	Kalihi	2293	37-43	2.57*	1962-1975
7	Moanalua	2277	55-56	0.62	1968-1975
8	Moanalua	2275	57-59	0.94	1968-1975
9	Moanalua	2280	60-62	1.17*	1946-1975
10	Hālawa	2270	65-69, 75-84	8.78	1953-1975
11	North Hālawa	2260	70-74	3.45	1953-1975
12	Kalauao	2245	95-100, 102	2.59	1957-1973
13	Waimalu	2230	105-116	5.97	1952-1971
14	Waiawa	2160	136-173	26.40	1952-1975
15	Kīpapa	2128	174-178	4.29	1957-1975

*For multi-gage basins (Kalihi, Moanalua), drainage area below next upstream gage.

charge is not runoff. Second, because the drainage area is quite large (116.291×10^6 m^2 [44.9 $miles^2$]) and land use and climate diverse, Waikele Stream discharge represents an integration of a very heterogeneous runoff field. Little information is yielded concerning runoff for the spatial unit of this study, the water balance-zone (wb-zone).

DATA ADJUSTMENTS. In order for streamflow to represent runoff, adjustments must be made for diversion, addition, seepage, and base flow. No significant amounts of addition occur upstream of the 15 gages selected for this study. The flow of Nu'uanu Stream, however, is regulated by several small reservoirs. Although observations concerning seepage indicate that many leeward Ko'olau streams are perennial in their upper reaches and intermittent below, the amount of implied seepage is considered small. In a study of streamflow in the Pearl Harbor basin, Hirashima (1971, p. 14) states:

> ...alluvial streambeds are poorly permeable. Thus once water collects in channels and fills all the pools and interstices of the alluvium, additional inflow of water will flow out to sea, only slightly decreased by seepage.

Based on measurements of streamflow at two Kīpapa Stream gages, Hirashima reported that dry weather seepage amounts to only 1.75×10^{-3} m^3/s (0.04 mgd) per mile of stream (Hirashima 1971, p. 15). Therefore, assuming that addition and seepage of water are negligible, accounting must be made only of diversion and base flow.

Records of streamflow diversion for irrigation kept by sugarcane plantations were obtained for this study (see Irrigation section, pp. 29-34). Significant amounts of water were diverted for sugarcane irrigation from Waimalu and Waiawa streams above their gages. The data for these gages were adjusted by adding diverted volume recorded for each month.

Basal groundwater springs are found near the mouths of several streams where they enter Pearl Harbor. Discharge of groundwater into streams occurs upstream of the gages of Hālawa, Kalauao, Waimalu, and Waiawa streams. Hirashima (1971, p. 13) has estimated the spring inflow for these stations to be 0.052 m^3/s (1.19 mgd) for Hālawa, 0.003 m^3/s (0.07 mgd) for Kalauao, 0.026 m^3/s (0.60 mgd) for Waimalu, and 0.114 m^3/s (2.60 mgd) for Waiawa. These figures were converted to monthly values and subtracted from the respective discharge records.

Estimating Monthly Runoff

As Table 10 and Figure 7 indicate, available streamflow data do not provide complete coverage of the study area and study period. Additionally, only five of the gages were operational during the entire 1946 through 1975 study period. Therefore, runoff had to be estimated where and when measurements were lacking.

The spatial unit of this study, for which each element must be evaluated, is the water balance-zone (wb-zone). Each of the gaged stream basins consists of several wb-zones and each measurement represents an aggregated runoff value. The individual runoff contribution of each wb-zone had to be derived by disaggregating the total stream discharge.

The basic tasks requiring runoff modeling were to (1) extend the records of all stream gages to the full 30 yr study period, (2) disaggregate basin discharge totals into individual wb-zone runoff values, and (3) estimate runoff in ungaged areas.

RUNOFF PROCESSES. Runoff is essentially a response to rainfall. The nature of the response varies according to a number of time and space dependent evironmental conditions. Any method of estimating a runoff series must deal with rainfall and the factors influencing the runoff response.

In the classic model of Horton (1933), runoff is described as consisting principally of overland flow. In many situations, however, significant amounts of runoff may originate from water which has infiltrated the soil and returned to the surface (Dunne and Leopold 1978, p. 262).

"Interflow", or throughflow, a process which returns infiltrated water to the surface, is favored in soils in which hydraulic conductivity decreases with depth (Whipkey 1969). Interflow is a lateral, downslope movement of water through the soil, which eventually emerges at the surface. Recent studies, such as by Harr (1977), have demonstrated the importance of interflow in humid vegetated regions especially on steep slopes. In a study of soil development in Brazil, evidence of frequent lateral flow within hillslope Ultisols was found by Moniz and Buol (1982).

A second process involves the return of groundwater to the surface through springs. In Hawai'i, surface flow may originate from the main basal groundwater body only in low-lying coastal areas (Visher and Mink 1964, pp. 34-35). In this report, this process is termed "base flow" which is not considered, here, to be part of runoff. Other forms of groundwater in Hawai'i are perched and high-level dike-confined water bodies, both of which contribute to surface flow. In this paper, surface water originating from high-level perched or dike-confined aquifers is called spring flow. This water does not recharge the basal groundwater body and therefore must be included as a component of the runoff term in the water balance.

The following equations summarize the relationships among the various components of surface flow:

$$StF = RO + BF + AD - DIV \tag{3}$$

where

StF = streamflow
RO = runoff
BF = base flow
AD = addition
DIV = diversion

and

$$RO = OF + IF + SpF \tag{4}$$

where

OF = overland flow
IF = interflow
Spf = spring flow.

In Hawai'i's small, steep-sided watersheds, interflow response is rapid (Hirashima 1971, p. 7). Stream hydrographs indicate that the bulk of discharge occurs during and immediately after a storm (Wu 1967). Mink (1962, p. 157) found that, for Kīpapa Stream, more than 95% of total storm discharge occurred within 5 days of the event. On a monthly basis, therefore, it is quite reasonable to lump overland flow and interflow together when relating runoff to rainfall.

The response of spring flow is more complex. Some high-level springs have been observed to respond to local rainfall, and in some cases cease to flow during dry spells (Stearns and Vaksvik 1935, p. 436). Other springs appear to flow partially or wholly without response to rainfall. These perennial springs are observed to flow at approximately a constant rate through rainless periods (Stearns and Vaksvik 1935, p. 437). It is reasonable to assume, then, that high-level spring flow consists of a variable (responsive to rainfall) component and a perennial (nonresponsive) component. The following relation is suggested as a simple model of spring flow in the Ko'olaus:

$$SpF = a'' + b''P \tag{5}$$

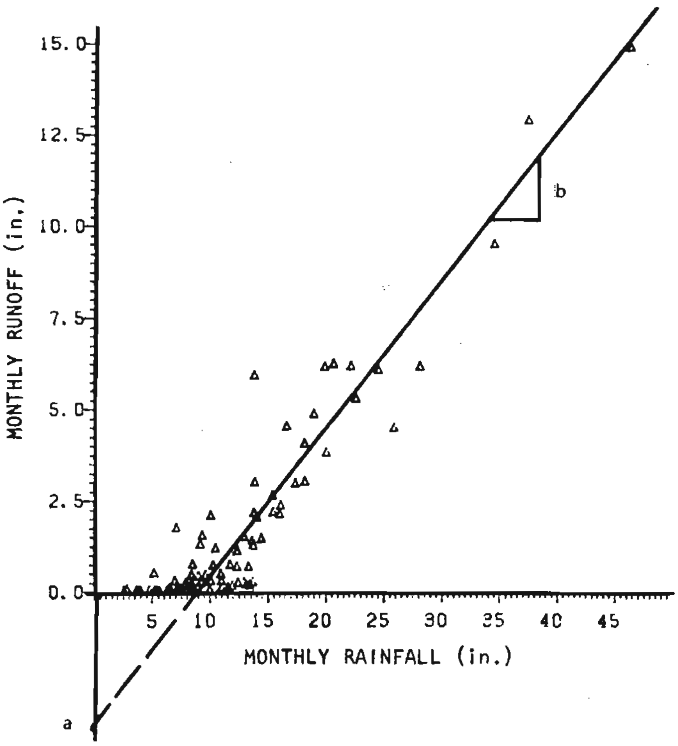
where

SpF = spring flow
a'' = perennial flow constant
b'' = responsive flow constant
P = precipitation.

RUNOFF MODELS. While adhering to physical principles, a runoff model may take various forms differing in accordance with the scale of the problem and the availability of data. Because of the inherent complexity of the problem, the use of a completely deterministic approach to compute runoff is usually impractical. If a series of streamflow measurements is available, empirical techniques often provide the best estimates.

Modeling runoff in Hawai'i, as elsewhere, has been mainly undertaken to estimate flood probabilities. Studies made in recent years (Wu 1969; Chong 1974; Lopez 1975) are concerned chiefly with determining the frequency distributions of extreme runoff events, rather than with estimating continuous runoff volume. Most modeling studies in Hawai'i, in fact, concentrate on calculating peak discharge and assume that runoff volume is already known (Shade 1981, p. 13). Several studies have employed detailed hydrological models for estimation of peak flow and continuous runoff in Hawai'i (Fok et al. 1973; Phamwon 1976; Shade 1981). These state-of-the-art models involve estimation of many basin parameters, and require short-interval rainfall measurements as input data, but have had only limited success in estimating continuous runoff volume. A simpler approach, however, has been used by Anderson, Duffy, and Yamamoto (1966) with excellent results. They used multiple regression techniques to derive an empirical rainfall-runoff relation to model monthly runoff in two small leeward Ko'olau watersheds. The values of the constants were derived for each watershed by season. The coefficients of determination, r^2, ranged from 0.85 to 0.95, indicating a very close relationship.

A typical scattergram of monthly runoff vs. precipitation is shown in Figure 11. A simple linear relation of the form,



NOTE: Best-fit line for non-zero runoff, a = runoff-axis intercept, b = slope of precipitation vs. runoff.

Figure 11. Scattergram of monthly rainfall vs. runoff for Moanalua Stream, O'ahu, showing best-fit line for non-zero runoff

$$RO = a + bP \qquad (6)$$

where

RO = basin runoff
P = basin precipitation
a = runoff-axis intercept
b = slope of the runoff vs. precipitation line

may be derived by linear bivariate regression to yield the line shown in Figure 11. The graph shows that for precipitation less than about 7 in. (177.8 mm), little or no runoff results. Precipitation greater than 7 in. yields runoff equal to a constant percentage of P - 7 (precipitation in excess of 7 in.). Let P_0 represent the critical precipitation minimum. The best-fit line for all non-zero runoff values may be used for all precipitation greater than P_0. Runoff will be equal to zero for all precipitation less than or equal to P_0. Stated mathematically, the model is

$$RO = b(P - P_0) \quad \text{for } P>P_0 \qquad (7)$$

$$RO = 0 \quad \text{for } P<P_0 \qquad (8)$$

where

$$P_0 = -a/b \ . \qquad (9)$$

The quantity represented by P_0 may be interpreted as an aggregate storage term, the sum of all rainfall stored in the soil, on the soil (detention-storage), or on the vegetation (interception storage) during a typical month. The slope, b, represents the proportion of rainfall in excess of P_0 which becomes runoff.

Both a and b, and therefore P_0, would be expected to vary spatially and perhaps seasonally. The constants, a and b, are functions of the environmental conditions (soil type, vegetation, land use, geology). In addition, b may vary according to the rainfall intensity characteristics of the region.

Spring flow, assumed to have a constant and a rainfall-dependent component, influences the a and b constants. The linear model may be revised to illustrate the effects of spring flow. If we assume that a linear relationship exists between rainfall and each runoff component, we have for overland flow plus interflow,

$$(OF + IF) = a' + b'P \qquad (10)$$

and for spring flow, SpF = a'' + b''P (eq. [5]). Substituting into eq. (4) we now have

$$RO = a' + b'P + a'' + b''P \qquad (11)$$

or

$$RO = (a' + a'') + (b' + b'')P \qquad (12)$$

where

a' = aggregate storage detention (negative)
a'' = constant spring flow
b' = proportion of rainfall in excess of P_0 which runs off due to overland flow and interflow
b'' = proportion of rainfall which appears as spring flow in response to local rainfall.

Recalling equation (6) we have

$$a = a' + a'' \qquad (13)$$

and

$$b = b' + b'' \qquad (14)$$

or in the form of equations (7), (8), and (9),

$$RO = b'(P - P_0) + a'' + b''P \quad \text{for } P>P_0 \qquad (15)$$

and

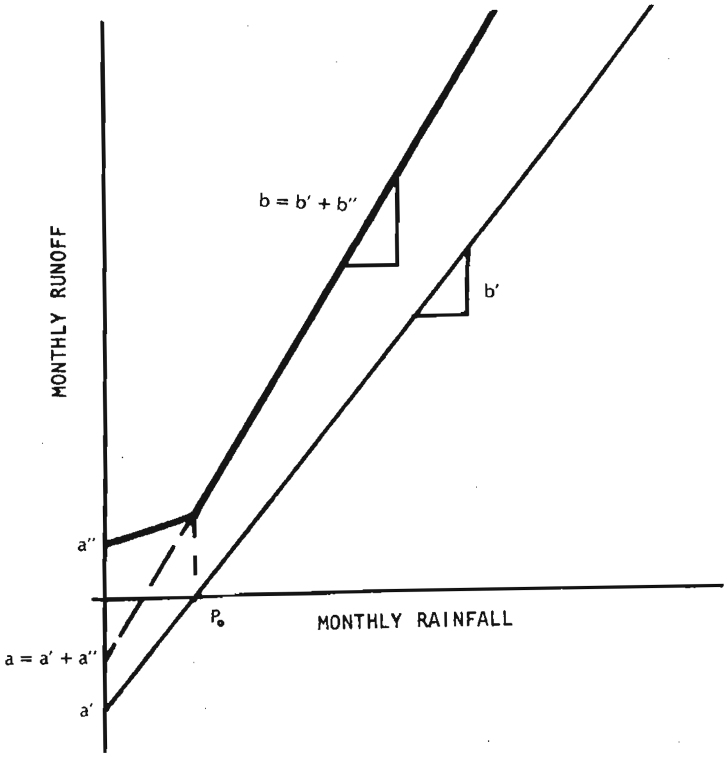
$$RO = a'' + b''P \quad \text{for } P<P_0 \qquad (16)$$

where

$$P_0 = -a'/b' \ . \qquad (17)$$

These relationships are illustrated in Figure 12.

Multiple regression analysis may be used to include time-variant hydrological variables, for instance, a term for antecedent moisture. Inclusion of one or more terms to account for spatial variation in hydrological characteristics allows the use of a single equation to describe a heterogeneous region.



NOTE: a, b = y-axis intercept, slope for runoff including spring flow; a', b' = y-axis intercept, slope for runoff excluding spring flow; a'', b'' = y-axis intercept, slope for spring flow.

Figure 12. Idealized monthly rainfall-runoff model including spring flow

Higher rainfall totals during a month may indicate higher intensity storm rainfall. As such, the rainfall-runoff relationship has a tendency to be nonlinear, with the slope of the curve increasing as precipitation increases. Hirashima (1971) used a logarithmic equation to allow for this nonlinearity. In the study by Anderson, Duffy, and Yamamoto (1966), a precipitation-squared term was included to account for nonlinearity of the runoff response. Their model also includes an antecedent moisture term,

$$RO = a + b_1P + b_2P^2 + b_3AP \tag{18}$$

where

RO = monthly runoff
P = monthly precipitation
AP = previous month precipitation
a = constant
b_1 = precipitation coefficient
b_2 = squared precipitation coefficient
b_3 = antecedent precipitation coefficient.

Extension of Stream Data and Isolation of Lower Reaches

The first task requiring runoff estimation in this study was the extension of the records of the 15 stream gages to the full 30 yr period. To accomplish this, adjusted volumetric streamflow data were first converted to depths for each gaged basin. Because downstream gages in multiple-gaged basins include the runoff contribution of the entire watershed upstream of the gage, streamflow was adjusted by identifying the contribution of the drainage area between the gages. This was done by taking the difference of concurrent discharge measurements of upstream and downstream gages. Before this could be carried out, however, the incomplete records of the upstream gages were extended to the full 30-yr period of record by regression techniques described below.

The data of Basins 1 to 4, 7, 8, and 11 to 15 were analyzed by multiple regression. The model of Anderson, Duffy, and Yamamoto (1966) was used to extend the streamflow records (see eq. [18]). Areal basin precipitation was computed for each month by averaging the precipitation depths of each wb-zone in a particular basin. The precipitation depth of each wb-zone was weighted according to its area as

$$P = (a_1p_1 + a_2p_2 + \ldots + a_np_n)/A \tag{19}$$

where

P = average basin precipitation
a_1 = area zone 1
a_2 = area zone 2
a_n = area zone n
p_1 = precipitation zone 1
p_2 = precipitation zone 2
p_n = precipitation zone n
A = basin area.

Monthly average basin precipitation thus derived was entered into Anderson's multiple regression model against monthly recorded streamflow. The regressions were computed separately for each basin and a different set of constants was derived for each.

Following the procedure of Anderson, Duffy, and Yamamoto (1966), the multiple regression was also carried out separately for summer (May-October) and winter (November-April). Because this seasonal stratification did not significantly alter the results, the relationships derived by regressing all months together were used here.

The records of Basins 4, 7, 8, and 11 to 15 were extended by inserting the appropriate constants into the equation for each basin and by calculating monthly runoff by using basin areal precipitation averages calculated earlier. Runoff was estimated for all months of the study period for which observations were missing. Estimated runoff was also computed for months with observations to illustrate the goodness-of-fit of the model. Scattergrams of estimated vs. observed runoff (Giambelluca 1983, Fig. 18) show that the fit is reasonable.

With all upper-reach gages having complete records (measured or estimated), the runoff of the lower portions of multiple-gaged basins were computed. Multiple and bivariate linear regression analyses were performed for the lower gages as for the others. The results of multiple regression for all basins appear in Table 11. The high coefficients of regression for the multiple and bivariate regressions indicate that a good relationship exists between runoff and the independent variables. The records of Basins 6 and 10 did not cover the entire study period, and were extended using the multiple regression model in the same manner as for the other basins with incomplete records.

TABLE 11. RESULTS OF MULTIPLE REGRESSION OF MONTHLY RUNOFF

Basin	R^2	Constant a	Precipitation Coefficient b_1	b_2	b_3	SE*	N†
1	0.775	1.2606	0.2251	0.0042	0.0904	1.30	360
2	0.886	-0.7284	0.1393	0.0081	0.0764	0.87	360
3	0.797	-0.2330	-0.0202	0.0115	0.1380	1.00	360
4	0.755	0.8495	-0.2228	0.0236	0.0467	1.85	58
5	0.843	-1.4278	0.2603	0.0028	0.0914	1.02	360
6	0.858	-0.9462	0.2386	0.0132	0.1040	1.04	162
7	0.901	-0.7796	0.0842	0.0043	0.0022	0.64	87
8	0.888	-1.2941	0.1518	0.0048	0.0148	0.94	87
9	0.794	-0.7504	0.0167	0.0089	0.0481	1.02	360
10	0.841	0.1543	0.0470	0.0154	0.0158	0.68	111
11	0.789	-0.7513	0.0488	0.0086	0.0478	1.16	270
12	0.764	-0.8345	0.1542	0.0097	0.0293	0.91	222
13	0.750	-0.8627	0.2089	0.0066	0.0018	1.00	220
14	0.734	-1.0153	0.2034	0.0076	0.0324	1.00	282
15	0.888	-1.3878	0.1617	0.0041	0.0369	0.94	228

*Standard error of estimate.
†Number of cases.

In the process of computing runoff collected by lower stream reaches, the monthly runoff volume recorded at the upper gage was found to occasionally exceed that of the lower gage—an indication that seepage is occurring. All negative differences, however, occurred during dry period (no rain in the drainage area of the lower reach) and were of very small magnitude (all less than 1.27 mm [0.5 in.]). Such small negative values of residual local inflow volume may reflect errors in observed flows (Nordenson 1968; p. 10) or small quantities of seepage. In either case, this finding tends to support the assumption that streambed seepage is insignificant.

Basin Runoff Disaggregation and Estimation in Ungaged Areas

The first runoff modeling task, extension of incomplete streamflow records to the complete 30-yr period, was accomplished by using the Anderson multiple regression model. The remaining tasks were to disaggregate this basin runoff and to estimate runoff in areas without gages. Both required a method of estimating the rainfall-runoff relationship on the basis of known hydrological characteristics of the region. Such a method is the Soil Conservation Service (SCS) runoff model (U.S. Department of Agriculture 1972).

The SCS model requires daily rainfall input, which makes it unsuitable in its original form for this study. Therefore, a relationship was derived relating the SCS model to the basic linear bivariate rainfall-runoff model (see eq. [6]), enabling the SCS technique to be used with monthly rainfall input. Before making this modification to the SCS model, the bivariate linear model was applied to the gaged basins by using regression techniques. The results of the regressions were used later to modify the SCS model.

LINEAR BIVARIATE RAINFALL-RUNOFF RELATION. Linear bivariate regression of monthly basin runoff vs. basin precipitation was computed for each of the gaged basins (Table 12). Comparing the coefficients of variation, r^2, obtained using the multiple regression model (Table 11) with those of simple bivariate linear regression (Table 12), it is seen that, in most cases, the contribution of the P^2 and AP terms to the explanation of runoff variation is small. It is evident that the P variable alone accounts for most of the variation in runoff. The small contribution of the P^2 term indicates that the relationship between monthly runoff and precipitation is essentially linear in the leeward Ko'olaus. That the AP term provided only a small increase in r^2 indicates that antecedent moisture condition is not important on a monthly scale. This is not surprising since, as mentioned, the response of Hawaiian streams to rainfall events is very rapid (Mink 1962, p. 157).

TABLE 12. RESULTS OF BIVARIATE LINEAR REGRESSION OF MONTHLY BASIN RUNOFF VS. BASIN PRECIPITATION, SOUTHERN O'AHU, HAWAI'I

Basin	r^2	RO = a + bP (eq. [6])*		SE†	N‡
		a	b		
1	0.725	1.2948	0.3736	1.43	360
2	0.830	-1.4760	0.3986	1.06	360
3	0.615	-0.7573	0.3178	1.37	360
4	0.665	-1.9148	0.4349	2.13	58
5	0.790	-1.1305	0.3623	1.18	360
6	0.814	-1.3796	0.5366	1.18	162
7	0.854	-1.7240	0.2542	0.77	87
8	0.856	-2.453	0.3425	1.05	87
9	0.711	-1.8230	0.2951	1.20	360
10	0.783	-1.1742	0.3577	0.80	111
11	0.730	-1.8271	0.3229	1.31	270
12	0.736	-1.4969	0.3637	0.96	222
13	0.737	-1.7258	0.3649	1.02	220
14	0.716	-1.6693	0.3684	1.03	282
15	0.855	-2.1798	0.3296	1.07	228

*RO = basin runoff, P = basin precipitation, a = intercept, b = slope.
†Standard error of estimate.
‡Number of cases.

As discussed earlier, the basic rainfall-runoff relation can be expressed in terms of the contributions of overland flow and interflow as one component, and spring flow as a second component. To do this, the contribution of each of these two components must be identified. Recall that the regression constants, a and b, can be broken down as $a = a' + a''$ (eq. [13])

and as b = b' + b" (eq. [14]), where a' and b' = contributions to regression constants by overland flow and interflow, and a" and b" = contributions to regression constants by spring flow; and that the monthly aggregate detention storage, P_0, may be identified as $P_0 = -a'/b'$ (eq. [17]). The a and b constants have been computed by linear regression (Table 12). To separate the spring-flow contribution, these results were analyzed.

The valleys in the Honolulu area, Mānoa, Nu'uanu, and Kalihi (basins 1-5) receive spring flow from perched and dike-confined high-level water bodies (Visher and Mink 1964, p. 18; Wentworth 1951, p. 67), while elsewhere in the study area, i.e., the Pearl Harbor area, significant amounts of high-level spring flow are not found (Hirashima 1971, p. 7). That the upper reaches of some Pearl Harbor streams are observed to flow perennially is indicative of the persistence of rainfall along the Ko'olau crest, not of the existence of perennial springs.

To evaluate a" and b" for the Honolulu basins, the constants obtained for the Pearl Harbor basins were examined. For these basins, it can be assumed that a = a' and b = b". Of the basins without spring flow, lower Kalihi (Basin 6), Hālawa (Basin 10), Kalauao (Basin 12), Waimalu (Basin 13), and Waiawa (Basin 14), have values of b which are, in general, higher than in the others. This is attributable to the urbanization or cultivation of portions of those basins. In the all-forested basins of the Pearl Harbor area, Moanalua (basins 7, 8, 9), North Hālawa (Basin 11), and Kīpapa (Basin 15), the average values of the constants are a = -2.00, and b = 0.3089. Ko'olau basins, a" and b" can be estimated for basins 1 through 5 from equations (13) and (14) as

$$a'' = a - (-2.00) \tag{20}$$

$$b'' = b - 0.3089 \ . \tag{21}$$

The values of P_0 may be estimated from a' and b' (Table 13).

Based on model assumptions, the following conclusions can be drawn.

1. The average monthly bivariate linear rainfall-runoff relation for the forested leeward Ko'olau region is

$$RO = -2.00 + 0.3089P \text{ (in.)} \tag{22}$$

or

$$RO = 0.3089 \ (P - 6.4746) \text{ (in.)} \tag{23}$$

Thus, on the average, about 6.5 in. (165.1 mm)/mo of rainfall is necessary to initiate overland flow and/or interflow. Approximately 31% of additional precipitation runs off.

2. Perched aquifers and dike compartments contribute to runoff in Honolulu valleys as follows:

Mānoa Basin 1 $Sp = 3.29 + 0.065 \ P$ (24)

TABLE 13. KO'OLAU RUNOFF PARAMETERS FOR EQUATIONS (15) TO (17)

Basin	a	a'	a''	b	b'	b''	P_0
1	1.29	-2.00	3.29	0.374	0.309	0.065	6.47
2	-1.48	-2.00	0.52	0.399	0.309	0.090	6.47
3	-0.76	-2.00	1.24	0.318	0.309	0.009	6.47
4	-1.91	-2.00	0.09	0.435	0.309	0.126	6.47
5	-1.13	-2.00	0.87	0.362	0.309	0.053	6.47
6	-1.38	-1.38	0.00	0.537	0.537	0.000	2.57
7	-1.72	-1.72	0.00	0.254	0.254	0.000	6.77
8	-2.45	-2.45	0.00	0.343	0.343	0.000	7.14
9	-1.82	-1.82	0.00	0.295	0.295	0.000	6.17
10	-1.17	-1.17	0.00	0.358	0.358	0.000	3.27
11	-1.83	-1.83	0.00	0.323	0.323	0.000	5.67
12	-1.50	-1.50	0.00	0.364	0.364	0.000	4.12
13	-1.73	-1.73	0.00	0.365	0.365	0.000	4.74
14	-1.67	-1.67	0.00	0.386	0.368	0.000	4.54
15	-2.18	-2.18	0.00	0.330	0.330	0.000	6.61

NOTE: $RO = b'(P - P_0) + a'' + b''P$ for $P > P_0$ (eq. [15]);
$P_0 = -a'/b'$ (eq. [17]).

Mānoa	Basin 2	$Sp = 0.52 + 0.090P$	(25)
Nu'uanu	Basin 3	$Sp = 1.24 + 0.009P$	(26)
Kalihi	Basin 4	$Sp = 0.09 + 0.126P$	(27)
Kalihi	Basin 5	$Sp = 0.87 + 0.053$	(28)

3. Both a and b tend to be higher, and thus P_0 lower, in basins which are not completely forested.

SOIL CONSERVATION SERVICE RUNOFF MODEL. The tasks of disaggregating basin runoff into individual wb-zone runoff and of estimating runoff in the ungaged wb-zones require the use of a model capable of deterministic runoff simulation based on the environmental characteristics of a region. The Soil Conservation Service (SCS) of the U.S. Department of Agriculture (1972) has developed a model for use in areas where no streamflow data exist. The portion of rainfall which runs off is estimated based on soil type and land use. The model was developed from physical principles and calibrated empirically. The validity of the SCS method for use in Hawai'i has been demonstrated (Cooley and Lane 1980) and at least one study of runoff in the islands has employed the technique (Lopez 1975). The SCS model was selected to disaggregate the basin runoff totals and to estimate runoff in the ungaged areas.

The basic equation of the SCS model is

$$Q = (P - 0.2S)^2/(P + 0.8S) \quad (29)$$

where

Q = daily runoff
P = daily precipitation
S = return parameter.

The retention parameters, S, is defined as the maximum amount of water which will be retained as storage by soil, vegetation, or in surface depressions and which will not run off under a particular set of circumstances. Operationally, the task is to choose the proper value for S depending upon the hydrological conditions of a region. The "curve number" (CN), a transformation of the retention parameter, is often used because CN produces a more linear rainfall-runoff curve and simplifies graphical computations. CN varies from 0 to 100 and is related to S as

$$CN = 1000/(S + 10) \ . \tag{30}$$

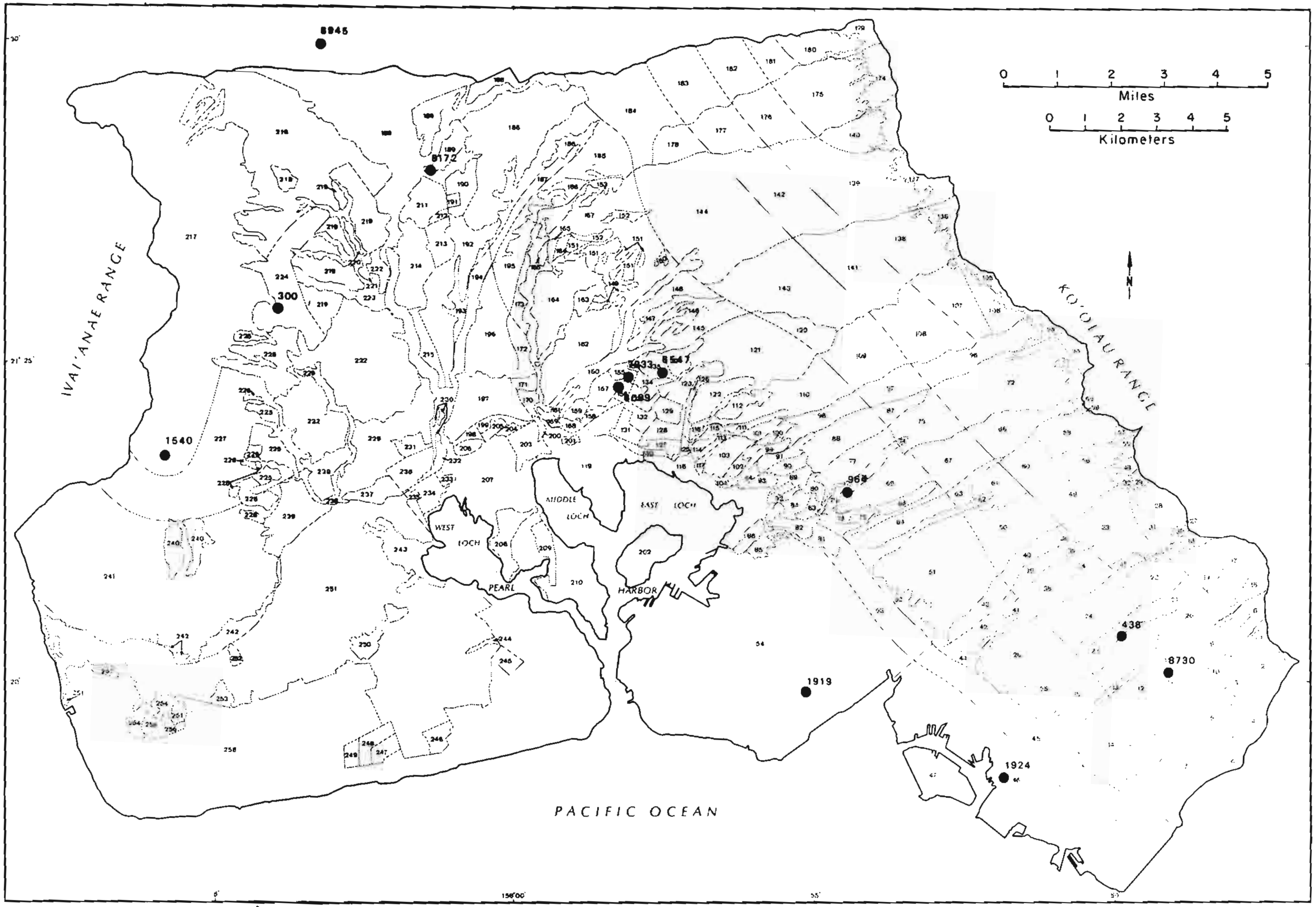
The SCS has empirically determined curve numbers for various categories of soil, vegetation cover, and land use. Each soil series in the U.S. is assigned to one of four "hydrologic soil groups", A to D. The A-group soils are those with the highest infiltration capacity and thus the lowest runoff potential. The B, C, and D groups include soils with progressively lower infiltration capacities and higher runoff potential. Based on SCS guidelines or by optimization, using streamflow data where available, curve numbers can be assigned to any land use and soil series.

The recommended curve numbers apply to an average antecedent moisture condition (AMC), called AMC II. For drier (AMC I) or wetter (AMC III) conditions, lower or higher curve numbers, respectively, must be used. The SCS handbook includes a table for converting the curve numbers to the appropriate AMC (U.S. Department of Agriculture 1972, p. 10.7). The three AMC conditions are defined according to the rainfall total of the preceding five days.

MODIFICATIONS OF THE SCS MODEL. The SCS runoff model provides a means to estimate runoff in areas lacking streamflow data. However, daily rainfall measurements are required. The monthly interval was chosen for this study, and as described in the Introduction, monthly precipitation has been computed for each wb-zone. For the purposes of this study, it was necessary to convert the SCS model to accommodate monthly rainfall data. To do this, the relationship between the SCS method and the linear bivariate model was statistically determined. This section describes the method of relating the two models.

Daily rainfall data are available for many stations within the study area. Among those, ten representative sites were selected (Fig. 13). The stations are listed in Table 14. Using the records of each station, daily runoff was computed by the SCS method and accumulated to obtain monthly runoff totals. For each station, the calculations were carried out for a range of CN values. For instance, monthly runoff totals were computed over a 99-mo period for station 300 using a CN value of 40. The same rainfall data were again input to estimate 99 monthly runoff totals at station 300 with a CN of 50. This procedure was repeated, changing the value of CN by tens up to 100.

At each station, several lists of monthly runoff totals were computed,



NOTE: See Table 14.

Figure 13. Locations of selected daily rainfall stations

TABLE 14. DAILY RAINFALL STATIONS, O'AHU, HAWAI'I

Site	USWS No.	State Key No.	Station Name	Period of Record	No. of mo
1	0300	807.00	Camp 84	05/65-12/73	103
2	0438	780.80	Dowsett Highlands	06/65-12/73	99
3	0964	771.20	Hālawa Shaft	04/65-12/73	101
4	1540	725.20	Hōkūloa	05/65-12/73	102
5	1919	703.00	Honolulu WSO AP	10/62-12/73	131
6	1924	704.00	Honolulu Substation	04/63-12/73	99
7	6089*	754.20	Mānana	03/70-05/72	27
	6547*	835.10	Pearl City Mauka	06/72-12/73	18
	7933*	754.10	Pearl City Terrace	03/66-01/70	47
8	8172	820.20	PRI Wahiawā	12/67-12/73	70
9	8730	780.00	Tantalus Peak	07/65-12/73	84
10	8945	863.00	Wahiawā Dam	03/65-12/73	105

*Data combined and treated as one station record due to their proximity.

At each station, several lists of monthly runoff totals were computed, each for a different value of CN. For each of these lists, the non-zero runoff totals were entered into a bivariate linear regression with concurrent monthly precipitation (Giambelluca 1983, Table 24). The intercepts and slopes computed for various values of CN are plotted for each station in Figures 14 and 15. These graphs provide a means of determining the intercept and slope of a linear model of monthly runoff as a function of monthly precipitation for any given curve number. The consistent alignment of points along the curves in Figures 14 and 15 is indicative of the reliability of the relationship between the SCS model and the linear bivariate model.

The results of all regressions for curve numbers below 40—and some for higher curve numbers—were not significant due to small sample sizes. This occurred because only non-zero runoff values were entered into the regressions. The frequency at which zero runoff is predicted by SCS increases as the value of CN decreases; thus, the sample size for the regressions diminished. In any case, curve number values less than 40 are rare in Hawai'i.

The curves of slope and intercept have the same general shape for all stations. However, the position of the curves differs among stations. The curves represent the relationship between runoff computed from daily rainfall and the monthly rainfall total. The relationship is based upon the connection between the intensity of daily rainfall and the total monthly rainfall. The correlations (Giambelluca 1983, Table 24) indicate that such a connection exists, but the curves suggest that the relationship differs according to location. For instance, higher than normal rainfall may indicate a greater number of rainy days, but no change in intensity at one location. At another, a high month total may be more likely to result from increased rainfall intensity with little change in the number of rainy days. The runoff response, as estimated by the SCS model (as well as the actual runoff, presumably), would be different in each case. This is reflected in the differences among the curves in Figures 14 and 15.

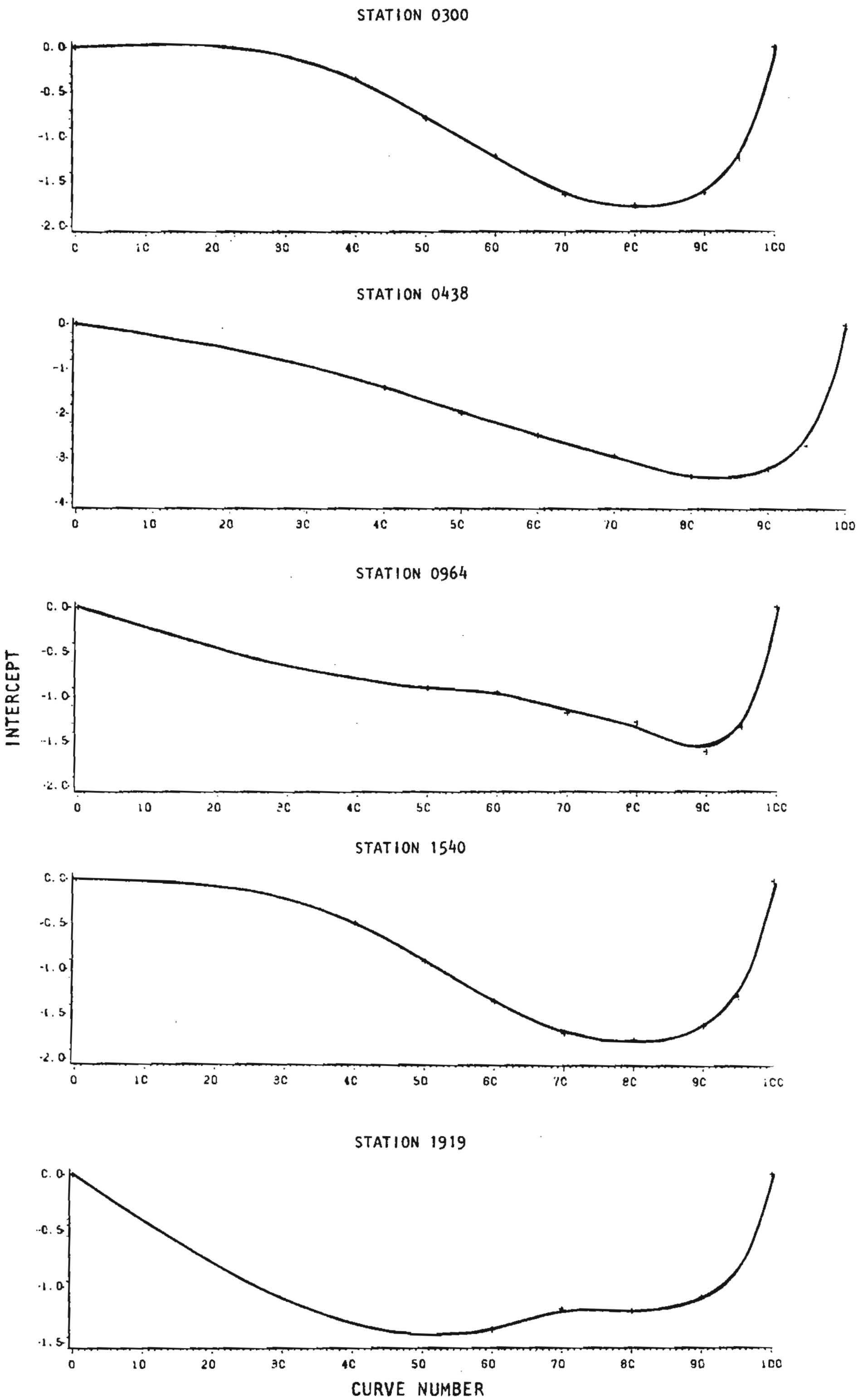


Figure 14. Y-axis intercept of linear rainfall-runoff model as a function of SCS curve number for 10 locations on southern O'ahu, Hawai'i

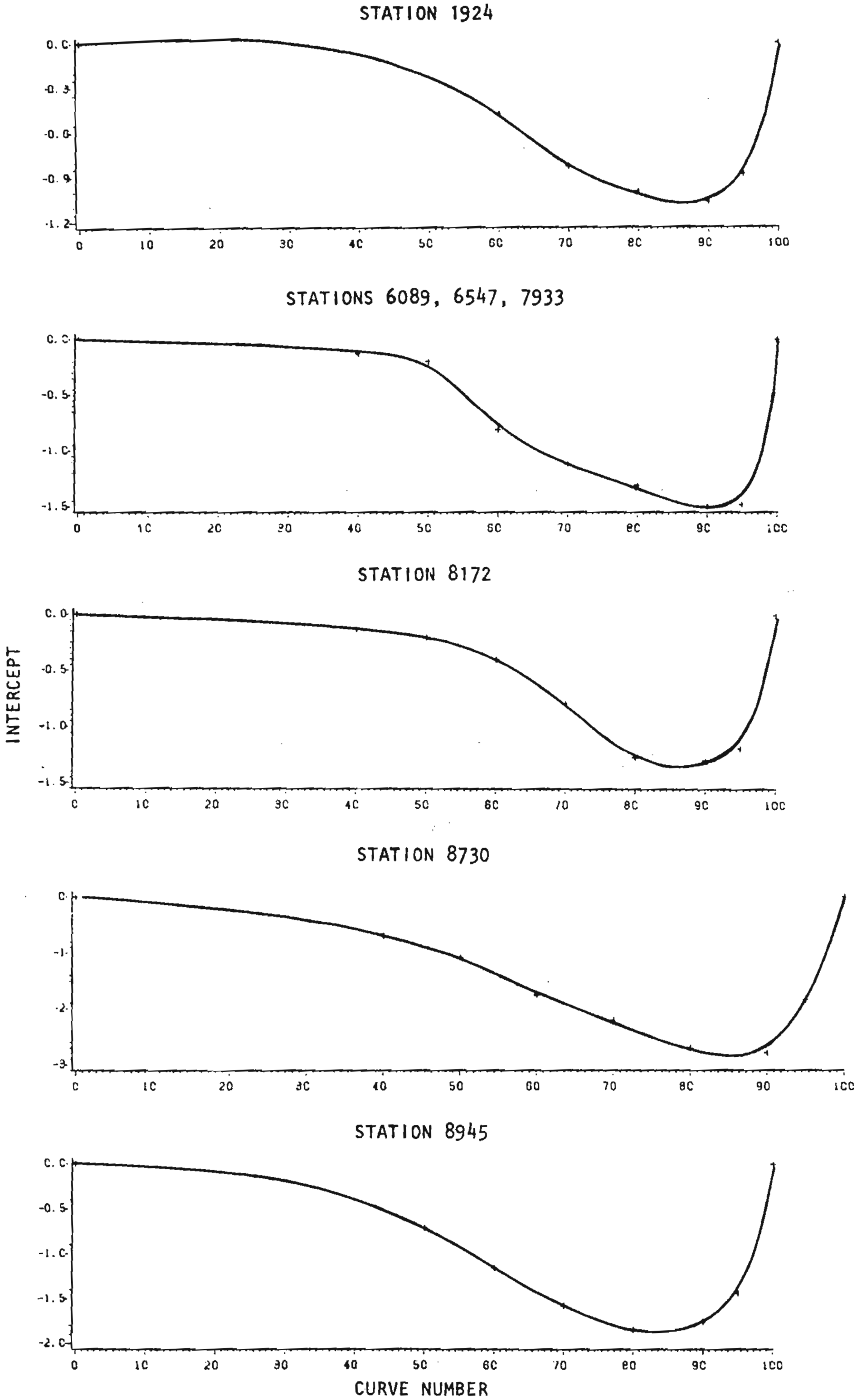


Figure 14.—*Continued*

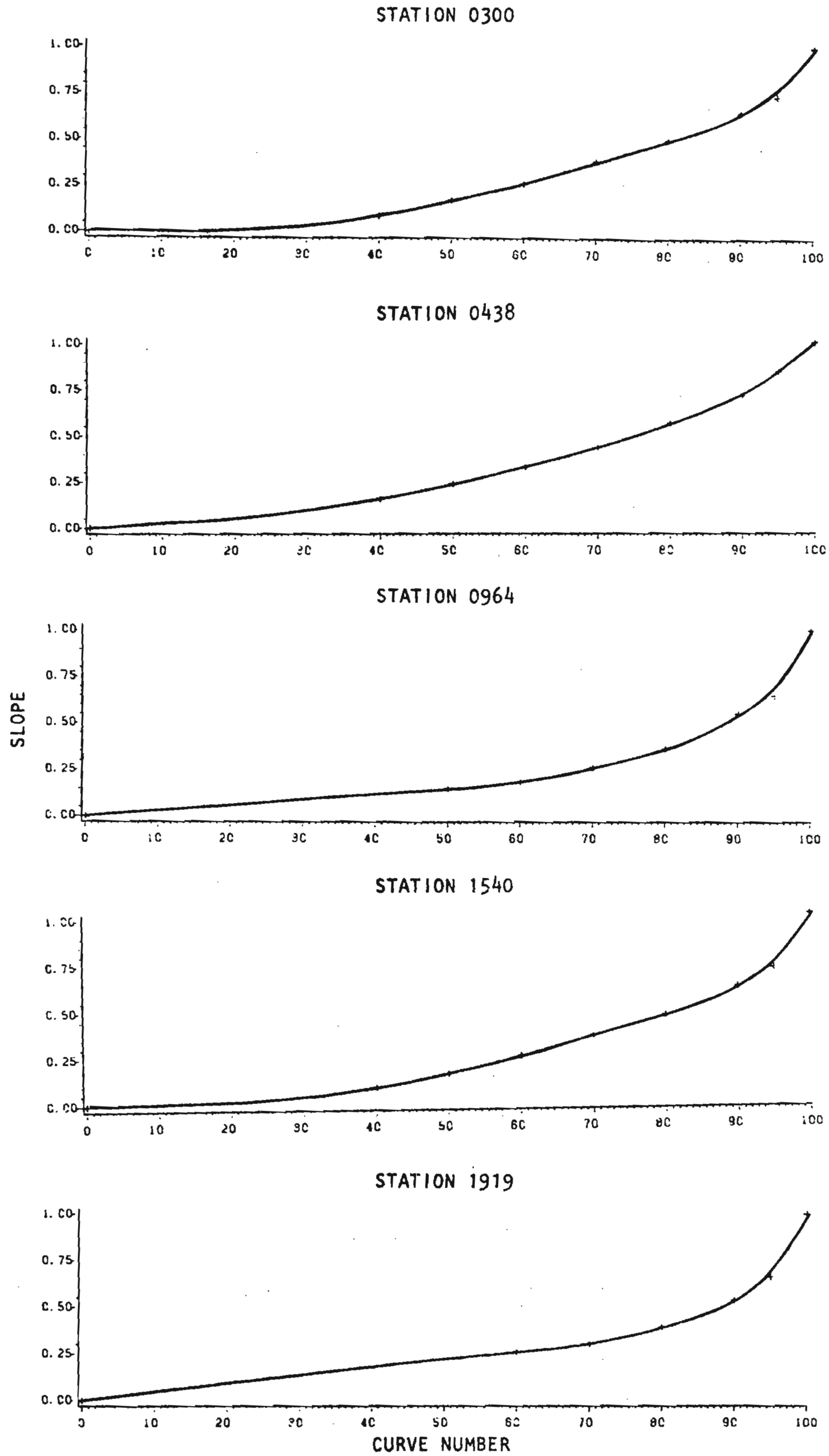


Figure 15. Slope of linear rainfall-runoff model as a function of SCS curve number for 10 locations on southern O'ahu, Hawai'i

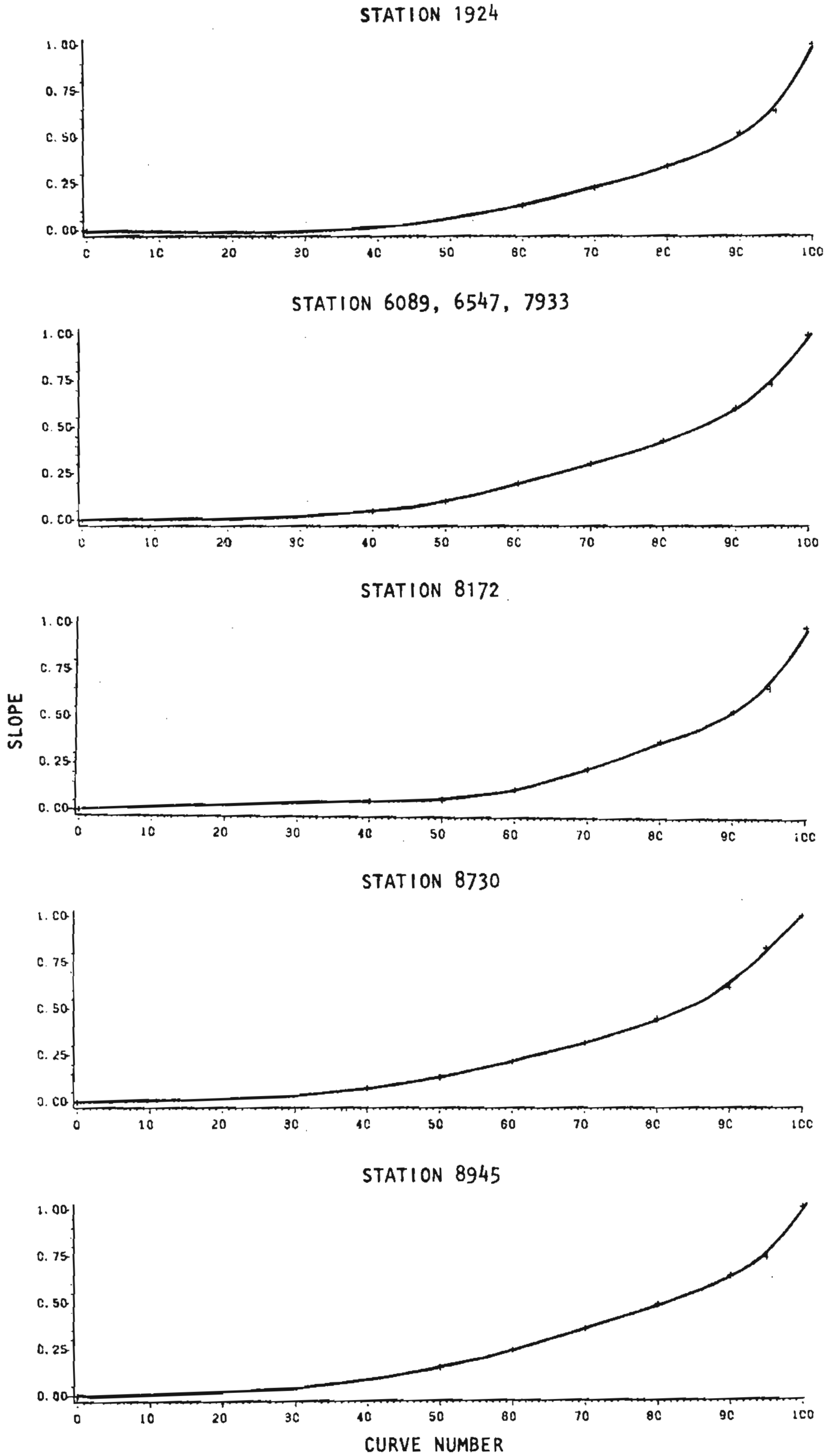


Figure 15.—*Continued*

By overlaying the graphs in Figure 14, three groups having similar curves were easily identified. The same three groups emerge when the slope graphs (Fig. 15) are superimposed. Table 15 lists the stations in each group. The breakdown reveals a regionality in the rainfall-runoff relationship which is attributable to a regionality in rainfall frequency (intensity-duration) characteristics. Group 1 represents the leeward Ko'olau Range, and has the lowest intercept and highest slope curves. Group 2 stations are found along the windward Wai'anae Range and have intermediate intercept and slope curves. Group 3 includes the central plateau and the coastal plains of Honolulu, Pearl Harbor, and 'Ewa, and has the highest intercept and lowest slope curves. Composite curves representing each group were constructed by averaging the values for the stations in each group (Figs. 16, 17).

The slope curves indicate that, given identical hydrological conditions, a greater percentage of rainfall runoff would occur for typical leeward Ko'olau rainfall than for the same quantity of Honolulu rainfall. Again, the differences among these curves reflect regional differences in rainfall duration and intensity characteristics. A comparison of Groups 1 and 3 slope curves is certainly consistent with known rainfall characteristics of the leeward Ko'olaus and Honolulu (higher intensity rainfall in the Ko'olaus than in Honolulu). That windward Wai'anae station fall between the other two groups is also reasonable.

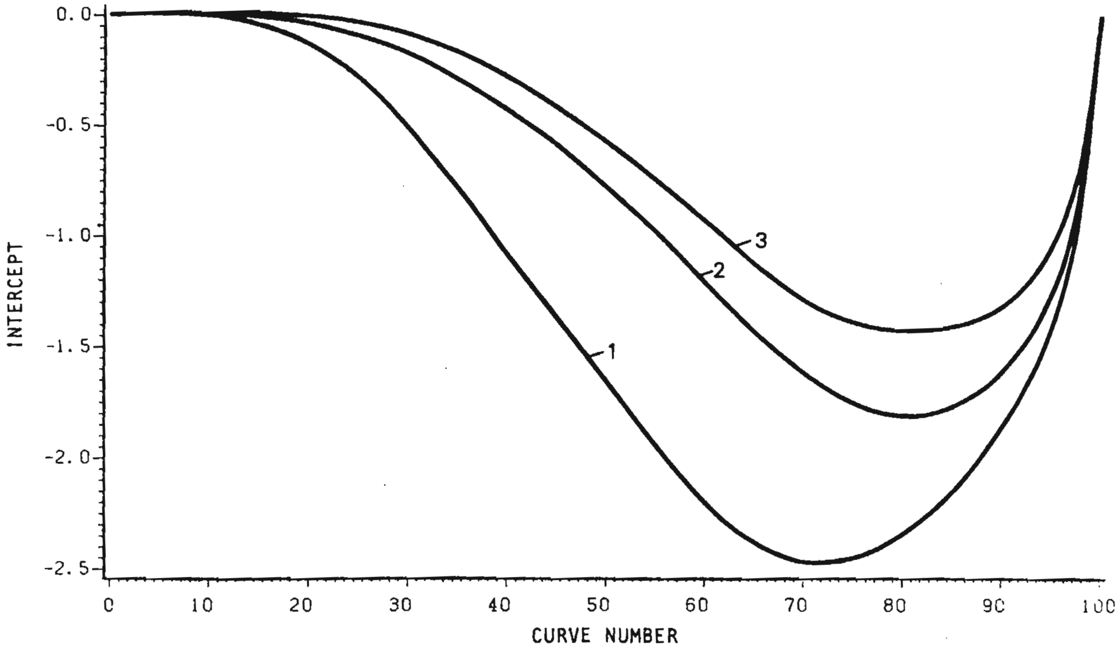
Interpretation of the intercept curves is less obvious. The precipitation-axis intercept, P_0 (Fig. 12), has a more meaningful interpretation than the runoff-axis intercept, a. P_0 represents a retention parameter, which would be expected to vary principally as a function of hydrological condition, and not according to regional rainfall characteristics. The curves indicate that regional differences in slope (b) are opposite to differences in intercept, a. Thus, P_0 $(=-a/b)$ does not vary in any consistent manner with respect to location, and is primarily a function of CN.

The curves in Figures 14 and 15 provide a means of selecting appropriate constants for a linear model of runoff as a function of monthly rainfall (eq. [6]) anywhere on southern O'ahu, for any given curve number. These curves effectively convert the computational interval of the SCS model to a monthly unit. A method of selecting appropriate curve numbers is presented subsequently.

TABLE 15. GROUPING OF DAILY RAINFALL STATIONS BY RAINFALL TYPE

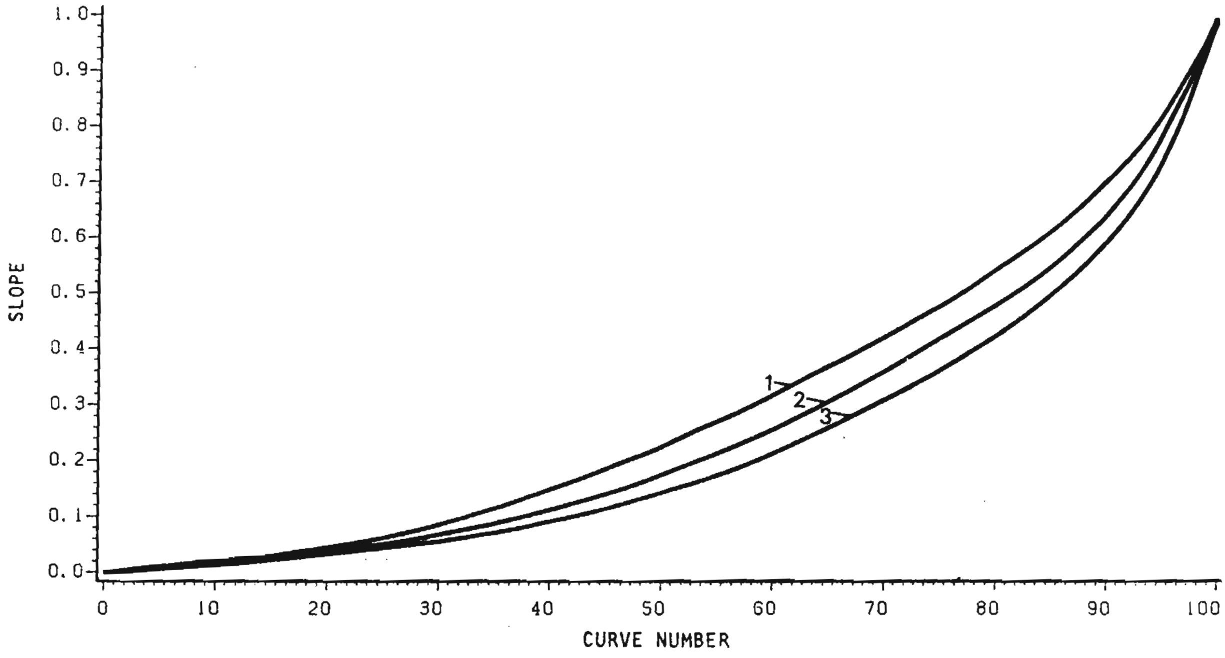
GROUP		
1*	2†	3‡
438	964	300
8730	1919	1540
	1924	8945
	6089	
	8172	

*Leeward Ko'olau Range.
†Windward Wai'anae Range.
‡Central plateau and coastal plains of Honolulu, Pearl Harbor, and 'Ewa.



NOTE: Regions 1—leeward Ko'olau Range, 2—windward Wai'anae Range, 3—central plateau.

Figure 16. Regional curves relating y-axis intercept of linear rainfall runoff model with SCS curve number



NOTE: Regions 1—leeward Ko'olau Range, 2—windward Wai'anae Range, 3—central plateau

Figure 17. Regional curves relating slope of linear rainfall runoff model with SCS curve number

DISAGGREGATION OF BASIN RUNOFF. The problem of disaggregation is essentially one of allowing for variation in runoff response among the wb-zones within a basin while preserving the runoff total measured (including both adjusted streamflow data and streamflow estimates obtained by multiple regression techniques) for the entire basin. The SCS model, implemented with a curve number selected individually for each wb-zone, provides a means of varying the runoff response. To preserve the measured basin total, the SCS estimates had to be adjusted. The amount of adjustment necessary in each basin for each month was computed by summing wb-zone runoff estimated by the SCS method and comparing this value with the measured basin total. For each month and wb-zone, the arithmetic difference was computed and used to adjust wb-zone runoff values.

The procedure for disaggregating basin total runoff derived from measured streamflow (extended by multiple regression) for each gaged basin is as follows:

1. Determine the proper curve number for each wb-zone within the basin, from known characteristics of soil and land use and from the results of the bivariate regression of streamflow vs. precipitation

2. Estimate monthly runoff for each wb-zone within the basin using the SCS model converted to the monthly interval

3. Sum SCS estimates of wb-zone runoff for each month to obtain the runoff total for the entire basin

4. Compute the arithmetic difference for each month for SCS-estimated and measured basin runoff

5. Adjust monthly SCS-estimated wb-zone runoff by using the difference computed for each month.

RUNOFF IN UNGAGED AREAS. To obtain runoff for ungaged portions of the study area, the modified SCS model was used. As with disaggregating the streamflow data, determination of the proper curve number for each wb-zone was required. Fortunately, the areas where streamflow data are lacking are, for the most part, areas where detailed soil and land use information is available.

ESTIMATION OF CURVE NUMBERS. The guidelines provided by the SCS for selecting curve numbers for various soil types and land use classifications were obtained by empirical methods using precipitation and runoff observations from representative mainland (U.S.) watersheds (U.S. Department of Agriculture 1972, p. 9.1). The SCS recommends that local knowledge of hydrological response or measurements of streamflow be used wherever possible in place of the general guidelines to select curve numbers (U.S. Department of Agriculture 1972, p. 5.7).

Supplementary tables by the U.S. Department of Agriculture (1972, p. 9.9) make specific recommendations for sugarcane- and pineapple-growing areas in Hawai'i. However, a more detailed investigation of runoff from Hawai'i's plantations fields by Cooley and Lane (1980) produced a different set of optimum curve numbers. In their analysis Cooley and Lane stratified the data according to the stage of crop development, identifying curve numbers for four different levels.

Historical retracing of the level of crop development in each wb-zone for each of the 360 months of the study period is an impractical task. In general, crop rotation is staggered so that planting and harvesting continue at approximately a constant rate. As such, the percentage of land at each level of crop development can be assumed constant over any significantly large area of cultivation.

Based on published accounts of acreages under crops of various ages (Oahu Sugar Company 1945-1964; Dupuy 1966), an assessment was made of average conditions for sugarcane. Similarly for pineapple, recommendations of a local agronomist* were used to estimate average cover conditions (Table 16). Based upon these assumed conditions and using the Cooley and Lane recommendations, a weighted average curve number for each soil group was computed for sugarcane and pineapple.

Urbanization greatly affects the runoff response. Covering natural surfaces with impermeable materials eliminates infiltration. Runoff from paved surfaces is nearly 100% of rainfall. Additionally, Murabayashi and Fok (1979, p.42) found that infiltration in unpaved portions of urban areas is reduced by as much as 83% compared with pre-urbanized conditions.

For curve number selection for urban watersheds, the SCS (U.S. Department of Agriculture 1975) published guidelines which may be used to convert from pre-urban to urban curve numbers according to the percentage of impervious surface.

Estimation of curve numbers in the remote areas of the leeward Ko'olaus is difficult because the soils there have not been identified. Local SCS hydrologists have suggested a curve number of 55 for forest areas in the Ko'olaus (Lopez 1975, p. 22). The results of the bivariate linear regression of runoff vs. rainfall (Table 12) indicate that the average intercept, a, and slope, b, for these areas are respectively -2.00 and 0.309. Figures 16 and 17 relate intercept and slope to curve numbers. Since a = -2.00 and b = 0.309 correspond to curve numbers between 56 and 59 for Group I rainfall, these values were used guidelines in selecting curve numbers for forested areas lacking soil classification. In the gaged basins, curve numbers for

TABLE 16. AVERAGE PERCENT OF TOTAL AREA CROP COVERAGE FOR SUGARCANE AND PINEAPPLE

CROP	PERCENT COVER			
	Bare (no cover)	Limited (0-50)	Partial (50-100)	Full (100)
Sugarcane	9	6	6	79
Pineapple	15	16	9	60

*W.G. Sanford 1982: personal communication.

the remote areas were identified from the values of a' and b' in Table 13.

Based on SCS guidelines, the recommendations of Cooley and Lane (1980), and the results of the bivariate linear regression of runoff and rainfall for the gaged basins, a curve number chart was developed for this study (Table 17). A curve number can be identified from the chart for each of the ten land-use categories identified earlier (see Introduction) and for each of the four hydrologic soil groups discussed in the Runoff section. The land use of each wb-zone was determined earlier for each year of the study period (Giambelluca 1983, Table 70).

TABLE 17. CURVE NUMBER CHART

Land-Use Classification	Hydrologic Soil Group*			
	A	B	C	D
1. Sugarcane	38	53	64	70
2. Pineapple	25	59	72	79
3. Low-density urban	51	68	79	84
4. Medium-density urban	68	79	86	89
5. High-density urban	89	92	94	95
6. Mixed (med. density urban/vacant)	54	70	80	85
7. Mixed (med. high density urban)	76	85	90	92
8. Mixed (high density urban/vacant)	64	77	84	88
9. Golf Course/Park	39	61	74	80
10. Forest/Grazing/Vacant	36	60	73	79
Reconnaissance Areas (Unclassified Soils)				
Ko'olau Conservation Area	55-60			
Wai'anae Conservation Area	73			

*A = lowest runoff potential; B-D = progressively higher runoff potential.

SOIL GROUP IDENTIFICATION. The U.S. Department of Agriculture (Foote et al. 1972; Sato et al. 1973) conducted soil surveys of the Hawaiian Islands. The results include a detailed description of the soils of all regions except remote mountainous areas which are categorized as rough, mountainous or steep land.

The relative proportions of the dominant soils of each wb-zone were identified from the SCS maps (Giambelluca 1983, Table 74). Each soil series is assigned to one of the four Hydrologic Soil Groups (U.S. Department of Agriculture 1972, App. B). Based on these assignments, the relative proportion of each soil group was determined for each wb-zone. No soil group assignment is made by the SCS for the reconnaissance categories nor for several other special categories. Reconnaissance areas were assigned curve numbers according to the results of the bivariate regression as described earlier. The other special categories were assigned to Hydrologic Soil Groups (Table 18) through consultation with a local soil scientist.*

*P.C. Ekern 1982: personal communication.

TABLE 18. SOIL GROUP ASSIGNMENT FOR SPECIAL CATEGORIES

Category	Hydrologic Soil Group	Remarks
Tropaquepts	A	Low runoff because of poor surface drainage
Coral outcrop	D	Coral or fused calcareous sand
Fill land		
Agricultural	D	Underlain by coral rock
Urban	C	Mixed dredged material, garbage
Cinder land	A	Loose unconsolidated material
Quarry	D	Soil removed

Using the chart in Table 17, curve numbers were selected for each wb-zone. Curve numbers were determined by weighting the CN of each soil group according to its relative occurrence in the wb-zone. In some instances land-use changes occurred during the study period. In such cases, a different curve number was assigned for each land-use category.

All wb-zones in the leeward Ko'olaus exceeding 3000 mm (118.1 in.) annual rainfall were assigned to the Group I rainfall curve. All other wb-zones were assigned to the Group III curve except those in the Wai'anae Range, Group II.

Using the graphs in Figures 16 and 17, the a and b constants were selected for each wb-zone according to its curve number and rainfall group. The rainfall group, curve number, and model constants for each wb-zone are identified by Giambelluca (1983, Table 75).

Results

Runoff in each wb-zone was estimated for each month during the 1946 through 1975 period. All available streamflow data were utilized to represent runoff within the drainage basin of each stream. Where data did not cover the entire study period, the multiple regression was used to extend the stream flow record based on precipitation data. The SCS method was modified for the monthly interval and served as the runoff model in areas without streamflow measurements. The modified SCS model was also used to disaggregate streamflow into component wb-zone runoff values.

The results are stored on magnetic tape in the form of 258 arrays (one for each wb-zone), each containing 360 monthly runoff depths (see App. B for details). In Appendix Tables A.9-A.12, regional runoff averages are summarized. Monthly and annual 30-yr averages for various portions of the study area are shown. The three major hydrogeologic divisions are represented in the tables. Each average is expressed as a depth (in.), a volume (mgd), and as a percentage of precipitation. The annual average runoff from the 57 005.9 ha (220.1 miles^2) of the Pearl Harbor-Honolulu Basin is 252.48 mm (9.94 in.) or 46.06 m^3/s (1051.3 mgd), equivalent to 16.22% of average annual precipitation. To illustrate temporal variation, the results are also summarized in the form of annual totals (Appendix Tables A.13-A.16). For the sugarcane portion, the area under cultivation each year is also listed because changes in the area cultivated are partly responsible for the variation in runoff.

Many studies have been made of runoff from various portions of southern O'ahu (Table 19), particularly the Pearl Harbor region. Hirashima (1971, p. 1) computed an average runoff of 2.07 m^3/s (47.27 mgd) for the 2.331 x 10^8 m^2 (90 $miles^2$) gaged portion of the Pearl Harbor basin. Adjusted to include all the non-caprock area, Hirashima's value becomes 2.87 m^3/s (65.4 mgd) (Mink 1980, p. 13). Takasaki (1978, Table 1) gave a value of 3.07 m^3/s (70 mgd) for Hydrographic Area IV (Pearl Harbor region) while the State Water Commission (1978, p. 2) used 2.85 m^3/s (65 mgd) for the same region. Mink (R.M. Towill 1978, p. IV-1) calculated average runoff for the non-caprock area to be 2.67 m^3/s (61 mgd) or 14% of precipitation. The average Pearl Harbor region runoff estimates computed in this study compare favorably with the results of the other recent studies (Table 19). For the entire Pearl Harbor region, average annual runoff was estimated as 3.10 m^3/s (70.79 mgd) or 10.45% of total water input (rainfall + irrigation) and 14.79% of rainfall. From the 3.19 x 10^8 m^2 (123.17 $miles^2$) non-caprock area, the average annual runoff is 2.74 m^3/s (62.65 mgd) or 12.01% of total water input (14.67% of rainfall).

TABLE 19. COMPARISON OF RUNOFF ESTIMATES FOR PEARL HARBOR AND HONOLULU REGION NON-CAPROCK AREAS

INVESTIGATOR	PEARL HARBOR Non-caprock (m^3/s)	(mgd)	HONOLULU Basalt (m^3/s)	(mgd)
Kunesh (1929)	----	--	1.49	34*
Wentworth (1951)	----	--	1.45	33*
Hirashima (1971)	2.85	65†	----	--
Takasaki (1978)	3.07	70	----	--
State Water Commission	2.85	65	----	--
Mink (1978)	2.67	61	----	--
This study	2.76	63	0.94	22

*Adjusted by proportion of areas represented.
†Adjusted by Mink (1980) to represent non-caprock area of Pearl Harbor region.

A few estimates have also been made for Honolulu area runoff. Kunesh (1929, p. 91) estimated non-caprock Honolulu runoff to be 1.53 m^3/s (35 mgd). Wentworth (1951, p. 64) computed a value of 1.49 m^3/s (34.1 mgd) for the same area. These values represent a 66.304 x 10^6 m^2 (25.6 $miles^2$) "mountain intake area" of the Honolulu region extending to Wailupe. To make the values comparable with present estimates, a proportional adjustment to the 67.573 x 10^6 m^2 (26.09 $miles^2$) basalt area was made. The Kunesh and Wentworth estimates become respectively 1.49 and 1.45 m^3/s (34 and 33 mgd) (Table 19). The average non-caprock runoff estimated for the present study, 0.94 m^3/s (21.54 mgd), is significantly lower than previous estimates.

ERROR ESTIMATE. Fortunately for the purpose of estimating runoff in the study area, streamflow data exist for precisely the region where detailed information concerning hydrologic conditions—particularly soils—is lacking. Unfortunately for the purpose of evaluating the accuracy of the modeling techniques used, streamflow data are not available in the areas where knowledge of hydrologic conditions is adequate to properly implement the model. Thus, particularly for the SCS model, a direct estimation of error is not possible. In tests by Cooley and Lane (1980), the SCS model yielded accurate results on O'ahu for daily runoff. If the process of conversion to the monthly interval is assumed to add no bias to the estimate, then the monthly estimate used here could be expected to be as accurate as the daily estimate. However, daily rainfall should be noted as providing a better indication of rainfall intensity than monthly rainfall and thus a better index of runoff. Assuming that curve number selection was reasonably accurate, the limitations of the converted SCS model are essentially those of the basic linear rainfall-runoff relation (eq. [6]). Bivariate linear regressions of rainfall vs. adjusted streamflow have shown that the relationship is good. Coefficients of determination (r^2) were uniformly high (Table 12). Individual monthly runoff values must be viewed with some caution, however, since the standard error of the estimate for these regressions averaged 29.72 mm (1.17 in.), a significant percentage of average runoff for the region.

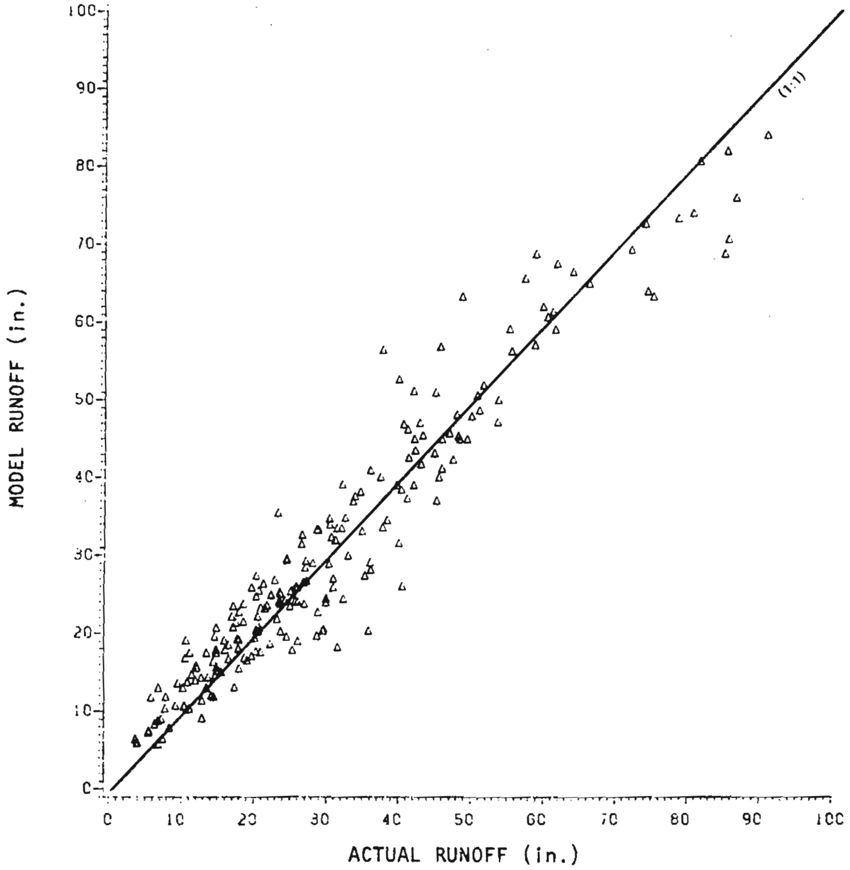


Figure 18. Scattergram of estimated (by multiple regression model) vs. observed annual runoff for Ko'olau basins, O'ahu, Hawai'i

The other model used in the runoff analysis was the multiple regression technique developed and used successfully by Anderson, Duffy, and Yamamoto (1966). Again, a good relationship was indicated by high values of R^2. However, the standard error of the estimate averaged 25.91 mm (1.02 in.). This value is high relative to monthly runoff, but represents only 10.6% of average precipitation in the area. Therefore, the effect on the total water balance is not excessive. In any case, there is no reason to suspect a bias in the estimates. Monthly deviations can be expected to cancel over a longer period. To illustrate this effect, annual values of actual vs. model-predicted runoff for the Ko'olau basins are plotted in Figure 18. In comparison with the scattergrams of monthly actual vs. model runoff (Giambelluca 1983, Fig. 18), this figure indicates that significant error cancellation does take place when integrating monthly runoff to obtain annual values.

EVAPOTRANSPIRATION

Evaporation is defined as the total flux of water vapor from all surfaces through the processes of evaporation and transpiration (Chang 1965, p. 141). Separate measurement of evaporation and transpiration is impossible in the field and, since both processes are governed by the same environmental factors, they are usually evaluated as one.

Evaporative Processes

Evaporation is the transformation of water from the liquid to the vapor phase. Transpiration is an evaporative process which occurs within the plant leaf. For evaporation to take place, energy must be supplied and vapor removed (Penman 1948, p. 122). At 20°C (68°F) about 62.1 x 10^6 J/m^2 (1484 cal/cm^2) are required to evaporate a 25.4 mm (1 in.) depth of water. The sources of energy for evaporation in the natural environment are net radiation (solar radiation retained at the surface) and positive advection (sensible heat transported horizontally via wind). The atmosphere can also act as a sink to sensible heat (negative advection). The presence of advected energy is indicated by horizontal temperature and humidity gradients, which result from heterogeneity of surface characteristics.

In an attempt to derive a formula to descirbe evaporation in terms of measurable quantities, Penman (148) combined the energy budget approach of Bowen (1926) with the aerodynamic approach. The result is known as the Penman equation,

$$E = (\Delta Q_n + \gamma E_a)/(\Delta + \gamma) \ , \qquad (31)$$

where

Δ = slope of saturation vapor pressure vs. temperature curve at air temperature

Q_n = net radiation

γ = psychrometric constant

E_a = aerodynamic term,

$$E_a = 0.35\ (1 + 0.01\mu)(e_a - e_d)\ , \tag{32}$$

where

μ = wind velocity

e_a = saturation vapor pressure of air

e_d = vapor pressure of air.

The relative contributions of the radiation and aerodynamic terms in equation (31) are determined, in part, by the weighting factors. Both Δ and Υ are temperature dependent and Υ also varies according to humidity and atmospheric pressure (elevation)(Storr and den Hartog 1975)). Using another version of the combination equation, Skidmore, Jacobs, and Powers (1969) found that the contribution of the aerodynamic term becomes more important as air temperature and wind speed increase and as humidity decreases. Figure 19 shows this relationship for net radiation levels of 96.85, 145.28, and 193.70 $J/m^2/s$ (200, 300, 400 $cal/cm^2/day$).

One of the chief advantages of the Penman equation is the elimination of unmeasurable surface terms. Although impractical for most applications, Slatyer and McIlroy (1961) advocated the use of a combination equation with the surface term, D_o, for latent heat flux, LE, as

$$LE = [\Delta/(\Delta + \Upsilon)]\ Q_n + (\rho\ C_p/r_a)(D_z - D_o) \tag{33}$$

where

ρ = air density

C_p = specific heat of dry air

r_a = aerodynamic resistance to diffusion of water vapor

D_z = wet bulb depression of overlying air

D_o = wet bulb depression of surface.

In this formulation, the aerodynamic term explicitly accounts for evaporation differences arising from variations in surface wetness (Wilson and Rouse 1972).

As a special case of equation (33) consider $D_z = D_o$ where the expression is reduced to

$$LE = [\Delta/(\Delta + \Upsilon)]Q_n\ . \tag{34}$$

This relationship may be valid when $D_z = D_o = 0$, which describes saturated air passing over a wet surface (Monteith 1965; Tanner and Fuchs 1968). Slatyer and McIlroy (1961), however, ascribe this relationship, which they call "equilibrium evaporation" to the more general case of equal but finite surface and air wet-bulb depressions, a condition of mutual adjustment between the humidities of each.

Priestley and Taylor (1972) showed that a less restrictive relation-

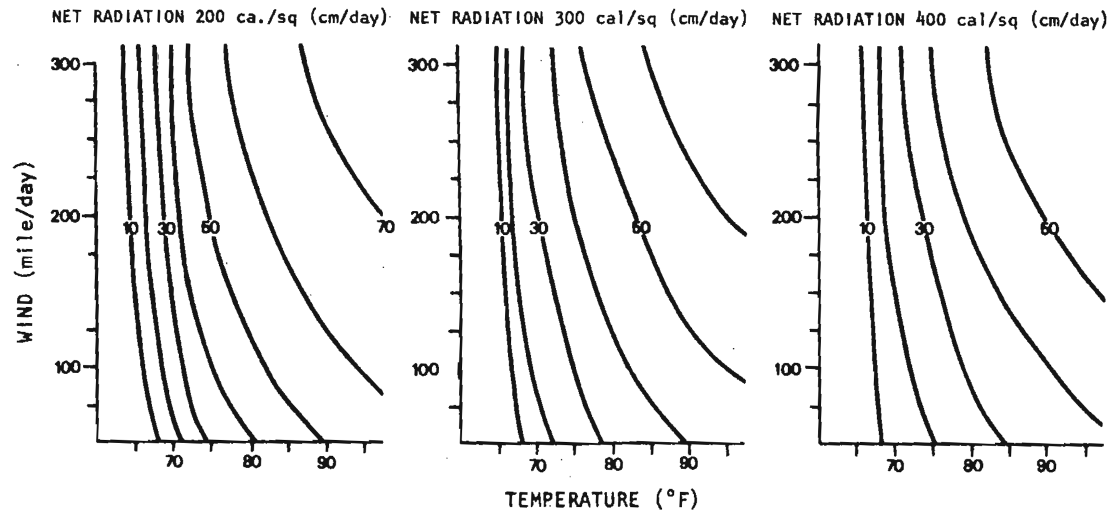


Figure 19. Relative contribution (%) of aerodynamic term in combination equation as a function of wind, temperature, and net radiation for a constant water vapor pressure of 20 mb

ship takes the form,

$$LE = \alpha\ (\Delta/\Delta + \gamma)\ Q_n\ , \tag{35}$$

in which the proportionality constant, α, was found to be 1.26 for oceanic and saturated land surfaces.

EVAPORATION FROM VARIOUS SURFACES. Evaporation may be visualized in terms of three flows (King 1965):

1. Radiant and sensible energy to the evaporating surface, and the return flow of latent heat

2. Water vapor by molecular and turbulent diffusion from the evaporating surface

3. Liquid water to the evaporating surface.

The characteristics of a particular surface affect each of these flows and thus influence the evaporation rate. In nature, three types of evaporative surfaces are found: open water, bare soil, and plant leaves. The differences in evaporative characteristics of each are discussed by Giambelluca (1983, pp. 150-53).

MOISTURE LIMITATION. The availability of liquid water is an important factor controlling soil evaporation and transpiration from plants. Diminishing soil evaporation with soil drying is related to increasing resistances to the three flows of energy, water vapor, and liquid water. Transpiration is similarly affected. Increasing soil dryness reduces flow of water to the roots. In response to resulting increased water potential gradient within the plant, most species prevent desiccation by narrowing the stomatal apertures, increasing internal resistance, and thereby reducing the transpiration rate (Slatyer and Gardner 1965).

As a convenience in dealing with evapotranspiration (ET), the limitations imposed by environmental factors (energy, wind, humidity) and the limitations of moisture availability are treated separately. To this end, Thornthwaite (1948) introduced the term "potential evapotranspiration" (PE) to denote the ET that would occur given an adequate water supply at all times. Penman (1948) defined the term "potential transpiration" as the amount of water transpired by a short green crop of uniform height that completely shades the ground and is never short of water.

Caution has been suggested in the use of the Thornthwaite and Penman definitions of PE because they lack a provision for advected energy (Chang 1965, p. 142). In humid climates where the original concepts were developed and tested, advection is not important. However, it must be accounted for in arid regions. In more recent work, PE is defined more broadly to to include advected energy if present. This new definition of PE corresponds to "potential maximum evapotranspiration" as suggested by Pruitt (1960*b*, p. 18).

Thornthwaite and Penman both developed techniques of estimating ET based on meteorological measurements. To obtain an estimate of actual evapotranspiration (AE), PE is first determined and AE is derived according to an empirical relationship between the ratio AE/PE and the available soil moisture.

Various studies of the relationship between ET and soil moisture have reached different conclusions. Veihmeyer and Hendrickson (1955) found that AE equaled PE until soil moisture was reduced to the wilting point (usually defined as the soil moisture content at a tension of 1.5×10^6 Pa [15 bars]), then declined sharply. Others have shown that AE declines before the wilting point as stomatal resistance increases beginning at some point after soil moisture storage drops below field capacity (the maximum soil water storage after initial drainage). Thornthwaite and Mather (1955) presented evidence that ET declines as a linear function of relative soil moisture depletion, beginning immediately below field capacity. Most other researchers, such as Pierce (1958), put the onset of AE decline somewhere between field capacity and the wilting point. Chang (1968, pp. 135-36) has concluded that the varying results indicate the relationship is dependent on soil, rooting depth, vegetation, and atmospheric conditions.

Denmead and Shaw (1962) presented empirical evidence that AE proceeds at the potential rate to a critical point, dropping thereafter in a curvilinear fashion. Evaporative demand was shown to be of great importance in in determining the critical point where AE falls below PE (called by Denmead and Shaw, the "turgor loss point"). Their results indicate that under conditions of high evaporative demand, flow resistance reaches sufficient levels to restrict AE at high soil moisture contents. When demand is low, flow of moisture within the soil and plant is able to maintain AE at the maximum rate to very low soil moisture levels. With this relationship Denmead and Shaw were able to reconcile the apparently conflicting results of previous research on the subject, attributing the differences to the level of PE under which the experiments were made.

Holmes and Robertson (1959) proposed a model to account for ET from a developing crop surface. Based on data of Marlatt (1958) and Lemon (1956) they showed that the critical point occurred at lower soil moisture contents as rooting depth increased.

Soil texture and structure determine the rate of moisture movement within the soil. In sandy soils, water drains rapidly. But for soils of finer texture, hydraulic conductivity is reduced at relatively low tension levels and AE may be reduced (Chang 1968, p. 139). The point at which AE declines is also plant and growth stage specific (Taylor 1965). In general an increase in leaf area has the same effect as root ramification (Chang 1968, p. 139). Doorenbos and Pruitt (1975, Table 32) summarized critical soil water depletion values for various crops, soil types, and evaporative demand levels.

METHODS OF DETERMINING POTENTIAL EVAPOTRANSPIRATION. The only method of directly measuring ET is through the use of lysimeters. However, lysimeters are costly and difficult to use, generally suited only for research purposes. For operational use, the measurement of evaporation is preferred. Evaporation pans, especially the U.S. Class A pan, are the most commonly used evaporimeters. The use of evaporation pans to estimate water use by plants arises from the principle that both processes are controlled by the same environmental factors.

The class A pan has been found more accurate than empirical ET estimates (Chang 1968, p. 178; Stanhill 1961, 1963) and because of its response to advected energy, preferable to energy-budget approaches (Ekern 1965*b*; Robins and Haise 1961) especially in arid regions. However, under certain conditions, caution must be exercised in its use. In nearly all cases, pan values differ in magnitude from PE of plants and must be adjusted (calibrated) to reflect the water use of a particular crop.

Atmometers, evaporimeters having a porous evaporating surface, are intended to more closely model the transpiration process than open water evaporimeters. The Livingston and Bellini atmometers have porcelain evaporation surfaces, while the Piche atmometer uses filter paper. Ekern (1983) has developed a porous-surface atmometer, similar to those used by Wilcox (1967), equipped with a rain shield for use in high rainfall areas of Hawai'i.

Since evaporative demand is a function of environmental conditions, many predictive relationships have been derived relating PE to various meteorological parameters. While radiation accounts for most of the variability in PE (Mukammal and Bruce 1960), temperature is used as a surrogate for radiation in many empirical formulas for estimating PE because of the greater abundance of data. In the humid tropics, however, temperature is not a good index of radiation (Ransom 1963; Linacre 1968). For instance, while correlation of temperature and solar radiation gave r values greater than 0.8 for mid-latitude regions, r values were consistently less than 0.6 in humid tropical climates (Chang 1971, pp. 67-69). Therefore, temperature and temperature-based models are not useful for ET estimation in the moist tropics (Garnier 1956; Ekern 1965*b*).

Penman developed a practical, yet theoretically sound method of computing open-water evaporation (and later evapotranspiration). The original Penman equation calculated evaporation from an open water surface. Penman obtained PE from vegetation by adjusting the calculated open water values using a conversion factor ($f = PE/E_o$). Based on experimental data, Penman concluded that f = 0.75 on an annual basis, f = 0.6 in winter, and f = 0.8 in summer (Penman 1950, p. 374). Alternatively, by adjusting the net radiation for the particular surface, PE may be estimated directly from equation (31).

In his original derivation, Penman (1948, p. 123) recommended the use of the Brunt (1939, pp. 136-44) formula for computing net radiation as

$$Q_n = Q_a(1 - r - \mu) - \sigma T_a^4(0.56 - 0.092\sqrt{e_d})(1 - 0.09m) \qquad (36)$$

where

Q_n = net radiation

Q_a = global radiation

r = reflection coefficient

μ = fraction of Q_a used in photosynthesis

σ = Stephan Boltzman constant

T_a = absolute temperature

e_d = saturation vapor pressure (mm Hg)

m = cloud cover (tenths).

However, as Chang (1968, p. 166) points out, this method is crude. Thus, measured Q_n or a locally derived relationship should be substituted where possible.

The Penman formulation has been employed in many locations (Penman 1950; Ojo 1969; Chang and Okimoto 1970) and has proven reliable for estimating open water evaporation and PE (Chang et al. 1967; Van Bavel 1966; Ekern 1965*b*; Tanner and Pelton 1960). Comparisons with other methods of computing PE have shown the Penman approach to be the best in nearly all cases (Noguchi 1982; Grant 1975; Chapas and Rees 1964; Pruitt 1960*a*, 1960*b*; King 1956).

Transpiration under similar conditions has been observed to differ significantly among different species and according to growth stage (Russel 1980; Doorenbos and Pruitt 1975; Jensen, Robb, and Franzoy 1970; Ritchie 1972; Tanner and Jury 1976; Denmead 1969; Hanks, Gardner, and Florian 1968; Ekern 1965*c*). Therefore PE is commonly estimated for a reference surface, such as open water, and then adjusted to a specific surface by the use of a crop coefficient (Blaney and Criddle 1950; Doorenbos and Pruitt 1975; Burt et al. 1981).

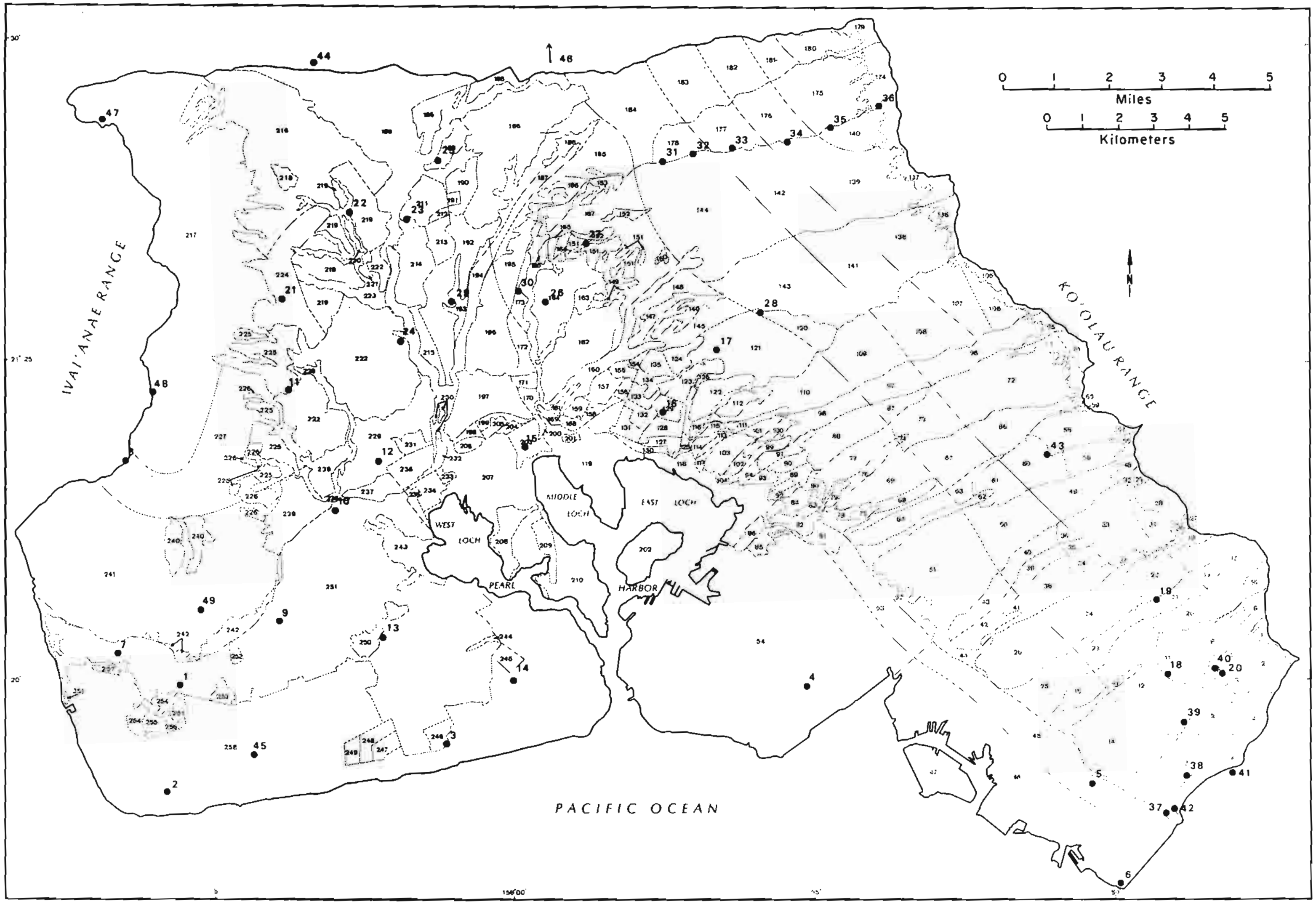
Research in Hawai'i, spurred principally by agricultural interests, has focused on consumptive use by plantation crops, sugarcane and pineapple. This body of information is centered around several lysimeter experiments conducted by the Hawaiian Sugar Planters' Association, the Pineapple Research Institute, and the University of Hawaii Water Resources Research Center. The experiments have measured ET of sugarcane (Campbell, Chang, and Cox 1960; Chang et al. 1967; Ekern 1972, 1977), pineapple (Ekern 1964, 1965*c*), grass (Ekern 1966*a*, 1983), and bare soil (Ekern 1966*b*) and related ET to pan evaporation, net radiation, global radiation, and other meteorological factors and methods of ET calculation. Pan evaporation has also been related to various meteorological factors and methods of calculating evaporation (Baver 1954; Chang et al. 1967; Ekern 1965*b*, 1977; Juvik; Singleton, and Clarke 1978; Tagawa 1980; Noguchi 1982). Additional research relevant to ET includes investigations of net radiation over various surfaces in Hawai'i (Chang 1961; Ekern 1965*a*, 1972).

A principal aim of lysimeter research in Hawai'i has been the calibration of U.S. Class A pans as field instruments for the purpose of scheduling irrigation. Pan evaporation has been shown to be highly correlated with water use by fully-canopied, well-watered sugarcane (Campbell, Chang, and Cox 1960; Chang et al. 1967; Campbell 1967; Ekern 1972, 1977; Alcantara 1980). The ratio of sugarcane ET to pan evaporation was found to average close to 1.0 in early experiments (Campbell, Chang, and Cox 1960; Robinson, Campbell, and Chang 1963; Chang et al. 1967). Although these results have been questioned (Ewart 1967), subsequent research has verified that for surface level pans and furrow- or sprinkler-irrigated sugarcane, a pan ratio of 1.0 is appropriate (Ekern 1972). However, pan measurement has been shown to be sensitive to pan height. Chang (1961) found that cane-top pan evaporation was 5% less than ground level pan evaporation, while at another location, a pan fixed at 1.52 m (5 ft) above the ground had 10% greater evaporation than the ground level pan. The later observation has been borne out by later work (Ekern 1972, 1977; Alcantara 1980) which indicates that, in general, evaporation from elevated pans exceeds that from surface pans by 10 to 20%.

Water consumption by pineapple is reduced due to daytime suppression of transpiration. Lysimeter measurements revealed that ET diminishes as the pineapple canopy closes, until at full canopy, ET is only 20% of pan evaporation (Ekern 1965*c*). Bermudagrass sod uses water at about the same rate as a pan under moist conditions, but drops to as low as one-third the pan rate under soil moisture stress (Ekern 1966*a*).

Several studies have demonstrated the high correlation that exists between either water use by plants or by pan evaporation and solar radiation (Baver 1954; Campbell, Chang, and Cox 1960; Ekern 1965*b*, 1977; Chang et al. 1967). Evaluation of the energy budget of sugarcane (Chang 1961; Ekern 1972), pineapple (Ekern 1965*c*), sod (Ekern 1966*a*), and open water surfaces (Ekern 1965*a*) in Hawai'i have resulted in various computational procedures linking ET and pan evaporation with radiant energy.

Various empirical and theoretical methods of calculating ET have been compared with pan evaporation. Although a poor relationship exists between air temperature and open water evaporation in Hawai'i (Ekern 1965*b*), the temperature-based Thornthwaite method has given reasonable results when correlated with pan evaporation (Juvik, Singleton, and Clarke 1978; Tagawa 1980). The Penman formula has been shown to give very reliable estimates of pan evaporation in Hawai'i (Ekern 1965*b*; Chang 1965). In a comprison of several computational methods, Noguchi (1982) found Penman to give the best estimate of pan evaporation, with $r^2 = 0.914$ for a monthly interval.



NOTE: See Table 20.

Figure 20. Locations of climatological stations whose data were selected for ET analysis

TABLE 20. CLIMATOLOGICAL STATIONS USED IN EVAPOTRANSPIRATION ANALYSIS

Map Key	State Key	Station Name	Pan Evap.	Solar Rad.	Temp.	Dew Pt.	Wind	Evapo-rim.
1	700.00	Waimanalo ('Ewa)		x	x			
2	702.00	U.S. Magnetic Obsv.	sur.*					
3	702.20	Observatory	sur.					
4	703.00	Hono. WB (airport)		x	x	x	x	
5	707.00	Makiki	5'	x	x		x	
6	711.40	Waikiki Beach		x				
7	727.00	Pump 10	5'	x				
8	728.00	Pu'u Manawahua		x				
9	732.00	Reservoir 6	5'					
10	737.00	Reservoir 9	5'	x				
11	738.40	Field 155	5'	x	x			
12	740.40	Kunia	sur., 5'	x	x		x	
13	741.00	Ewa Mill	5'	x	x			
14	751.20	Rock Pile	5'					
15	752.00	Waipio	sur.	x	x			
16	756.00	Field 610	5'					
17	761.10	Field 615	5'	x				
18	780.00	Tantalus Peak		x				
19	782.00	Lower Luakaha	sur.					
20	785.00	Manoa HSPA		x	x			
21	807.00	Camp 84 CPC		x				
22	813.30	Field 260		x	x			
23	815.00	Field 245	5'					
24	818.10	Field 220	5'					
25	820.20	PRI Wahiawa	5'	x	x		x	
26	824.10	Field 525	5'					
27	825.30	Field 540		x	x			
28	834.30	Waimano 1		x			x	
29		Mililani STP	4'	x			x	x
30		Benchmark Soils	sur.					x
31		Koa Ridge	4'	x				x
32		Pu'u		x				x
33		Traveler's Palm		x				x
34		Site No. 4		x				x
35		Site No. 5		x				x
36		Site No. 6		x				x
37		Holmes Hall (UHM)	roof	x	x		x	x
38		Mauka Campus (UHM)	4'	x			x	x
39		Huelani	roof	x				x
40		Lyon Arboretum (UHM)		x				x
41		St. Louis Heights						x
42		Ag. Exp. Stn. (UHM)	sur.					
43		USGS Moanalua	sur.					
44	810.00	Wheeler AFB				x	x	
45	701 00	Barbers Pt. NAS				x	x	
46		Helemano					x	
47		Kolekole					x	
48		Mauna Kapu					x	
49		Makakilo					x	

NOTE: See Fig. 20 for station locations.
*Surface pan.

Few data of any kind are available for the high-rainfall areas of the leeward Ko'olau Range. Pan measurements in this region are of questionable value because of errors associated with heavy rainfall. Relationships derived in areas of lower rainfall may not be extrapolated with accuracy in these areas (Ekern 1982). Until recently estimates of ET in the leeward Ko'olaus were based on pan data from adjacent areas and on the early studies of Stearns and Vaksvik (1935) and Stearns and Macdonald (1940). A just-completed field study employed rain-shielded atmometers along with radiometers to determine ET and its relationship with solar radiation in this area (Ekern 1983). Significant differences were found between ridge (Kīpapa) and valley (Mānoa) transects. Apparently, a higher fraction of global radiation is used for ET within broad flat-bottomed valleys, such as Mānoa, than along a knife-edged ridge such as Kīpapa. Much of this difference may be attributable to a higher net radiation in the valley where the adjacent slopes entrap outgoing radiation and reduce net long-wave loss. Short-term observations in Kīpapa Valley indicate that this phenomenon is less pronounced in V-bottom valleys. The higher temperature (due to subsidence) in Mānoa Valley and advection from the urbanized areas may also be factors.

Analysis

Determination of evapotranspiration from each wb-zone during each of the 360 months from 1946 to 1975 was required for the water balance. ET was evaluated for this study using the concept of potential evapotranspiration. First, evaporative demand (PE) was determined. The portion of PE which actually evaporates (AE) was estimated according to the soil moisture content.

The lack of available data prevents an accurate evaluation of individual monthly PE during each year of the study period. Since PE is primarily a function of radiative energy, the seasonal cycle may account for most of the month-to-month variation. In other words, January PE was assumed to vary insignificantly from year to year. This assumption is supported by data, such as pan evaporation measurements. At station 741 (Ewa Mill), for instance, the coefficient of variation for January pan evaporation is only 0.066, and for July, 0.088. Mean monthly PE values were determined for each wb-zone and applied throughout the 30-yr study period. Variation in moisture availability, however, was accounted for on a continuous monthly basis allowing for 360 individual monthly AE estimates for each wb-zone.

POTENTIAL EVAPOTRANSPIRATION. Potential evapotranspiration (PE) is the maximum amount of evapotranspiration possible under the prevailing atmospheric conditions (radiation intensity, air temperature, humidity and wind), and surface characteristics (reflectance, roughness, and stomatal resistance), given that soil moisture stress is non-limiting. Because of spatial and temporal variations in land use, PE was first estimated for an assumed uniform well-watered sugarcane crop. PE for each land use was then estimated by adjusting the sugarcane value.

Four methods were used to estimate monthly PE at various locations:

1. The Penman equation (with parameters selected for a sugarcane crop

2. Pan evaporation (with the appropriate pan coefficient)

3. Atmometer (measurements from the Ekern [1982] ET transects in high rainfall areas)

4. Solar radiation (converted to net radiation over sugarcane and multiplied by a coefficient depending upon quantity of advection expected).

The selection of these methods was based upon data availability. More sophisticated techniques, such as the Penman-Monteith variation, require resistance parameters which are impractical to evaluate at the scale of this study.

DATA. Monthly pan evaporation, solar radiation, temperature, humidity, and wind data are available from numerous sites on southern O'ahu (Fig. 20). Data are collected primarily by the sugar plantations, the U.S. Weather Service (USWS), and the U.S. Geological Survey (USGS), and are compiled and published by the Hawaiian Sugar Planters' Association (HSPA) (1978), Division of Water and Land Development (DOWALD) (1973) and the U.S. Weather Service (Climatological Data). Wind data were also published by Lawrence Livermore Laboratory (Shinn et al. 1979) and the University of Hawaii, Department of Meteorology (Ramage et al. 1977). Atmometer and radiometer measurements were made available.* Table 20 lists the climatological stations whose data were used to evaluate ET for this study.

Solar radiation, temperature, humidity, and wind data are required for Penman PE calculation. Few stations routinely collect all four elements. Wind and humidity measurements, in particular, are lacking at most stations. Absolute humidity (dew-point temperature), however, is relatively uniform throughout the study area, so that data from the three stations, Honolulu International Airport, Wheeler Air Force Base (AFB), and Barbers Point Naval Air Station (NAS) provided sufficient information for all areas. Table 21 lists monthly mean-dew point temperature for each of these stations. It is evident that spatial variability is small. Dew-point temperature for each month at other locations was estimated as being the same as that of the nearest station or was equated to the average of the three.

Wind measurements have been collected on a short-term basis at several sites to estimate wind energy potential. Based on these observations, long-term wind data, and on several wind distribution studies (Noguchi 1979; Ramage et al. 1977; Ramage, Oshiro, and Yokogawa 1979; Siler 1964; Morrow 1974, 1976), a map of mean annual wind velocity at a 2-m (6.6-ft) height was constructed for a portion of the study area (Fig. 21). Assuming that seasonal wind fluctuations are similar from place to place on the island, the ratios of monthly mean to annual mean each month at an index station can be used to estimate monthly mean wind anywhere in the study area. The Honolulu International Airport, which has a long continuous wind record, was selected as the index. Mean annual wind at stations without wind measurements were estimated from Figure 21 and each monthly mean determined using the airport ratios (Table 22). The strong spatial correlation of

*P.C. Ekern 1983: personal communication.

TABLE 21. MEAN MONTHLY DEW-POINT TEMPERATURE

STATION	MEAN DEW-POINT TEMPERATURE (°F)											
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Hono. Int. Airpt.	62.5	61.6	61.6	62.4	63.7	65.3	66.0	66.6	66.5	66.3	65.1	63.3
Barbers Point	63.1	62.2	62.3	63.1	64.3	65.7	66.5	66.9	66.8	66.9	65.4	63.8
Wheeler AFB	61.0	60.3	60.8	62.0	63.5	65.0	65.6	66.5	66.2	65.8	65.1	63.0
Mean	62.2	61.4	61.6	62.5	63.8	65.3	66.0	66.7	66.5	66.4	65.2	63.4

TABLE 22. RATIOS OF MEAN MONTHLY TO MEAN ANNUAL WIND AT HONOLULU INTERNATIONAL AIRPORT

Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
0.828	0.862	1.069	1.052	1.008	1.103	1.181	1.112	1.017	0.939	0.897	0.879

wind velocity in the region demonstrated by Ramage et al. (1979) supports the validity of this technique. In addition, comparison of the Honolulu International Airport with Wheeler AFB showed similar ratios of monthly to annual means.

With these methods of estimating mean monthly dew-point temperature and wind velocity, the Penman calculation can be made wherever solar radiation and air temperature data are available.

PENMAN POTENTIAL EVAPOTRANSPIRATION. Seven stations which were located in agricultural environments in southern O'ahu and which had solar radiation, air temperature, and pan evaporation data (all pans at 1.52 m [5 ft] elevation above ground) were selected. Using humidity and wind measurements or estimates of these data, Penman PE (eqq. [31], [32]) was calculated and compared with pan data.

Net radiation was estimated from measured solar radiation by two methods. The first was developed by Chang (1970) as

$$Q_n = (1 - r)Q - \sigma T^4 [286.18 + 202.6(Q/Q_a) - 45.24\sqrt{e_d} - 10.92(Q/Q_a)\sqrt{e_d}] \quad (37)$$

where

Q_n = net radiation (cal/cm^2/day)

r = reflection coefficient (ratio)

Q = global radiation (cal/cm/day)

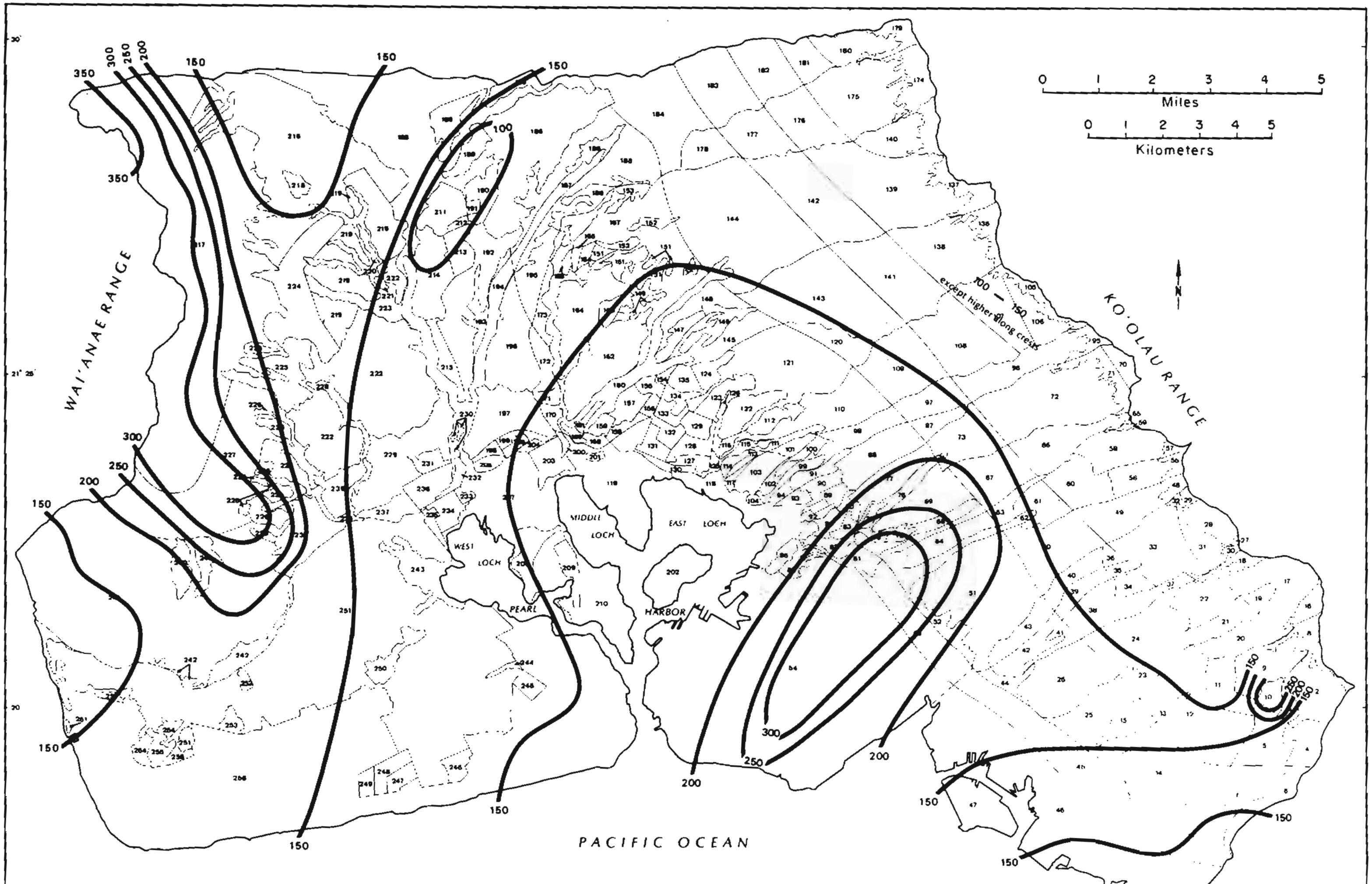
σ = Stephan-Boltzman constant (8.17 x 10^{-11} cal/cm/min/T^{-4})

T = air temperature (K)

Q_a = Angot value (cal/cm/day)

e_d = saturation vapor pressure at dew-point temperature (mb).

Particularly useful where temperature and humidity data are not available



NOTE: In miles/day.

Figure 21. Distribution of mean wind velocity

is a simpler method suggested for use in Hawai'i by Ekern (1972),

$$Q_n = (1 - r)\ Q - 150(Q/Q_c) \qquad (38)$$

where

Q_c = maximum clear day global radiation (cal/cm/day).

Chang (1961) used an inverted Eppley pyrheliometer to measure reflected short-wave radiation over sugarcane. His results suggest an average reflection coefficient of 0.15. Ekern (1972) also measured sugarcane reflectance, using an inverted Monteith solarimeter and found 0.21 to be the average coefficient. The average of these two results (0.18) was used as the reflectance in the Penman calculation.

The psychrometric constant γ is dependent on pressure, humidity, and temperature. For the calculation of the Penman PE, γ was estimated using the approximation of Storr and den Hartog (1975),

$$\gamma = 0.3863P/L + 0.02694RH[10^{7.5T/(237.3+T)}]/L \qquad (39)$$

where

P = atmospheric pressure

RH = relative humidity (%)

T = temperature (°C)

L = latent heat of vaporization of water (cal g^{-1}).

PENMAN POTENTIAL EVAPOTRANSPIRATION VS. PAN EVAPORATION. Monthly mean solar radiation, net radiation, Penman PE, and pan evaporation for seven southern O'ahu stations are presented graphically in Figure 22. Correlations were computed among the various parameters and the results appear in Table 23.

TABLE 23. COEFFICIENTS OF DETERMINATION (r^2) AMONG RADIATION, POTENTIAL EVAPOTRANSPIRATION, AND PAN EVAPORATION MEASUREMENTS AND ESTIMATES FOR SEVEN SOUTHERN O'AHU STATIONS

		COEFFICIENTS OF DETERMINATION (r^2)					
		Q	Qn1	Qn2	Pe1	Pe2	Pan
Q	Global radiation	1.000	0.996	0.997	0.899	0.899	0.751
Qn1	Net radiation (Chang)		1.000	0.998	0.898	0.895	0.760
Qn2	Net radiation (Ekern)			1.000	0.895	0.896	0.749
Pe1	Penman PE* (Chang)				1.000	0.999	0.890
Pe2	Penman PE (Ekern)					1.000	0.883
Pan	Pan evaporation						1.000

NOTE: See Fig. 22 for seven stations.
*PE = potential evapotranspiration.

The graphs (Fig. 22) and r^2 values (last column, Table 23) illustrate the strong relationship between radiation and pan evaporation. Both solar and calculated net radiation are highly correlated with the pan data. The

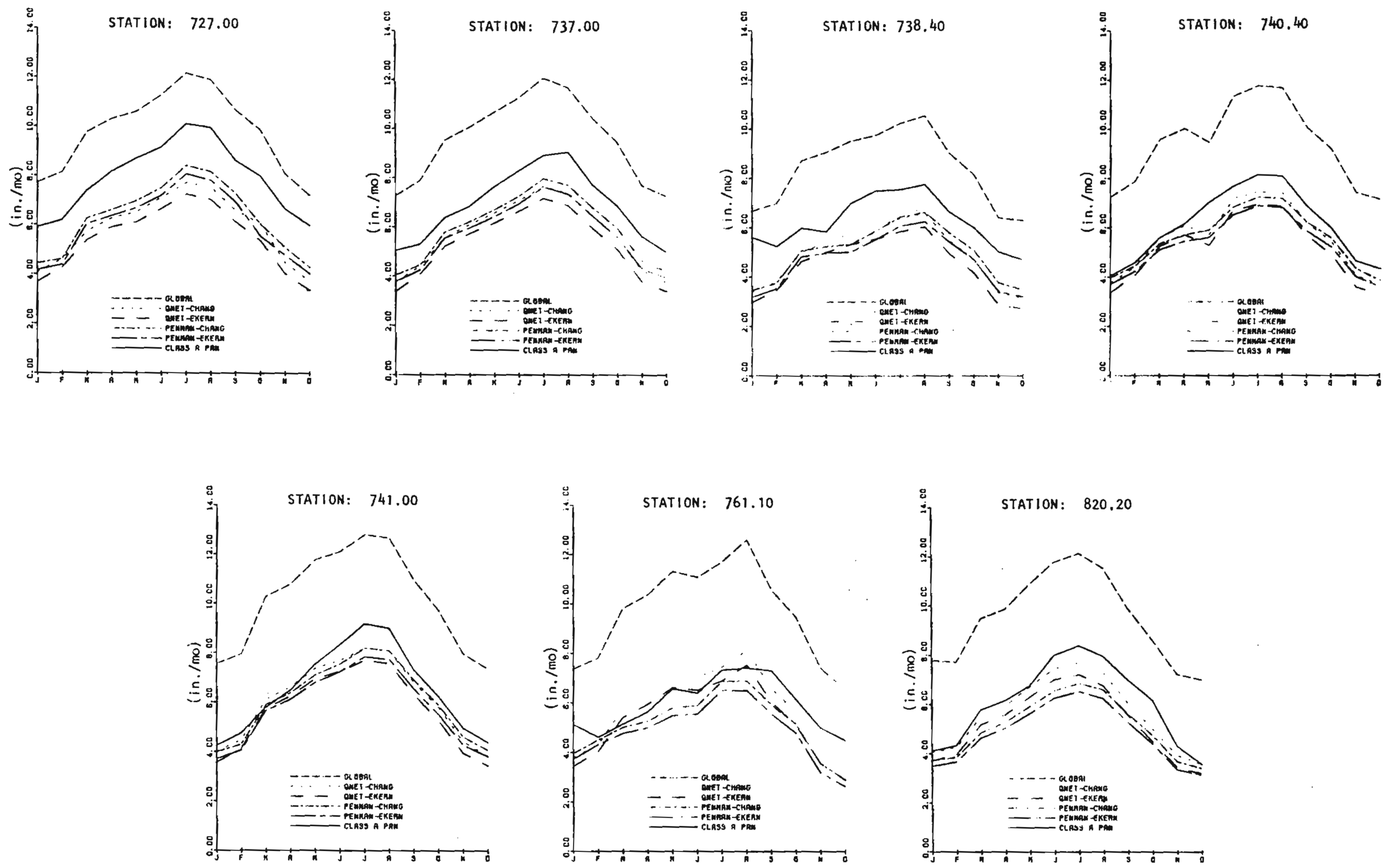


Figure 22. Seasonal variation of solar radiation, net radiation (Chang and Ekern formulas), Penman PE (Chang and Ekern net radiation formulas), and pan evaporation for seven southern O'ahu stations

Penman equation using the Chang net radiation formula (eq. [37]) was found to predict pan evaporation most accurately (highest r^2). Noguchi (1982) also compared pan evaporation with the Penman ET using various net radiation equations and found that the Chang formula gave the best results. The value of r^2 (0.89) is similar to that of previous Penman vs. pan correlations in Hawai'i (Chang et al. 1967; Noguchi 1982).

Table 24 gives the ratios of the average values of each parameter to each of the others. Of particular interest is the Penman/pan ratio, 0.86. Figure 23 illustrates the relationship. This value is in agreement with Chang et al. (1967), who found that pan evaporation exceeds calculated Penman PE by 18%. If the Penman estimate is assumed to be properly calibrated to sugarcane PE, a pan coefficient of 0.86 is suggested. Previous studies using lysimeter data indicate that sugarcane PE equals approximately 0.8 to 0.9 of evaporation from elevated pans and is about equal in magnitude to surface level pan evaporation.

TABLE 24. AVERAGE RATIOS AMONG RADIATION, PE, AND PAN EVAPORATION MEASUREMENTS AND ESTIMATES FOR SEVEN SOUTHERN O'AHU STATIONS

DENOMINATOR		NUMERATOR					
		Q	Qn1	Qn2	Qe1	Pe2	Pan
Q	Global Radiation	1.000	0.596	0.549	0.586	0.534	0.680
Qn1	Net Radiation (Chang)	1.679	1.000	0.921	0.988	0.930	1.142
Qn2	Net Radiation (Ekern)	1.823	1.086	1.000	1.068	1.009	1.239
Pe1	Penman PE* (Chang)	1.707	1.012	0.933	1.000	0.945	1.163
Pe2	Penman PE (Ekern)	1.807	1.076	0.991	1.058	1.000	1.229
Pan	Pan Evaporation	1.407	0.876	0.807	0.860	0.814	1.000

NOTE: See Fig. 22 for seven stations.
*PE = potential evapotranspiration.

A limited survey of Class A pan sites at five stations was conducted on 8 January 1983. All sites surveyed were located in the sugar growing region of southern O'ahu. The stations were maintained either by Oahu Sugar Company (OSC) or by the Hawaiian Sugar Planters' Association (HSPA). All surveyed stations were found to have pans elevated to a height of about 1.52 m (5 ft). The HSPA station at Kunia had an elevated pan and a surface pan. The survey verified that OSC uniformly maintains their pans at the 1.52 m elevation over grass. Most OSC stations are located near sugarcane fields and are often situated adjacent to and to the southwest side (downwind) of reservoirs.

The pan survey and discussions with present and former HSPA personnel* revealed that all plantation pans are operated 1.52 m above the ground, while pans at experiment stations (HSPA and PRI) may be either surface or elevated. Other pans, such as those operated by the U.S. Geodetic Survey, are on the surface.

*K. How 1980, J.H. Chang 1983, P. Haraguchi 1983: personal communications.

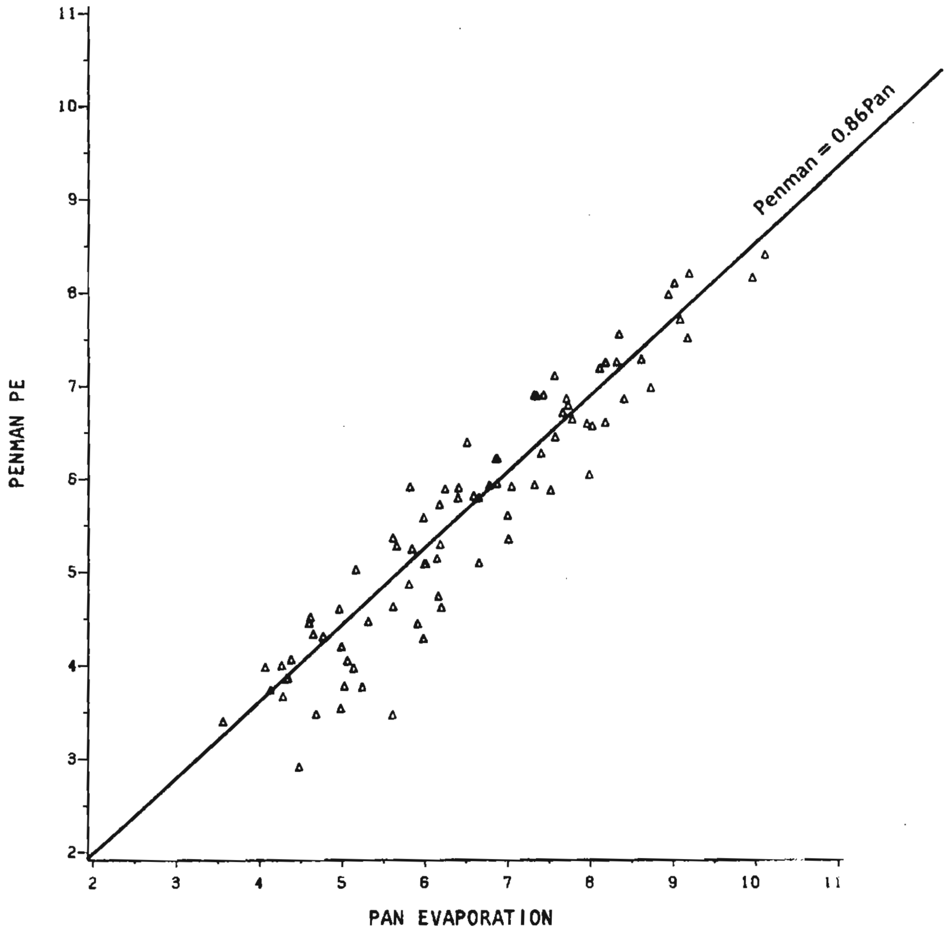


Figure 23. Scattergram of monthly pan evaporation vs. Penman PE

All seven pans used in the comparison with Penman PE were elevated pans. The average Penman/pan ratio of 0.86 was therefore selected as the pan coefficient for elevated pans. Surface pans were assumed to evaporate at a rate equivalent to sugarcane PE (pan coefficient = 1.00).

POTENTIAL EVAPOTRANSPIRATION IN HIGH RAINFALL AREAS. The difficulty of assessing evapotranspiration in remote high rainfall areas of the Ko'olau Range has plagued all previous attempts at estimating the water balance of O'ahu. Evaporation pans are subject to large errors when used in areas of heavy or persistent rainfall. Attempts to extrapolate ET from measurements in drier areas are fraught with uncertainty. Ekern's (1983) recent study using specially designed rain-shielded atmometers offers the first opportunity to accurately define ET in this region.

Ekern's atmometers were found to require a 0.6 calibration to elevated pan evaporation. Assuming a 0.86 pan coefficient, the atmometer evaporation was multiplied by a 0.516 (0.6 x 0.86) factor to obtain an equivalent sugarcane PE.

In addition to the Kīpapa and Mānoa transects of Ekern's study, pan evaporation measured in Nu'uanu by Stearns and Vaksvik (1935), and in Moanalua by the USGS, were used to map PE. The pan values were used with caution because of previously mentioned reservations. Both records were considered better than standard pan data because of special measures taken to minimize rainfall-related errors. The Nu'uanu pan included an overflow device, thus eliminating part of the problem. These data however appeared to be too low in winter months. The USGS pan has a continuous recording apparatus so that actual rain catchment by the pan was monitored. The Kaukonahua Valley pan measurements taken by Stearns and Vaksvik (1935) as well as their panicum grass and fern lysimeter data were not included in the PE analysis because they appear to be erroneous in light of more recent measurements.

POTENTIAL EVAPOTRANSPIRATION FROM CALCULATED NET RADIATION. To estimate the fraction of net radiation (Qnet) used in evapotranspiration, Qnet was calculated by either equation (37) or (38) for all locations with Penman, pan, or atmometer PE estimates. The ratio of annual PE/Qnet at each location was plotted. Figure 24 is an isopleth analysis of the PE/Qnet ratio. The map indicates that the fraction of Qnet used in ET varies from about 0.6 in areas of frequent fog occurrence to greater than 1.25 in areas of high positive advection. Seasonal fluctuation of the ratio at a given location was found to be small relative to the spatial variation.

PE was estimated for all stations having solar radiation measurements (but lacking other data required for Penman calculation) as a fraction of calculated Qnet. The fraction at each station was determined from Figure 24.

POTENTIAL EVAPOTRANSPIRATION MAPS. Estimates of monthly PE at 43 locations were used in the PE analysis. The results are shown on Figures 25 through 36. The PE maps represent atmospheric demand and ignore surface characteristics. The distribution is determined by solar radiation and advection.

In all months, the general pattern strongly resembles the solar radiation distribution (Yoshihara and Ekern 1978, p. 45), except in dry areas where advection becomes important. Minima occur along the crests of the Ko'olau and Wai'anae ranges. The very low value in the upper Ko'olaus reflects an abrupt PE decline in areas above 609.6 m (2000 ft) elevation. The influence of large amounts of irrigation in the sugar-growing areas is very prominant especially in the 'Ewa region. PE is reduced by 30% or more compared with adjacent unirrigated areas because of lower advection. Highest PE values are generally found along the leeward coast, especially near the maximum. Another PE maximum is found extending inland from the coast south of Nānākuli, which is also an areas of high radiation and low rainfall, but which contrasts sharply in evaporation demand with the irrigated 'Ewa Plain.

Seasonal variation also follows the radiation pattern with the maximum for most areas occurring in June or July. In areas of strong positive advection, higher values occur during the temperature maximum in August or September. The gradients are also much higher in summer as a consequence of an inverted seasonal radiation regime in high rainfall areas. Here, persistent cloud cover controls insolation and the low sun angle in winter per-

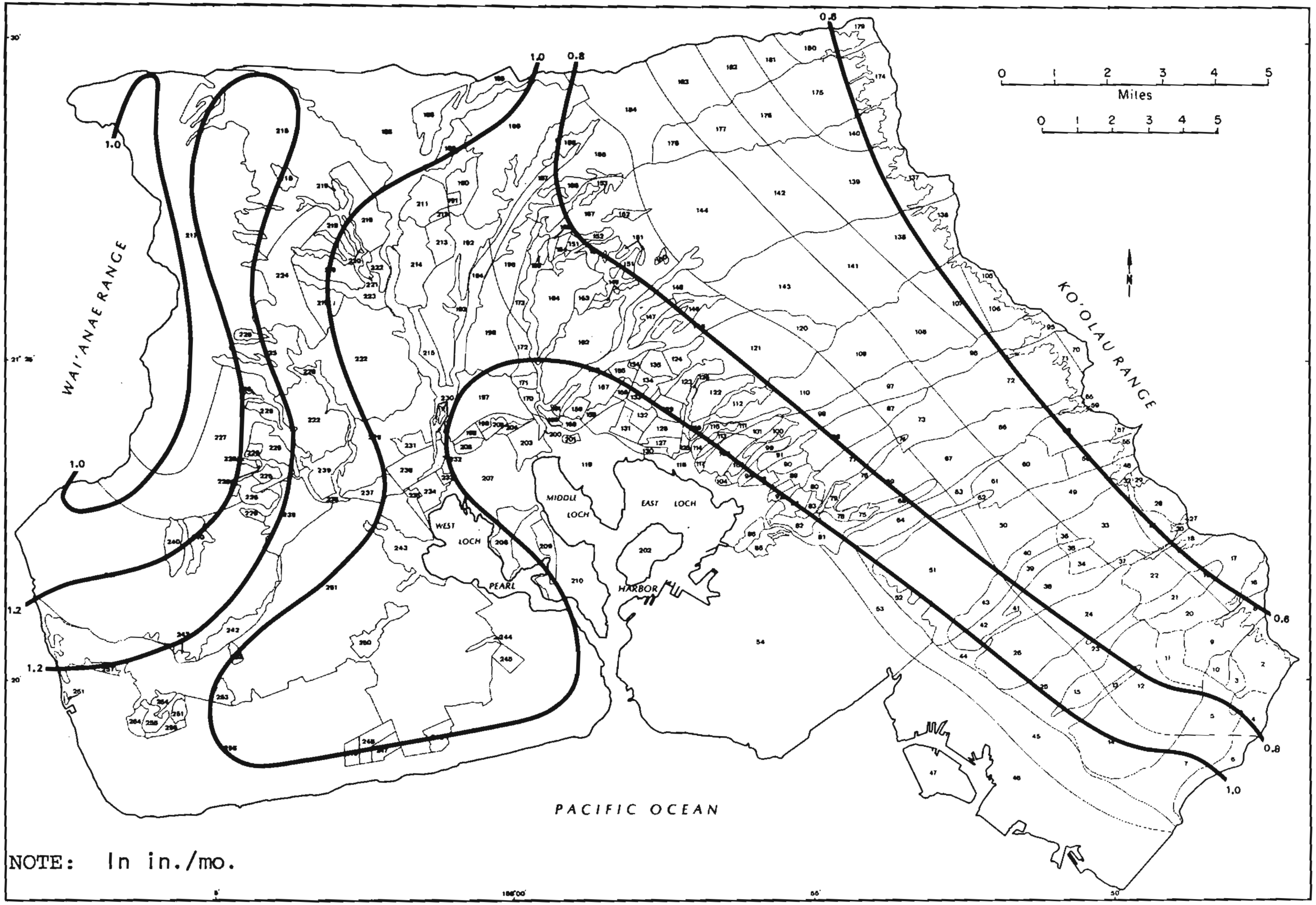


Figure 24. Distribution of ratio of potential evapotranspiration to net radiation

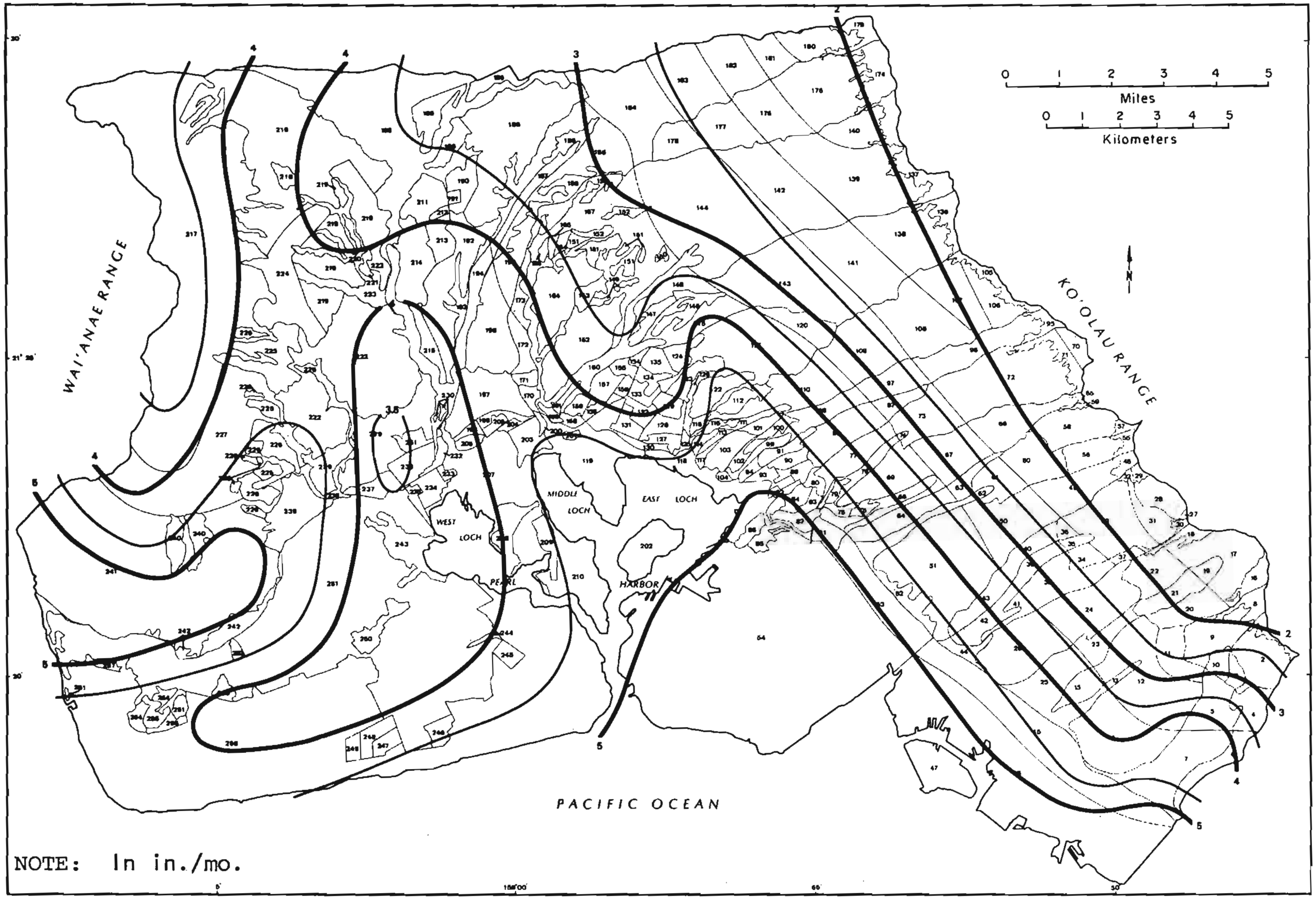


Figure 25. Distribution of reference surface (sugarcane) potential evapotranspiration, January

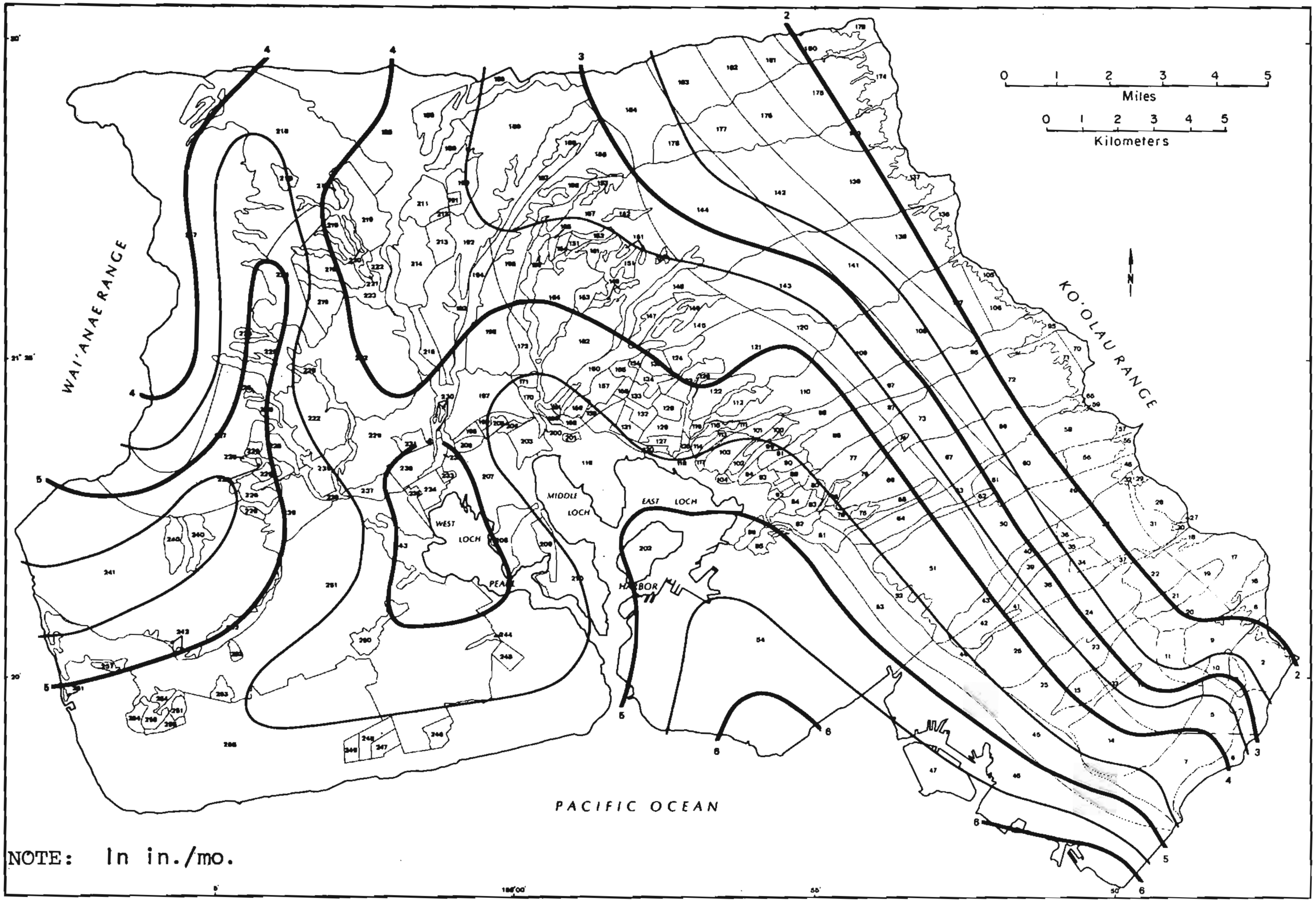


Figure 26. Distribution of reference surface (sugarcane) potential evapotranspiration, February

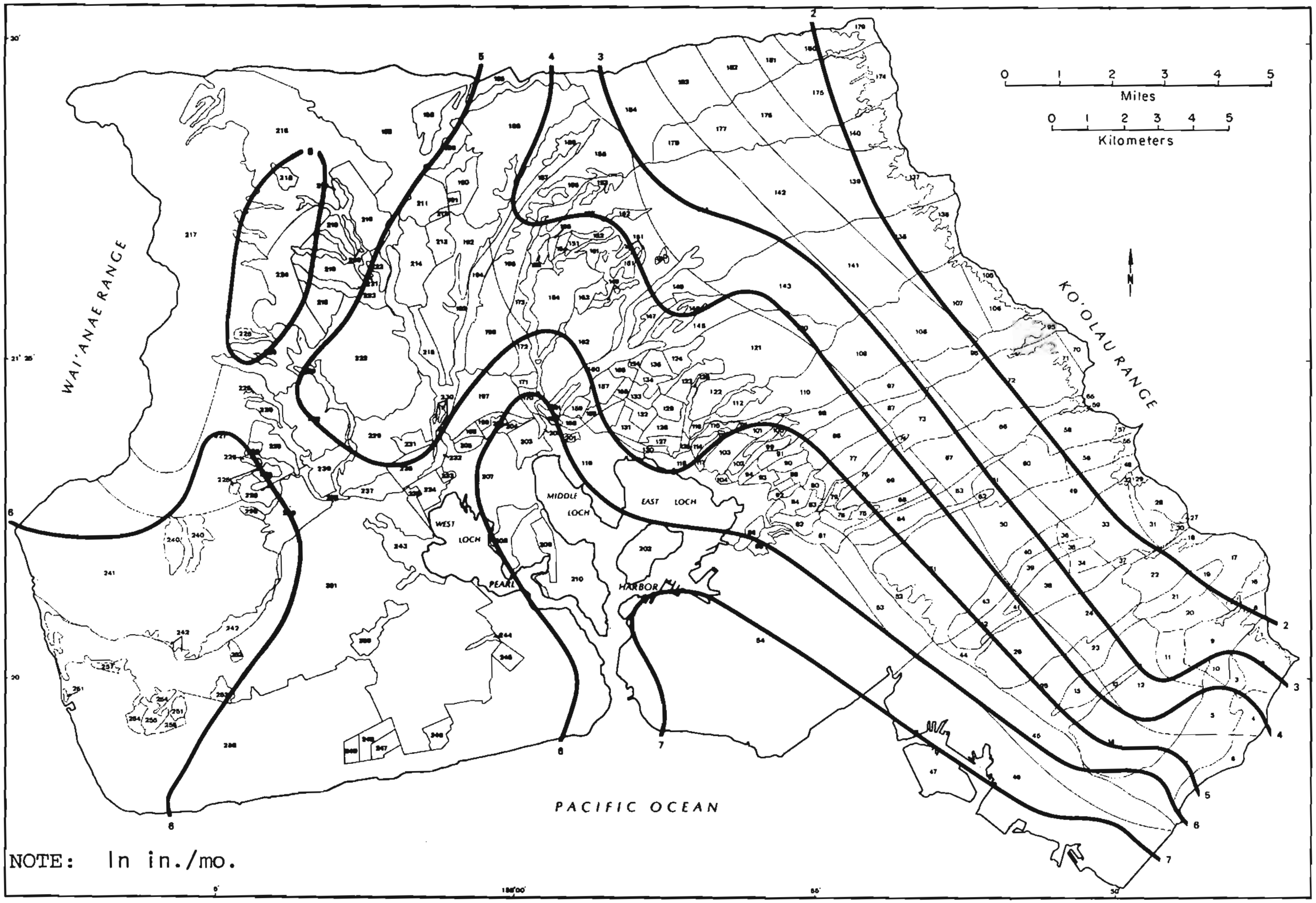


Figure 27. Distribution of reference surface (sugarcane) potential evapotranspiration, March

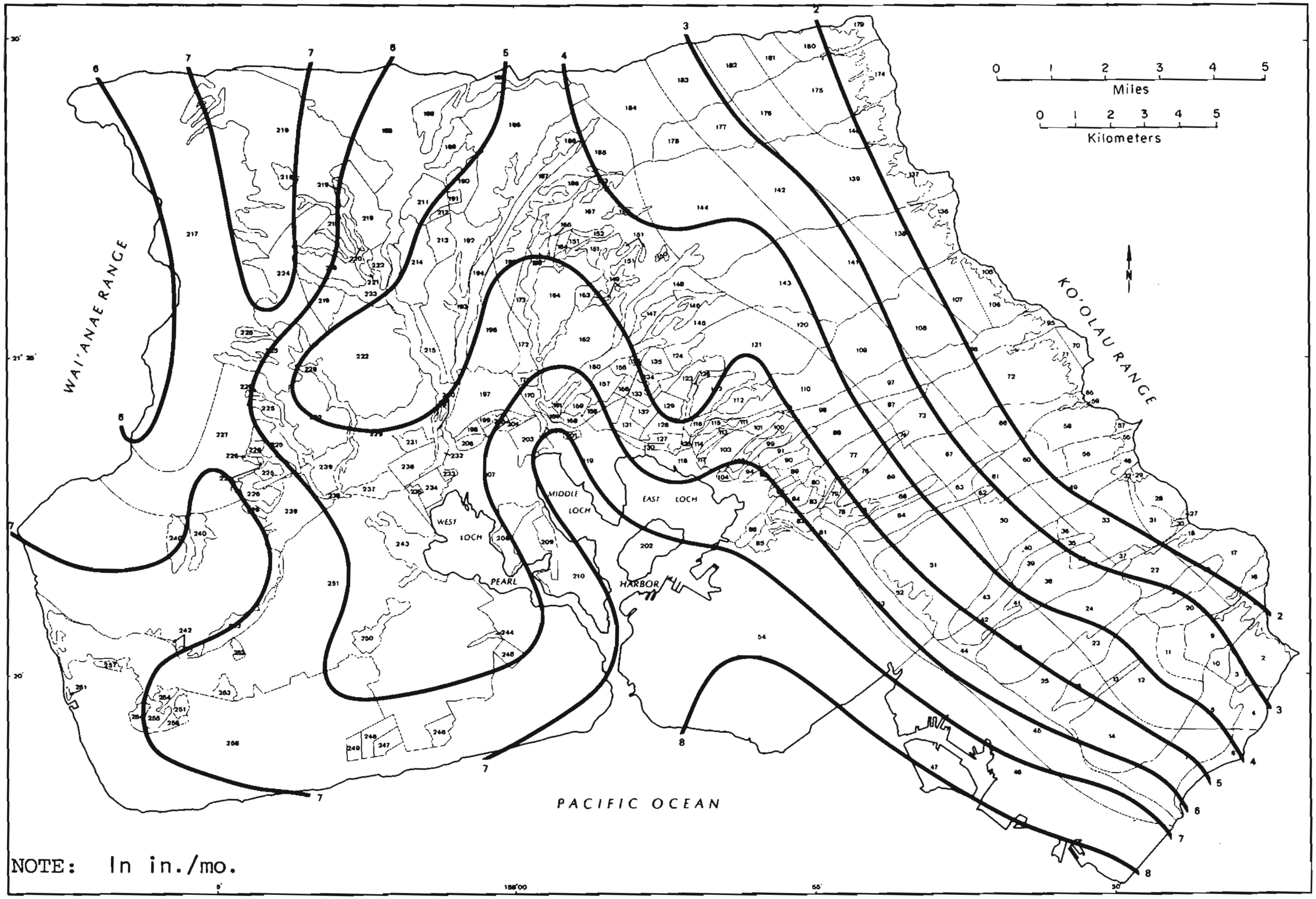
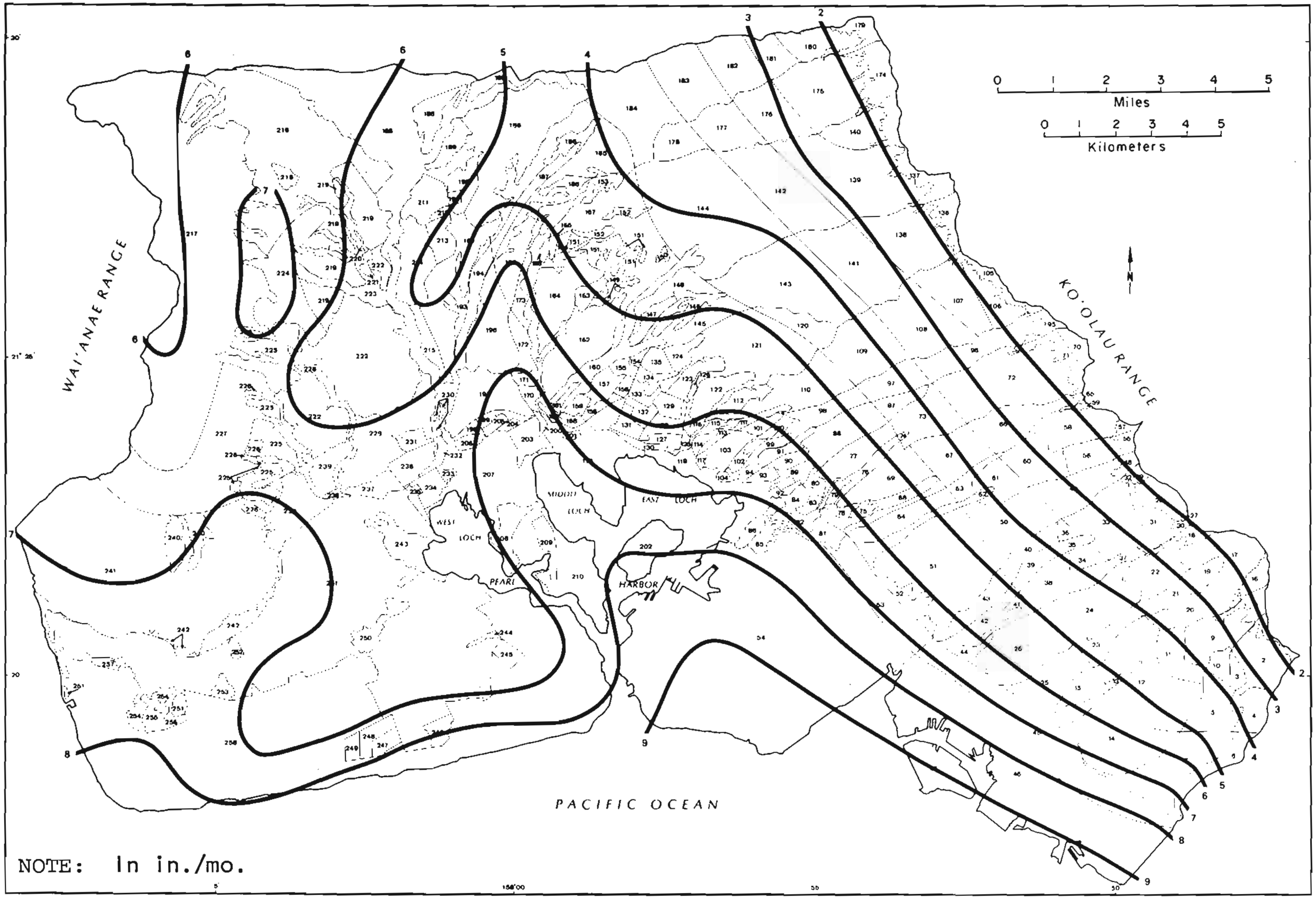


Figure 28. Distribution of reference surface (sugarcane) potential evapotranspiration, April



NOTE: In in./mo.

Figure 29. Distribution of reference surface (sugarcane) potential evapotranspiration, May

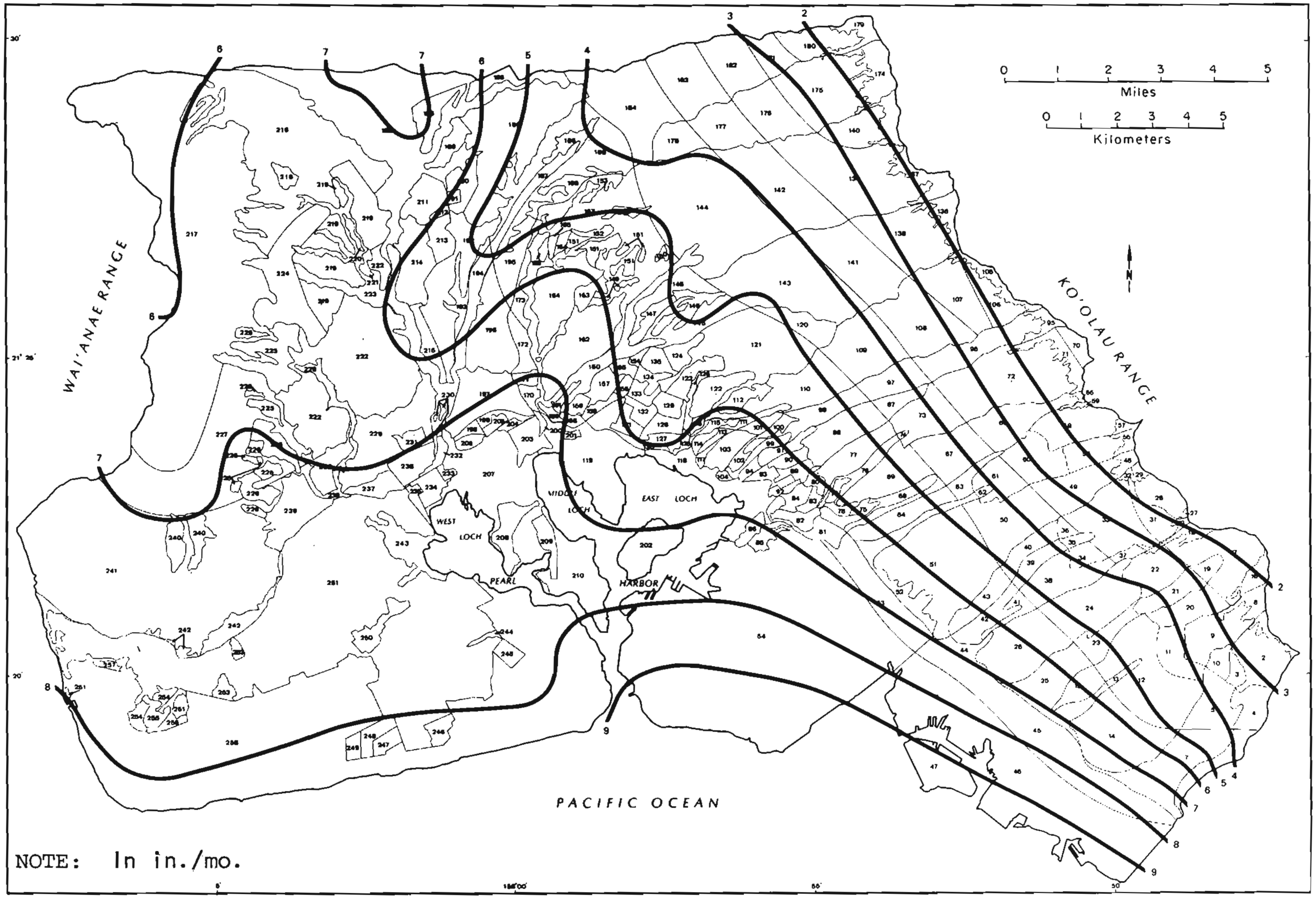


Figure 30. Distribution of reference surface (sugarcane) potential evapotranspiration, June

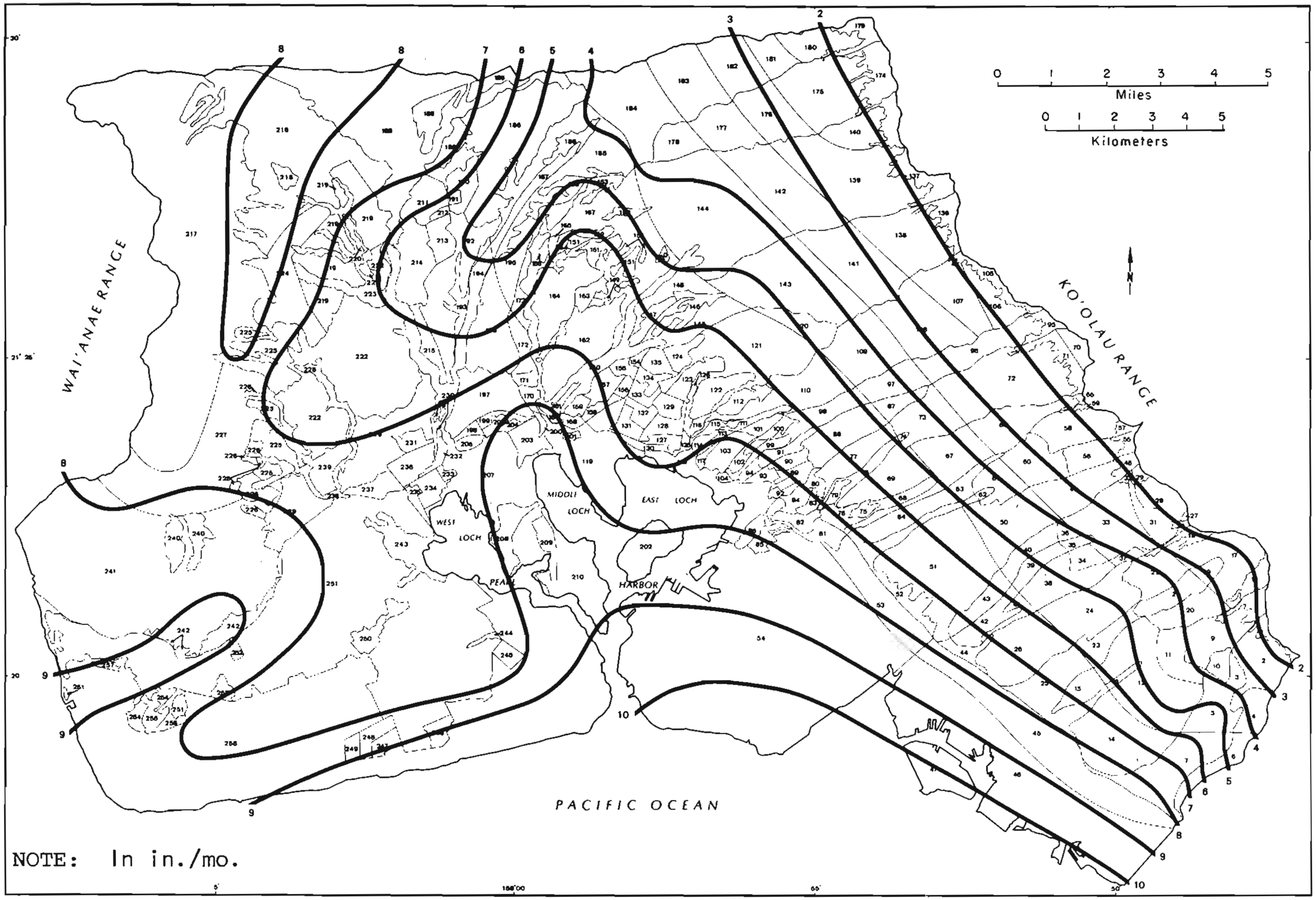


Figure 31. Distribution of reference surface (sugarcane) potential evapotranspiration, July

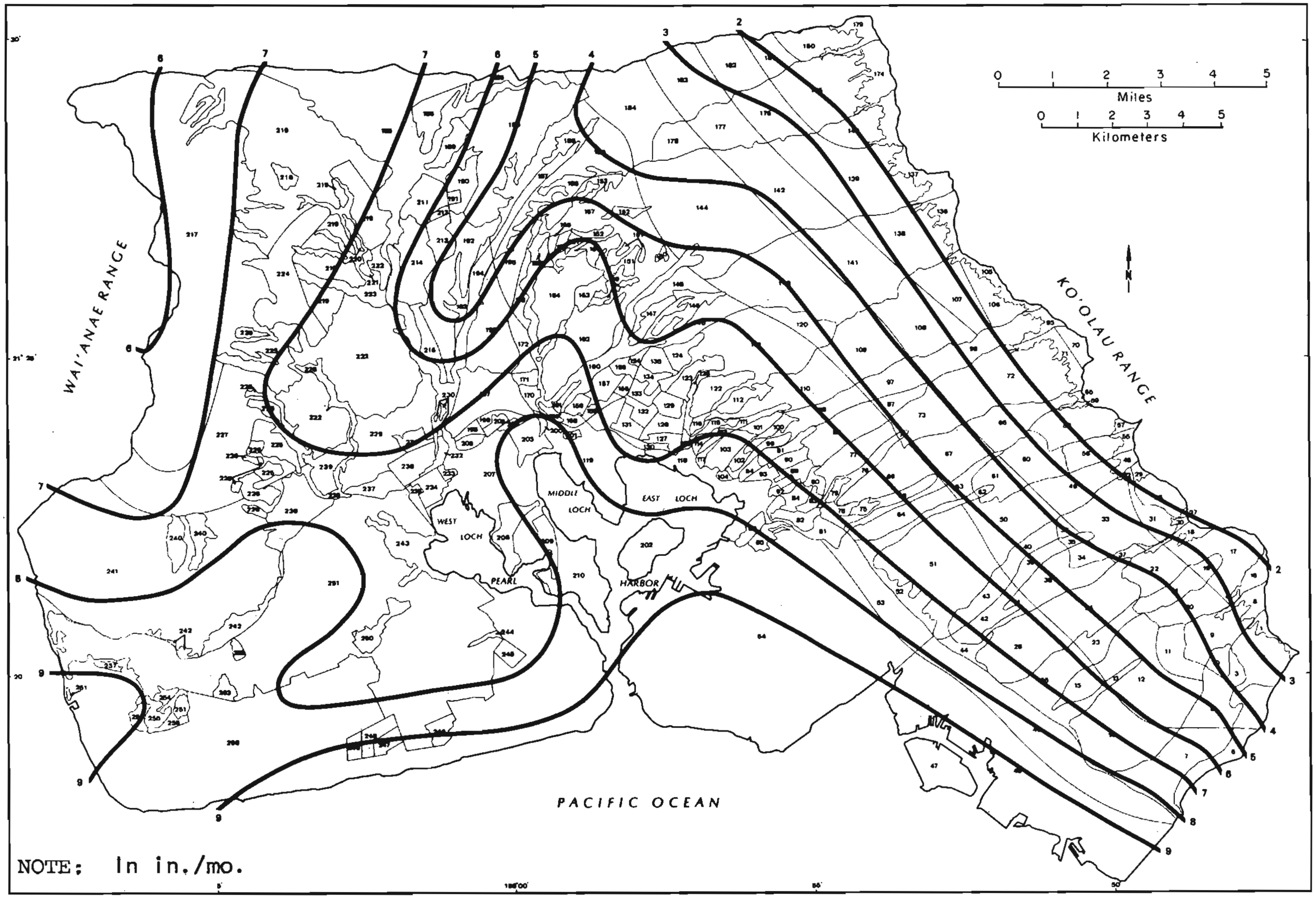


Figure 32. Distribution of reference surface (sugarcane) potential evapotranspiration, August

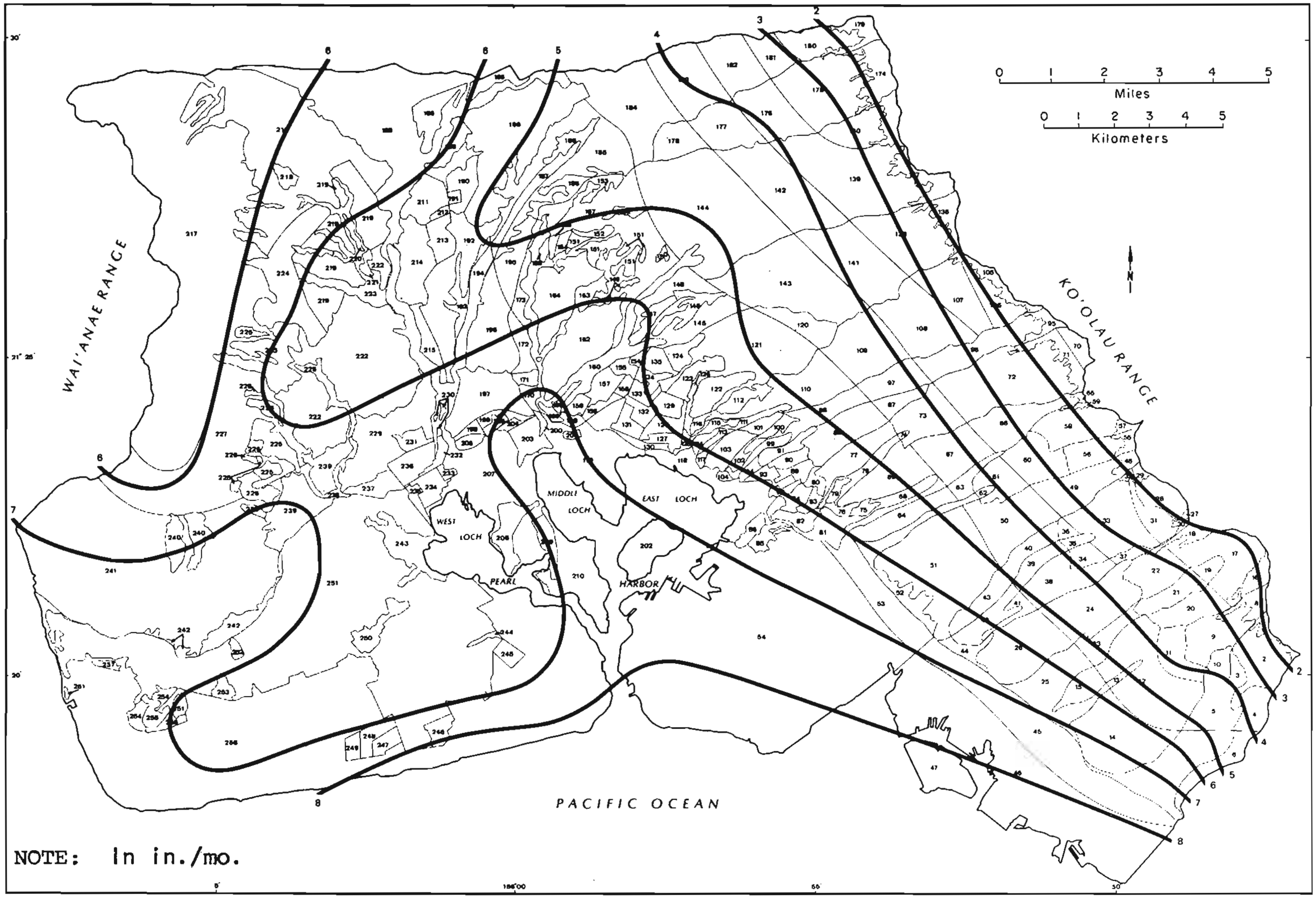


Figure 33. Distribution of reference surface (sugarcane) potential evapotranspiration, September

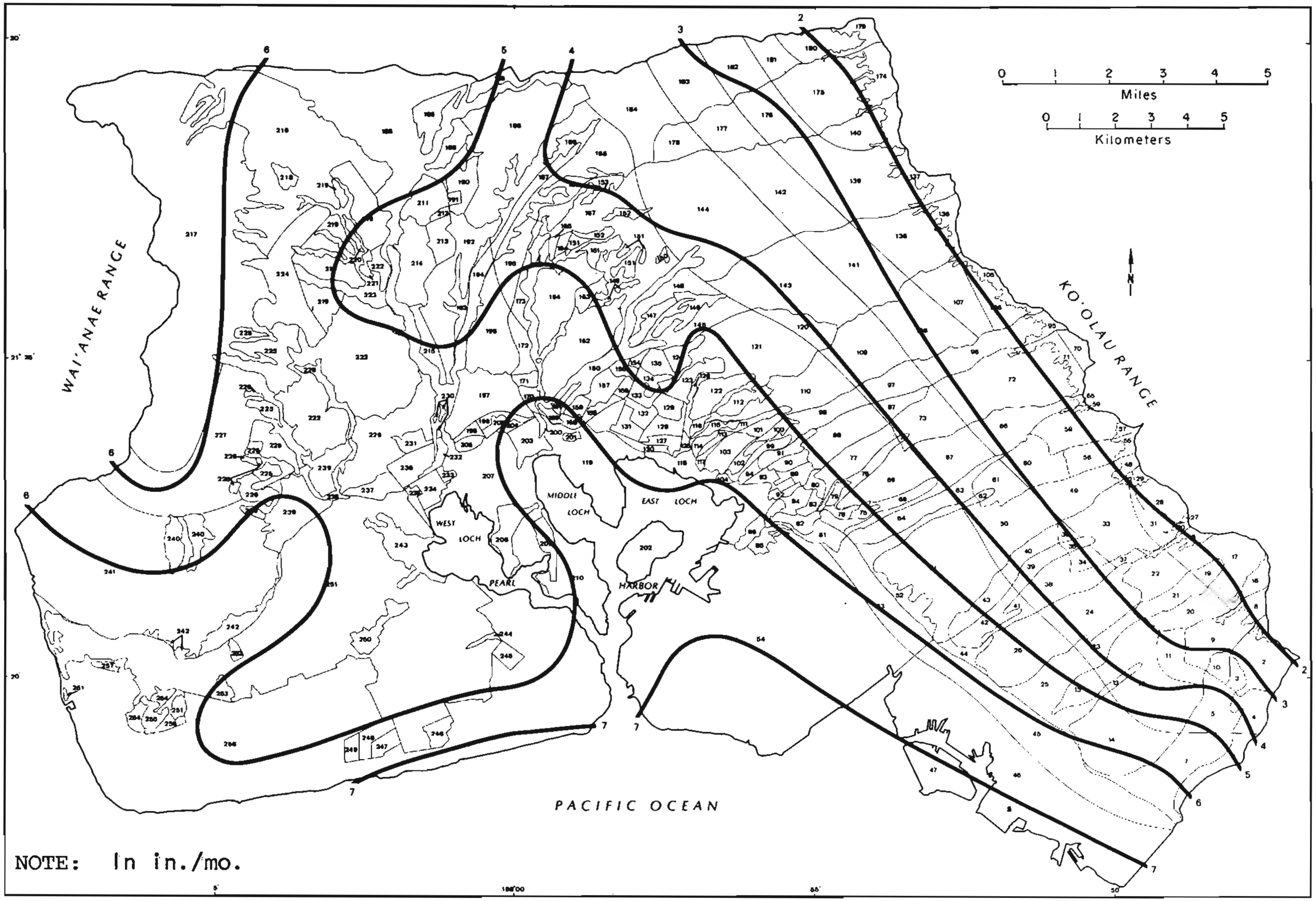


Figure 34. Distribution of reference surface (sugarcane) potential evapotranspiration, October

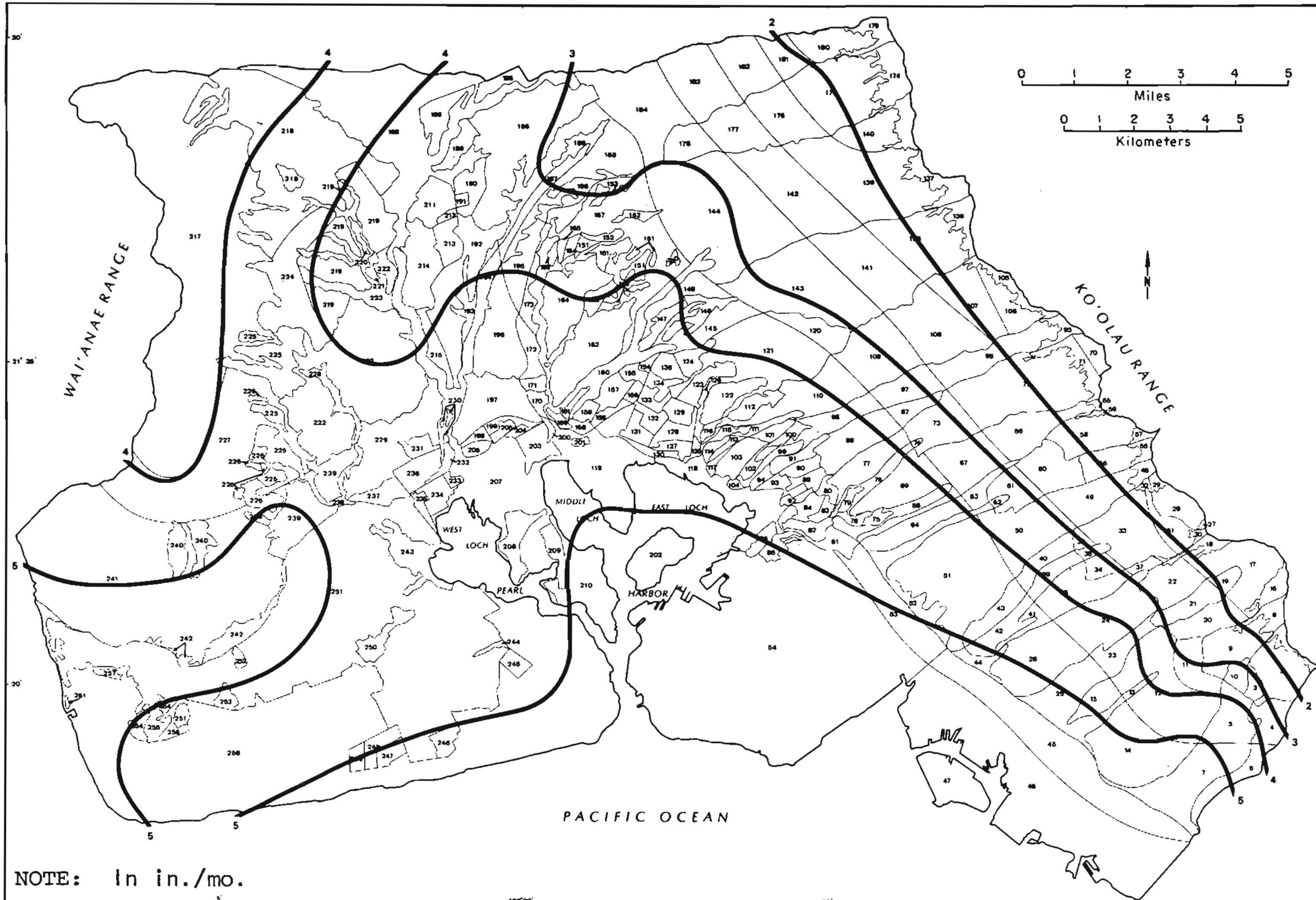


Figure 35. Distribution of reference surface (sugarcane) potential evapotranspiration, November

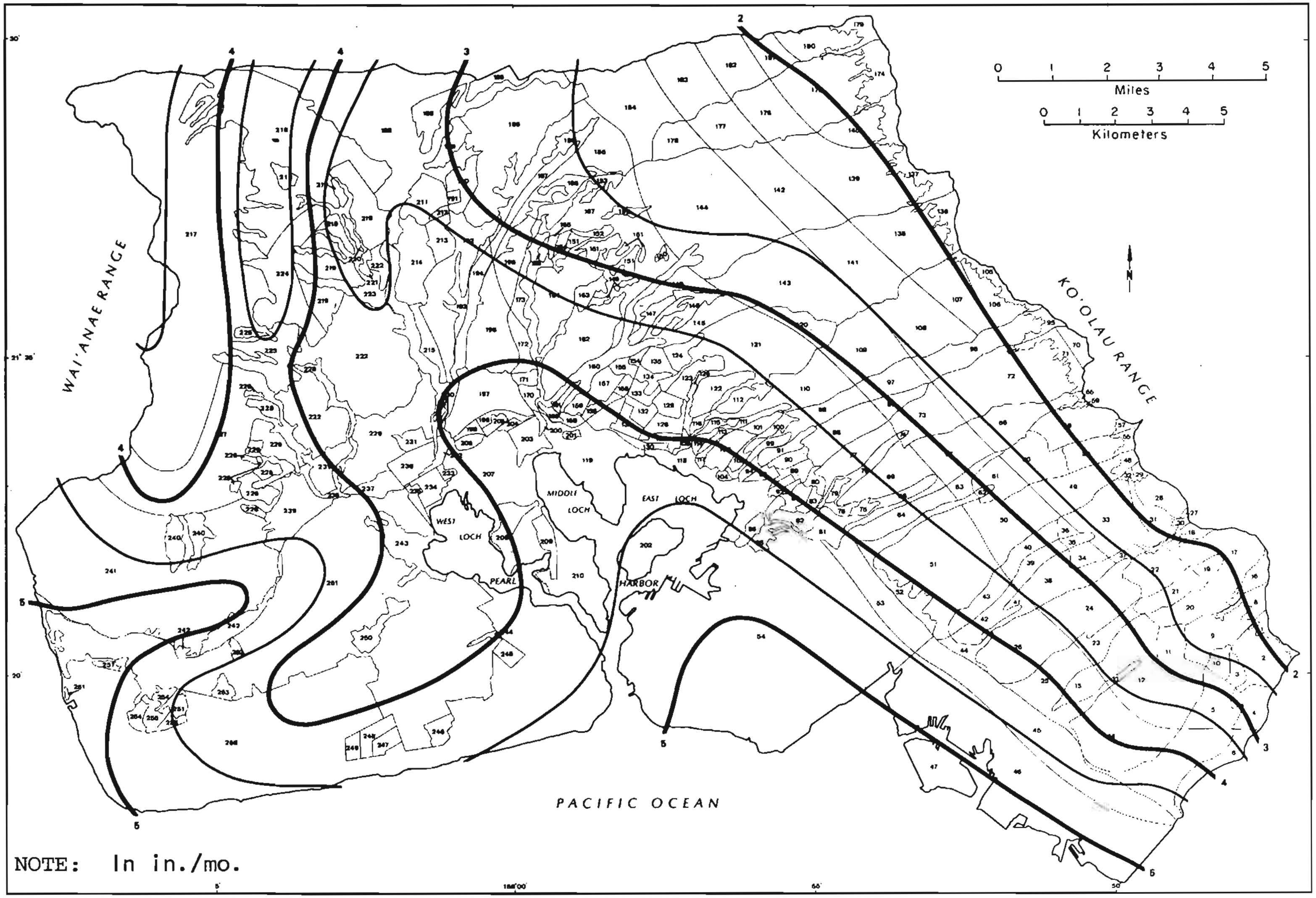


Figure 36. Distribution of reference surface (sugarcane) potential evapotranspiration, December

mits greater amounts of direct sunlight to be received. In addition, the absence of trade winds for periods during the winter months reduces the frequency of orographic cloud cover.

ADJUSTMENT OF POTENTIAL EVAPOTRANSPIRATION FOR COVER. Figures 25 through 36 show the distribution of monthly PE for an assumed uniform cover of mature sugarcane. The actual cover, however, varies spatially and temporally. Adjustment must be made for the particular cover (areal vegetation density and type) present in each wb-zone in each year. This was conveniently accomplished by using a cover coefficient for each land use category.

The degree of vegetative cover is an important factor in determining ET. Californiagrass, for instance, was observed to evapotranspire at a rate proportional to total biomass (Ekern 1983). Similar results have been obtained in studies of the variation of ET during the growing cycle of various crops (Aase and Siddoway 1982; Tan and Fulton 1980; Russell 1980; Tanner and Jury 1976; Jensen, Robb, and Franzoy 1970), and Ritchie (1972) has developed a model to account for varying cover density in estimating ET. The areal density of cover determines the relative quantity of radiant energy intercepted by the leaves, an indication of the relative contributions of transpiration and soil evaporation. Ekern (1966*b*) has shown that at relatively high soil moisture contents, when a vegetated surface would experience maximum ET, Wahiawa silty clay (Tropeptic Haplustox) had very low evaporation rates because of the development of a surface mulching layer. His data show that bare soil evaporation at field capacity amounts to only 36% of the ET from a fully vegetated surface. Areas of partial cover then can be expected to have PE rates equivalent to a weighted average of the vegetated rate and the bare soil rate. A density coefficient may be computed as

$$D = 0.36 + 0.64a \qquad (40)$$

where

D = cover coefficient

a = proportion of area covered with vegetation.

The cover density was determined for each land use type. Sugarcane and pineapple coverage were determined in the previous section (Table 16) for assumed crop cycle and road density conditions. Urban and part-urban areas were given coverages of greater than 100% (for pervious portion only) to allow for tree canopy overhang. Parks and golf courses were assumed to to have 100% coverage. Forest/vacant wb-zones were given a 100% cover except in dry regions (<762.0 mm [30 in.] annual rainfall) where a 50% coverage was assumed.

Coefficients are included in some ET models to allow for differing transpiration characteristics of various plants (Burt et al. 1981; Doorenbos and Pruitt 1975; Ritchie 1972; Blaney and Criddle 1950). Because it was used in this study as the reference surface, sugarcane was given a vegetation coefficient (V) of 1.0. The V coefficient for other land use types were defined as the ratio of PE for a particular vegetation to sugarcane PE. Pineapple, with its unusual physiology, suppresses ET to very low levels.

Using the results of lysimeter measurements (Ekern 1965*c*), pineapple was assigned 0.25 as a vegetation coefficient. All other vegetation was assumed to have ET similar to sugarcane, with the exception of the wet forested areas. Because of the dense multistory canopy, lower albedo, rougher surface, and the continuous wetting of the soil, ET in these areas was considered to be higher than the sugarcane standard (coefficient greater than 1.0).

Blaney and Criddle (1950) used coefficients of 1.2 and 1.3 for dense and very dense forests as compared with 0.75 for corn. Ekern (1983) calibrated his evaporimeters at 1.10 times elevated pan to estimate wet forest ET. He supports this high factor by citing lysimeter measurements (Ekern 1966*a*; Campbell, Chang, and Cox 1960) in which ET rates have reached 1.1 for short periods of very dense canopy, vigorous growth, and continuous wetting of the soil surface. The significance of a wetted soil surface has been demonstrated in comparisons of overhead sprinkler and subsurface drip irrigation (Ekern 1977).

Another indication of the expected ET for the wet areas is provided by the Priestley-Taylor (1972) approach. According to their model, the proportionality constant α (see eq. [35]) should equal 1.26 for saturated land surfaces. At the 0.86 pan calibration (sugarcane ET), α was 0.96 at Lyon Arboretum, 0.94 at Koa Ridge, 0.97 at Pu'u, 0.99 at Site No. 4, and 0.97 at Site No. 5. At Site No. 6, frequently within the cloud, $\alpha = 0.88$. The average for the five wet forest sites beneath the cloud was 0.966. This indicates that ET should be increased by a factor of 1.30 if α is to equal 1.26, which is equivalent to using a pan coefficient of 1.12 (1.30 x 0.86) that is very close to the 1.1 value suggested by Ekern (1983).

Differences in transpiration have been observed among various forest species in Hawai'i. For instance, Yamamoto (1961) reported that the drying rates of soils under bamboo were double those of adjacent eucalyptus-covered soils. Small-scale variations such as these are acknowledged to exist, but cannot be dealt with practically in a study of this scale.

The cover coefficient (K) is defined as the ratio of PE for a particular cover to sugarcane PE, taking into account cover density and vegetation type. K is the product of C times V. Table 25 summarizes cover coefficients.

TABLE 25. COVER COEFFICIENTS FOR VARIOUS LAND USES

	SUGAR-CANE	PINE-APPLE	URBAN	PARKS	FOREST		
					Dry	Mod.	Wet
Coverage	0.85	0.71	1.25	1.00	0.50	1.00	1.00
Density coef., D	0.90	0.81	1.25	1.00	0.68	1.00	1.00
Vegetation coef., V	1.00	0.25	1.00	1.00	1.00	1.00	1.30
Cover coef., K	0.90	0.20	1.25	1.00	0.68	1.00	1.30

To obtain the PE for any land use, multiply the given value of K times the value shown in Figures 25 through 36.

Actual Evapotranspiration

Monthly PE was determined for each wb-zone as described in the preceding section. To obtain the actual evapotranspiration (AE), a model was developed which relates relative soil moisture availability to the relative ET rate (AE/PE ratio). This section addresses the AE/PE question beginning with the estimation of relevant soil properties. Following that the details of the water balance computation are described.

SOIL MOISTURE STORAGE. The amount of moisture available for evaporation or transpiration at any time is that which is held in storage within the root zone of the soil. Water which percolates beyond the depth of the roots is no longer available to be transpired. The amount of water which remains in a wetted soil after initial drainage is called the field capacity (FC) and is a property of individual soils that depends primarily on texture. The field capacity is usually defined as the soil moisture quantity, expressed as a proportion of soil volume or depth held at a soil moisture tension of 1.0×10^4 Pa (0.1 bar). As soil dries, the remaining water is held at increasingly higher tensions. The point at which transpiration ceases is often assumed to be 1.5×10^6-Pa (15-bar) tension and is termed the wilting point (WP). A soil moisture retention curve constructed by laboratory testing of a particular soil can be used to determine the relative soil moisture quantities corresponding to field capacity and wilting point. The difference between these values is called the available water capacity (AWC). Ekern (1966*b*) presented the moisture release curve of a typical agricultural soil on O'ahu, Wahiawa silty clay (Tropeptic Eutrustox). The volumetric fraction is 0.37 at 1.0×10^4 Pa and 0.26 when the tension reaches 1.5×10^6 Pa. The AWC by conventional definition equals 0.11 (0.37-0.26).

Although 1.5×10^6-Pa tension may indeed be the point at which most plants cease biological function, evidence shows that transpiration continues, although at a low rate, to much higher levels of tension. Black (1979, p. 169) used the term "zero extraction point" (ZEP) to describe the soil water storage when ET has practically ceased. ZEP is a more meaningful representation of the lower limit of water availability and was used in place of the wilting point. By this definition we have

$$\text{AWC} = \text{FC} - \text{ZEP} \ . \qquad (41)$$

For the purpose of the water balance, field capacity was assigned to 1.0×10^4-Pa tension. Based on local evidence which will be presented later, AE was assumed to proceed to a ZEP equal to a volumetric water content of 0.06 less than the 1.5×10^6-Pa level. Although this assumption significantly increases the estimated AWC, the effect on the total AE is small because of the slow ET rates at high tensions.

Moisture retention characteristics have been measured for most soils in the study area (U.S. Department of Agriculture 1972) for tensions of 33 000 (0.33 bar) and 1.5×10^6 Pa. These values were used to estimate AWC, as defined in this study, for each wb-zone.

ROOT DEPTH. To calculate the water balance, soil moisture must be defined in units of water depth. Conversion from relative units (depth of water per depth of soil) requires knowledge of the depth from which soil water is available. For a vegetated surface this corresponds to the rooting depth and varies according to plant species, soil, and climate.

The depth from which sugarcane roots effectively extract water under Hawaiian conditions has been studied by a number of investigators. Waterhouse and Clements (1954) found that sugarcane roots in well-watered soils on Maui extended to 0.76 m (30 in.) and, in some cases, to 1.52 m (5 ft). Baver et al. (1962) reported that cane plants absorbed water from a depth of nearly 1.52 m at an age of only 4 wk. Using a "window-box" technique they also observed roots at a depth of 1.02 m (40 in.) within 7 wk and primary roots reaching 2.44 m (8 ft) when the cane was 8 wk old. Extensive proliferation of roots was observed to a depth of 3.048 m (10 ft) after 4-mo growth (Hawaiian Sugar Planters' Association 1961). While roots may reach these depths, the zone of effective water extraction is confined to the depth to which a dense network of fine roots develops. Lee (1927) studied the distribution of cane roots in Hawaiian soils and concluded that regardless of cane variety, soil type, or fertilization treatment, approximately 70% of roots (by weight) are found in the upper 0.20 m (8 in.) of soil. Though some roots were observed as deep as 1.02 m (40 in.) from the surface, 85% or more of the root mass occurred in the upper 0.61 m (24 in.). Mongelard's (1962) report of rooting depths of cane in Mauritius, where 70% of roots were found in the top 0.31 m (12 in.), supports Lee's earlier findings.

In many cases, the structure of the soil profile may be more significant in determining rooting depth than the physiological habits of the sugarcane plant. Rooting depth is, of course, limited to the depth of soil, which is of particular importance in coastal lowland areas where shallow soils overlie coral limestone. In addition, high bulk density of the subsoil or the existence of a hard pan in many Hawaiian soils inhibits root penetration (Hawaiian Sugar Planters' Association 1960, p. 63). Of importance in this context is the effect of heavy cultivation and harvesting equipment on the soil density. Trouse and Humbert (1961) reported that the use of heavy hauling equipment increased soil bulk densities to depths of 0.41 to 0.46 m (16-18 in.). To increase moisture storage, i.e., root depth, and to alleviate the compaction by mechanized harvesters, plantations have to conduct deep tillage operations before replanting. Studies by Trouse and Humbert (1959) indicate that subsoiling and tillage commonly produce a 0.41- to 0.46-m (16- to 18-in.) depth of loose soil underlain by very dense subsoil. Ekern* pointed out that the construction of furrows in some cases leaves only 0.15 to 0.30 m (6-12 in.) of tilled soil beneath the cane stool.

Numerous soil profiles have been taken of agricultural soils in Hawai'i (Foote et al. 1972; U.S. Department of Agriculture 1976). Observations of root densities at various depths in sugarcane fields confirm the existence of a relatively inpenetrable pan-like surface in some areas at depths of 0.30 m (12 in.) (Paaloa [Humoxic Tropohumults] silty clay) to 0.61 m (24 in.) (Kolekole [Hustoxic Humitropepts] silty clay). In general, observations in

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*P.C. Ekern 1983: personal communication.

sugarcane fields of the central plateau region indicate abundant roots to a depth of 0.30 to 0.58 m (12-23 in.) with few roots penetrating deeper. However, in soils of the Waipahu area (including Waipahu [Vertic Ustropepts] silty clay and Honouliuli [Typic Chromusterts] clay) plentiful roots were reported at depths to 1.22 m (48 in.). The depth of 'Ewa (Torroxic Haplustolls) silty clay loam overlying coral limestone was found to be 0.25 m (10 in.) with pockets to 1.02 m (40 in.).

For the water balance, soils under sugarcane cultivation were assumed to have roots penetrating to 0.41 m (16 in.) in the central plateau where soils are dominantly of the Helemano-Wahiawa association. In the region immediately surrounding Waipahu and Honouliuli, root depth was assumed not to be limited by massive subsoil or tillage pan and thus was given a greater value. The observations of Lee (1927) suggest a depth of 0.61 m (24 in.) for roots uninhibited by soil density. A rooting depth of 0.51 m (20 in.), chosen by Robinson (1963) for monitoring soil moisture near Waipahu, seems reasonable and was used for this study. On the 'Ewa Plain, an average soil depth of 0.51 m (20 in.), fully penetrated by roots, was assumed. On O'ahu, pineapple is grown on the higher portions of the central plateau region on the same Oxisol order soils (Wahiawa and Lahaina [Tropeptic Haplustox], and Molokai [Typic Torrox] series silty clays and silty clay loams) as the sugarcane of that area. Soil profiles taken in this region indicate that pineapple roots commonly extend 0.38 to 0.43 m (15-17 in.) (USDA 1976). Ekern (1964, p. 123), however, showed that almost no moisture withdrawal occurs beneath the upper 0.305 m (12 in.). Therefore, an effective root zone of 0.305 m was assumed for all pineapple growing areas.

Areas of natural vegetation include a wide range of environments from the continuously wet upper Ko'olaus to the near desert conditions of the leeward coast. In all areas, a variety of vegetative structure is found. Rooting depths vary considerably even within a small area, due to species diversity alone. For the purpose of estimating soil moisture capacity, some generalizations were necessary.

By assuming that large plants have deep roots, the density of tree cover may be used as a rough guide of relative root depth. A survey was conducted by the U.S. Forest Service (Klingensmith and Honda 1964) to assess the commercial timber potential of portions of the state, including O'ahu. The map, which includes the distribution of various crown density ranges, was used as a general guide to the occurrence of deep-rooted plant forms.

Plant adaptation to drought often includes the development of extensive root systems (Watts 1971, p. 156). Therefore, drier areas with relatively sparse cover, may have high soil moisture capacity because of deep roots. Two species common to the dry forests, kiawe (*Prosopis chilensis*) and koa haole (*Leucaena glauca*), have been shown to behave a phreatophytes, plants whose roots extend to the groundwater, in low-lying areas of the Wai'anae coast (Zones 1963). Although not phreatophytic within the study area, these species are capable of root penetration up to 6.1 m (20 ft).

Based on these considerations and on the forest canopy survey, the dry to moderately wet forested regions were estimated to have a rooting depth of 0.61 m (24 in.). In drier regions supporting only scrub vegetation, a 0.305 m (12 in.) root zone was assumed.

Very steeply sloping surfaces near the crests of both mountain ranges and along some smaller ridges cannot support deep soils. Scott (1975) observed rooting depths in the leeward Ko'olaus of 0.15 m (5.9 in.) for grass, 0.23 m (8.9 in.) for fern, and 0.50 m (19.7 in.) for *Acacia koa*. Foote et al. (1972, p. 119) reported that soils on steeply sloping mountain lands are limited to a 0.03- to 0.25-m (1- to 10-in.) depth. In the persistently wet Ko'olaus, rooting depth need not be estimated since the soil may be assumed to remain at field capacity at all times. Elsewhere, steep slopes were assumed to have rooting depths limited to an average of 0.15 m (6 in.).

The combination of lawn grass, shrubs, and trees of the urban areas, parks, and golf courses was assigned an average rooting depth of 0.305 m (12 in.). The soil moisture budget of urban wb-zones is computed only for the pervious portion.

Table 26 summarizes root-zone estimates for this study.

TABLE 26. ESTIMATES OF ROOT DEPTHS

Land Use	Root Depth (m)	(in.)	Land Use	Root Depth (m)	(in.)
Sugarcane			Urban, park, golf course	0.31	12
Wahiawa region	0.41	16			
Waipahu region	0.51	20	Natural vegetation		
'Ewa Plain	0.51	20	Steep slopes	0.15	6
			Dry forest	0.61	24
Pineapple	0.31	12	Dry scrub	0.31	12

AE/PE AS A SOIL-MOISTURE FUNCTION. A variety of functional relationships have been proposed to model the reduction of actual evapotranspiration (AE) below potential evapotranspiration (PE) as a result of increasing soil moisture stress. As previously discussed, the differences in experimental results are attributable to differences in various conditions, especially evaporative demand, vegetation type and density, root depth and density, and soil texture.

A general analytical model for describing empirical AE/PE relationships was proposed by Dyer and Baier (1979). The various observed curve shapes (concave-upward, convex-upward, and linear) and different critical points may be specified using the equations,

$$Y = ZX \tag{42}$$

and

$$Z = [(X/R)^{hmn} (X/R)^{m} (n/X)] + \{[(R - X)/R]^{n} (m/R)\} \tag{43}$$

where

Y = AE/PE

X = AW/AWC

AW = available soil moisture (soil moisture content - zero extraction point) × rooting depth

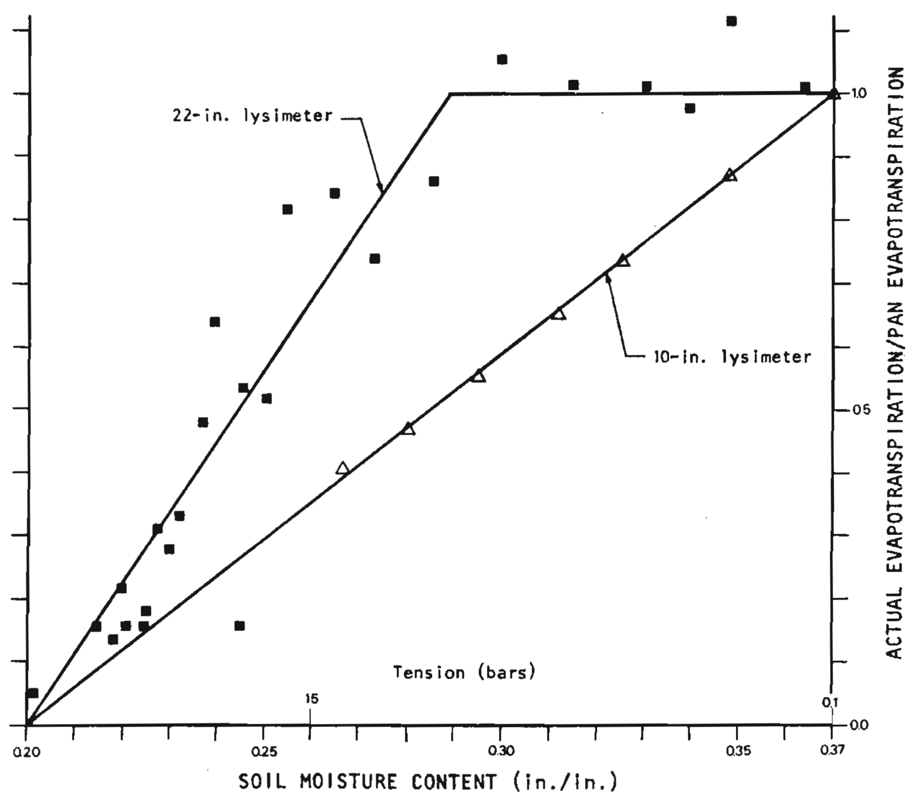
AWC = available water capacity (field capacity - zero extraction point) × rooting depth

R = critical point; AW below which AE declines

h,m,n = control parameters.

The control parameters are assigned certain values to produce the desired curve. Use of these equations requires a knowledge of the critical point.

The appropriate critical point and curve shape are best determined by using site-specific empirical evidence. However, because percolate lysimeters were often used, most lysimeter research in Hawai'i was conducted with soil moisture stress kept at a minimum. In one study using a weighing lysimeter (Ekern 1965*a*), the soil was allowed to dry to high tensions. The water use of bermudagrass sod, grown in two lysimeters 0.25 and 0.56 m (10 and 22 in.) deep, was measured against pan evaporation during periods of increasing soil soil moisture stress (Fig. 37). For the 0.25-m lysimeter, actual evapotranspiration (AE) declines as a one to one linear relationship with the relative soil water content between 0.37 in./in. (field capacity) and 0.20 in./in. Note that the lines converge to a zero extraction point (ZEP) equivalent to the wilting point minus 0.06 in./in. The critical point is therefore 1.0 AWC (available water capacity). AE from the 0.56-m lysimeter remained at the potential rate to a soil moisture content



NOTE: Based on Ekern (1966*a*) data.

Figure 37. Evapotranspiration of bermudagrass sod under varying soil moisture depletion

tent of about 0.288 in./in. or 0.52 AWC (AWC = 0.37 - 0.20 = 0.17 in./in.). The atmospheric demand as indicated by 0.86 pan averaged 7.57 in./mo during the 0.56-m (22-in.) lysimeter test (July-August 1960), and 0.14 m (5.43 in.)/mo during the 0.25 m (10 in.) lysimeter test (September 1960).

Lysimeter studies of sugarcane ET under soil moisture stress has not been conducted in Hawai'i. In a study of cane yield (Robinson, Campbell, and Chang 1963), however, gypsum block readings of soil moisture at a 0.305-m (12-in.) depth were monitored for different rates of irrigation. When irrigation equaled PE, soil moisture averaged 10^5 Pa (1 bar) or about 0.55 AWC. Rooting depth was assumed to be 0.5 m (20 in.) and PE during the observation period (April-October 1961) averaged 0.21 m (8.19 in.)/mo.

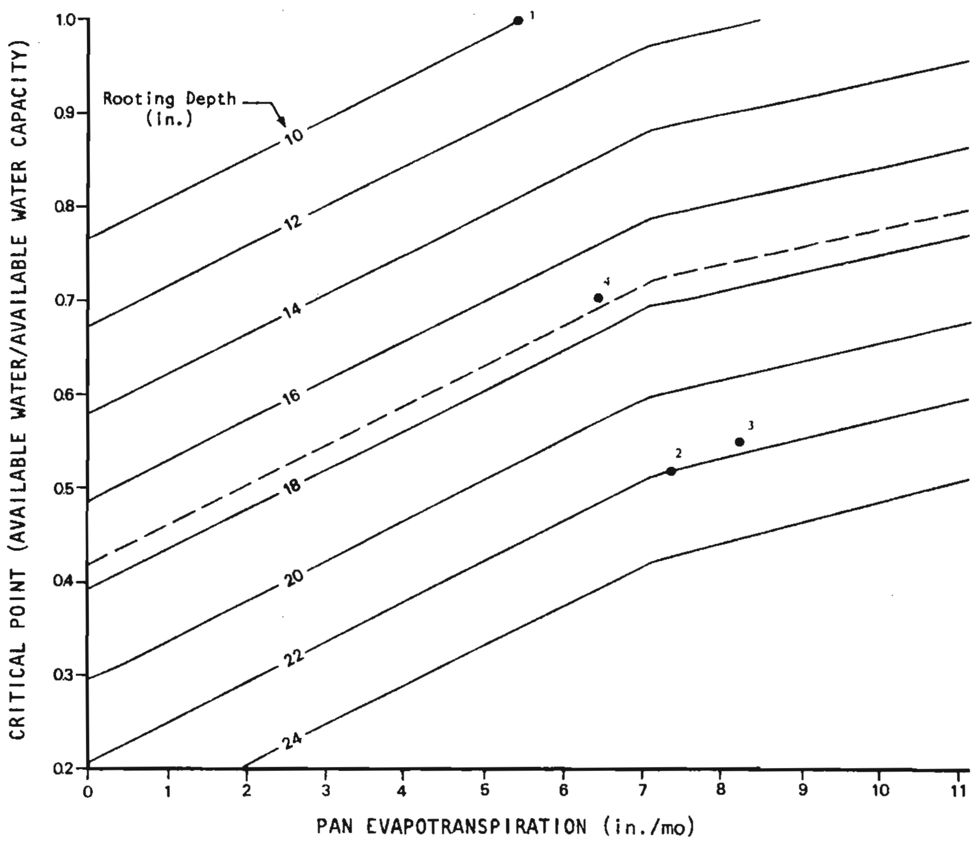
Numerous other investigations have been made of the relationship of water availability to sugarcane growth and yield (Waterhouse and Clements 1954); Robinson 1963; Chang et al. 1967; Mongelard 1973; Gibson 1978; Clements 1980; Jones 1980). Water stress affects growth and ET in similar fashion; thus, yield and ET are correlated. Sugarcane dry-matter production in Hawai'i is linearly related to the amount water transpired by the crop (Chang et al. 1967), confirming similar findings for various other crops and locations (Arkley 1963; Hanks, Gardner, and Florian 1969; Tanner 1981). Although research in Hawai'i (Jones 1980) has not establihsed a coincidence of the critical soil moisture levels of yield reduction and AE drop-off, in the absence of other data available water vs. yield provides general guidelines for the AE/PE problem.

Results obtained from tensiometer readings (Waterhouse and Clements 1954) indicated that sugarcane growth on Maui test plots was reduced when moisture stress exceeded 65 000 Pa (0.65 bar), equivalent to about 0.70 AWC. Average PE for the region is about 0.17 m (6.6 in.)/mo (DOWALD 1973). A rooting depth of 0.41 m (16 in.) was observed in the water-stressed soils.

Figure 38 was constructed using values recommended by Doorenbos and Pruitt (1975, Table 32) and the locally derived data cited above. The dashed line represents averages of values given by Doorenbos and Pruitt for cereals and grasses in medium and coarse soils. The data from the 0.25 and 0.56 m bermudagrass lysimeters were then plotted and the solid lines drawn in for various rooting depths by linear interpolation. The Doorenbos and Pruitt data determined the slope of the lines (relation to PE). Points obtained from the data of Robinson, Campbell, and Chang (1963) and Waterhouse and Clements (1954) are also plotted, and tend to support the proposed relationship relating the critical point to PE and rooting depth.

The assumption that the critical point declines linearly with increasing root depth is a generalization made necessary by lack of data. It is unlikely that the relationship continues linearly for rooting depths much greater than 0.56 m. Rather, the critical point-PE relationship probably remains relatively constant for rooting depths beyond a certain value. This assumption is supported by the work of Black (1979, p. 169) who found that critical points for two Douglas fir stands under similar PE conditions and having rooting depths of 0.64 and 0.81 m (25 and 32 in.) were approximately equal.

For the water balance calculation, the model of Dyer and Baier (1979) (eqq. [42], [43]) was employed with a linear shape and the critical point



NOTE: Dashed line derived from data of Doorenbos and Pruitt (1975). Points: 1 = bermudagrass 10-in. lysimeter (Ekern 1966*a*); 2 = bermudagrass 22-in. lysimeter (Ekern 1966*a*); 3 = sugarcane 20 in. rooting depth (Robinson et al. 1963); 4 = sugarcane yield reduction point, 16 in. rooting depth (Waterhouse and Clements 1954).

Figure 38. Critical point as a function of potential evapotranspiration for various rooting depths

selected according to PE and rooting depth (Fig. 38). Surfaces with much higher or lower leaf area indices than sugarcane were given lower and higher critical points, respectively, relative to the Figure 38 curves.

COMPUTATIONAL MODEL. The calculation of monthly AE requires that monthly precipitation, irrigation, runoff, and PE be known as well as the moisture retention properties of the soil. The key element of the model is the soil moisture content. Each month moisture inputs and outputs are entered into the soil moisture accounting. The level of soil moisture determines the AE rate. Recharge is produced when soil moisture exceeds field capacity. No percolation beyond the root zone is assumed to occur until the soil moisture reaches field capacity. A description of the water balance model used to calculate AE is given on pp. 11-21. A more detailed description of the actual computational procedure follows.

Soil moisture accounting on a monthly interval tends to overestimate AE and to underestimate recharge (Mather 1978, p. 16). Hence, although all elements have been determined on a monthly basis, a daily water balance had to be simulated to carry out the computations. To do so, the soil moisture balance was computed in approximate daily increments of 1/30 of a month. PE was considered constant at 1/30 of monthly PE per "day". Monthly runoff was substracted from monthly precipitation. The remainder, net precipitation, was distributed throughout the month so the number and length of rainy periods reflected the average rainfall frequency distribution. From the daily rainfall records of station 8172 (Table 14, Fig. 13), it was determined that significant rainfall (greater than 0.1 in./day) occurs in southern O'ahu on approximately 10 days/mo in 2- and 3-day storms. Net precipitation was therefore modeled to take place in two 2-day events and two 3-day events each month. One tenth of monthly net precipitation was added to the soil moisture on each rainy day. Urban irrigation (lawn sprinkling) was added in uniform amounts in each rainless day. Sugarcane irrigation required a more flexible approach.

The irrigation interval varies according to location, season, and crop age, averaging about 15 days.* The depth of water applied per round also varies but averages 0.09 to 0.11 m (3.5-4.5 in.) and probably seldom exceeds about 0.13 to 0.15 m (5-6 in.). On this basis, irrigation scheduling in the water balance model varied from one to three applications per month according to the monthly total. If monthly irrigation was less than 0.15 m, it was added to soil moisture on one day; between 0.15 and 0.31 m (6 and 12 in.), half the monthly total was added at the end of each 15-day interval; greater than 0.31 m (12 in.) was applied in thirds on each of 3 days.

Computation of the water balance for any given month, requires the beginning soil moisture content, which is equivalent to the previous month's ending storage. Because the starting value for the first month (January 1946) is unknown, the value was estimated by an iterative computation of the first year water balance. By adjusting the January starting water content on each successive iteration, this balancing procedure was repeated until the ending December soil moisture storage was approximately equivalent to the starting January value.

For each of the urban and part urban wb-zones (land use types 3-8), special procedures were necessary to compute the water balance. Calculations were carried out only for the pervious portion where all AE and recharge is assumed to occur. The volumetric total of net precipitation was entered into the soil moisture of the nonpaved area. Lawn sprinkling was distributed only to the pervious portions of medium- and low-density urban areas, parks, and golf courses. Wb-zone actual evapotranspiration and recharge calculated as depths over the pervious area were reduced by the ratio of pervious area to total wb-zone area. Thus the volume is properly represented by the depth over the entire wb-zone.

Finally, soil moisture in all areas with greater than 3 000 mm (118 in.) of rainfall annually was assumed to remain at or near field capacity at all times. This assumption was tested for several zones with less than 3 000 mm annual rainfall and found to be valid. As a result AE equals PE and the water balance can be computed by simple arithmetic.

Figure 39 is a graphic illustration of a sample water balance calculation using a simulated daily interval.

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*J. Wakatsuki (Oahu Sugar Company) 1983: personal communication.

Results

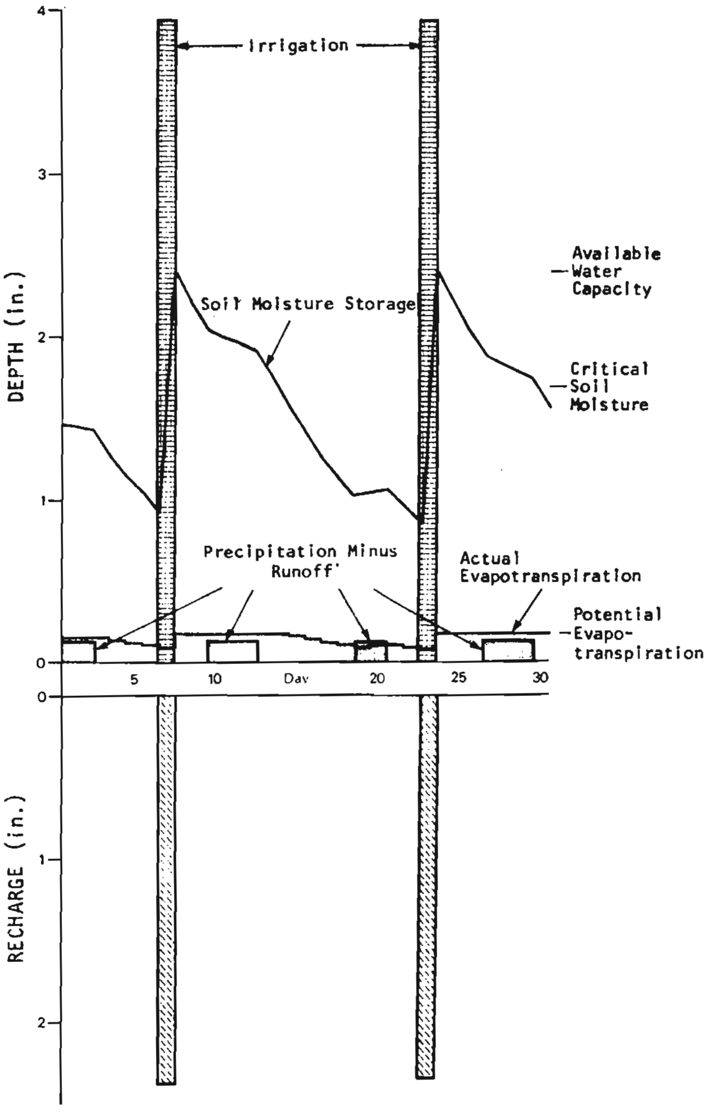


Figure 39. Sample water balance calculation for irrigated sugarcane area

The results of the computations include 258 matrices (one for each wb-zone) of monthly actual evapotranspiration, each containing 360 elements (12 mo by 30 yr). These data are stored on magnetic tape (App. B). Appendix Tables A.17 to A.20 summarize the ET in terms of monthly and annual averages for various portions of the study area. An annual total of 800.1 mm (31.5 in.) equivalent to 14.66 m^3/s (334.7 mgd) evapotranspires from the study areas as a whole. An average ET of 833.88 mm (32.83 in.) per year or 10.74 m^3/s (245.1 mgd) occurs on the non-caprock portion. Year-to-year variation is illustrated in Appendix Tables A.21 to A.24 which give annual totals for each year of the study period. The small interannual variation reflects only water availability changes, since PE was assumed constant

Several estimates have been made of "natural" evapotranspiration for the Pearl Harbor region. Most of these apply only to rain water evaporated and ignore the contributions of irrigation. Wentworth (1951) estimated an average of 4.38 m^3/s (100 mgd) ET for the non-caprock portion. Takasaki (1978, Table 1) put the value at 4.6 m^3/s (105 mgd)—presumably for the non-caprock portion—while Mink's (1980) estimate was 6.75 m^3/s (154 mgd). Mink also estimated ET in sugarcane areas (from both precipitation and irrigation) to be 2.28 m^3/s (52 mgd). In order to make a comparison with these values, average sugarcane ET was compared with ET from adjacent non-irrigated areas. The results of the present study indicate that, on the average, sugarcane irrigation adds 725.42 mm (28.56 in.) ET annually to the 626.87 mm (24.68 in.) average non-irrigated, non-pineapple ET on the central plateau region. Using average acreages over the 30-yr period, sugarcane irrigation contributes 1.11 m^3/s (25.24 mgd) to Pearl Harbor non-caprock ET. Total non-caprock ET in the Pearl Harbor region averages 8.40 m^3/s (191.72 mgd). ET due to precipitation is estimated to have an average annual value of 7.29 m^3/s (166.48 mgd).

The effects of pineapple cover on ET were significant in reducing total ET of the central plateau region. Comparing pineapple ET with adjacent areas of natural cover, it was found that ET was reduced by an annual average of 403.61 mm (15.89 in.). This is equivalent to an average of 0.59 m^3/s (13.51 mgd) during the 30 yr study period.

Wentworth (1951, Table 24) estimated evaporation and transpiration to be 2.95 m^3/s (67.37 mgd) for 66.304 x 10^6 m^2 (25.60 $miles^2$) of Honolulu mountain intake area. In the present study, 1.89 m^3/s (43.06 mgd) was found to be the average evapotranspiration for the 64.983 x 10^6 m^2 (25.09 $miles^2$) basaltic portion of the Honolulu region. Making a proportional adjustment for area, the Wentworth estimate becomes 2.68 m^3/s (61.13 mgd). Table 27 summarizes evapotranspiration estimates for comparison with the results of this study.

TABLE 27. COMPARISON OF EVAPOTRANSPIRATION ESTIMATES

INVESTIGATION	PEARL HARBOR NON-CAPROCK Evapotranspiration From Rainfall	Sugarcane Area	From Irrig.	Total	HONOLULU Basalt
	(mgd)				(mgd)
Wentworth (1951)	100	--	--	---	61*
Takasaki (1978)	105	--	--	---	--
Mink (1980)	154	52	30†	184†	--
This study	166	47	25	192	43

NOTE: mgd × 0.043 81 = m^3/s.
*Adjusted by proportion of areas represented.
†Mink's estimate of sugarcane evapotranspiration (52 mgd) minus nonirrigated evapotranspiration from natural cover (22 mgd) estimated by this study.

RECHARGE

The partitioning of available water at the surface and within the soil was modeled in this study using the water balance approach. The water balance was computed separately for each spatial unit on a monthly basis. First, moisture inputs, precipitation, fog drip, and irrigation were determined. Next, surface and subsurface runoff were estimated and subtracted from the inputs to the soil. Lastly, the soil moisture budget was computed with remaining water partitioned into evapotranspiration and recharge.

Results

Recharge was simultaneously determined with evapotranspiration by the computer model described in the previous section. Monthly recharge depths for each wb-zone are stored on magnetic tape in the form of 258 12-by-30 matrices in file ZONE.RCHG.DATA (App. B). Summaries of the results are shown in Appendix Tables A.25 to A.28. Thirty-year monthly and annual averages are given for various portions of the study area. The results are given in terms of depth, volume, and percentage of total water input (precipitation, fog drip, irrigation). For the basin as a whole, an annual average of 994.92 mm (39.17 in.) of deep percolation occurs, equivalent to 18.23 m^3/s (416.12 mgd). Over the non-caprock portion, where recharge of the basal aquifer takes place, 1 129.79 mm (44.48 in.) percolates annually over 400.518 x 10^6 m^2 (154.64 $miles^2$), a volume of 14.55 m^3/s (332.01 mgd). For the Honolulu region, 2.82 m^3/s (64.33 mgd) of recharge penetrates the non-caprock area out of 3.18 m^3/s (72.62 mgd) for the entire basin. The critical Pearl Harbor region basal groundwater recharge is 11.73 m^3/s (267.68 mgd). Including the caprock portion, an average of 15.05 m^3/s (343.50 mgd) was found.

Recharge in the irrigated sugarcane areas is also shown. The amounts shown include precipitation-induced recharge and irrigation return flow. To separate these values, the average recharge for unirrigated regions adjacent to the sugarcane areas was computed and compared with the irrigated portion. Over the non-caprock portion of the Pearl Harbor region, irrigated sugarcane areas have an average annual recharge of 2 217.67 mm (87.31 in.) or 3.38 m^3/s (77.18 mgd). Non-irrigated areas within the sugar-growing regions average annually only 274.07 mm (10.79 in.). Irrigation return flow (recharge due to irrigation) is therefore 1 943.61 mm (76.52 in.) annually or 2.96 m^3/s (67.63 mgd). This is equivalent to about 72.9% of applied water, implying an average irrigation efficiency of 27.1%. In-field efficiency is somewhat higher because irrigation amounts are based on well figures and do not account for transmission losses.

Pineapple cover contributes significantly to the Pearl Harbor Basin recharge by suppressing ET. Average annual pineapple area recharge is 839.22 mm (33.04 in.), Adjacent areas of natural cover average about 435.61 mm (17.15 in.) annual recharge. Pineapple increased recharge by 403.61 mm (15.89 in.) per year, an average of 0.59 m^3/s (13.51 mgd) during the study period, over that of natural cover. Recharge for the non-caprock Pearl Harbor region would be 8.17 m^3/s (186.54 mgd) for a natural cover without irrigation. Irrigation (sugarcane) and ET-suppression (pineapple) add another 3.55 m^3/s (81.14 mgd). Table 28 summarizes these figures.

Temporal variability is illustrated by the annual recharge totals for each year (1946-1975) in Appendix Tables A.29 to A.32. The year-to-year fluctuations are substantial. The study areas as a whole, for instance, had a range of annual recharge from 12.93 m^3/s (295.25 mgd) in 1959 to 24.56 m^3/s (560.56 mgd) in 1965. For the non-caprock Pearl Harbor region, the lowest recharge occurred in 1953, 8.22 m^3/s (187.64 mgd) and the highest in 1965, 15.86 m^3/s (362.11 mgd).

Previous estimates of recharge for non-caprock portions of the Honolulu and Pearl Harbor regions are shown in Table 29 for comparison with the new estimates. For the important non-caprock portion of the Pearl Harbor region, the present estimate of average recharge, 11.73 m^3/s (268 mgd), is not significantly different from previous estimates. There is a particularly close correspondence with Mink's (1980) recent estimate of 11.83 m^3/s (270 mgd). However, the irrigation return flow estimate is nearly 50% greater than the previous highest estimate. This difference is primarily attributable to the more precise calculation of ET under varying soil mois-

TABLE 28. AVERAGE NATURAL, IRRIGATION-INDUCED, AND EVAPOTRANSPIRATION-SUPPRESSION-INDUCED RECHARGE OF NON-CAPROCK PORTION OF PEARL HARBOR REGION, 1946-1975

Source	Recharge (m^3/s)	(mgd)	(m^3/s)	(mgd)
Natural Recharge			8.17	186.54
Sugarcane Areas				
Total recharge	3.38	77.18		
Natural recharge	0.42	9.55		
Irrigation-induced recharge	2.96	67.63	2.96	67.63
Pineapple Areas				
Total recharge	1.23	28.08		
Natural recharge	0.64	14.57		
ET-suppression-induced recharge	0.59	13.51	0.59	13.51
Total Recharge of Non-Caprock Pearl Harbor Region			11.73	267.68

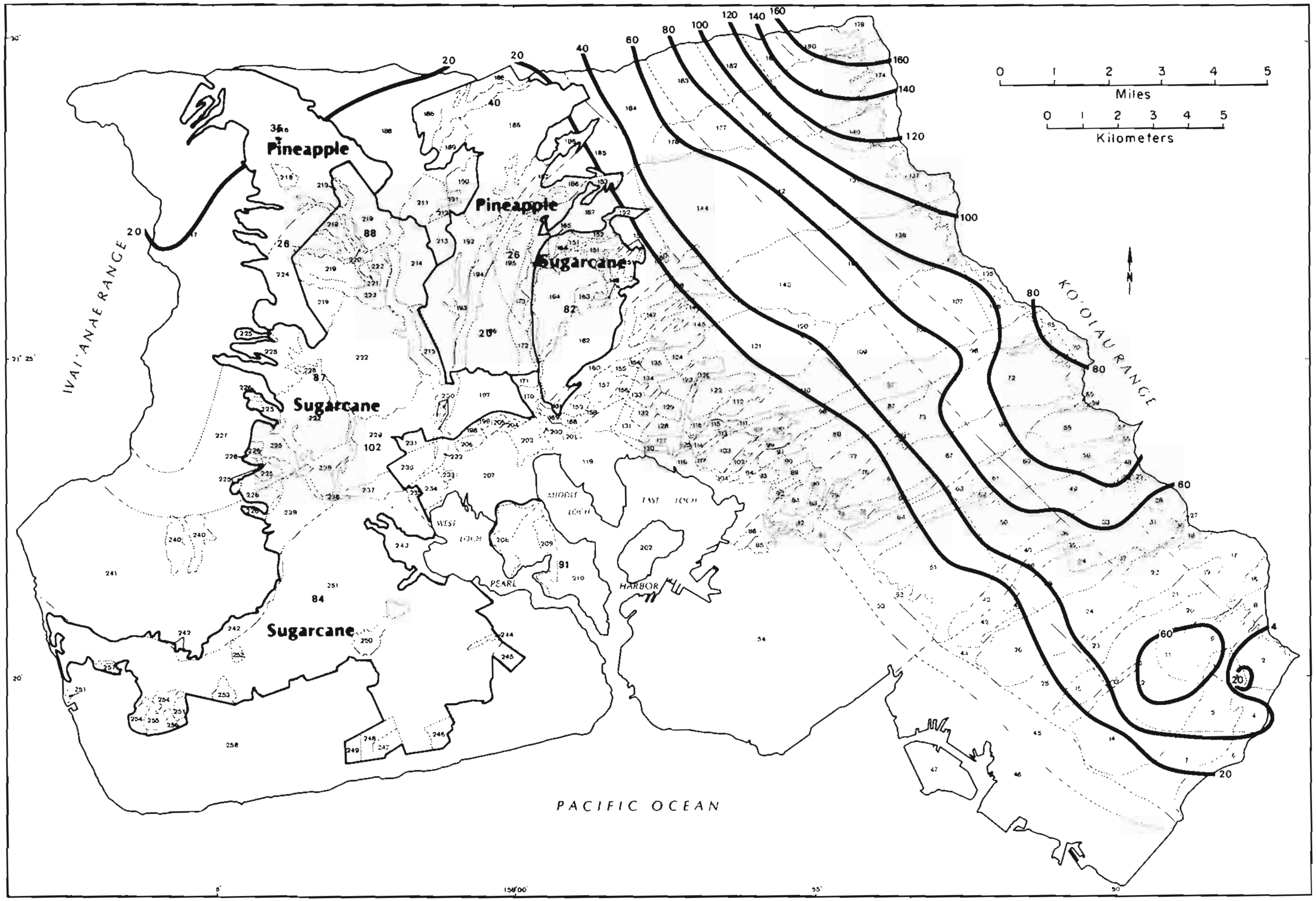
TABLE 29. COMPARISON OF VARIOUS RECHARGE ESTIMATES

INVESTIGATOR	PEARL HARBOR NON-CAPROCK: Precipitation-Induced Recharge	Irrigation Return	Non-Caprock Total	HONOLULU: Non-Caprock	Basalt
	(mgd)				
Wentworth (1951)	211	--	---	--	39*
Dale (1967) 1931-1932	210	40	250	--	--
1964-1965	220	30	250	--	--
Takasaki (1978)	250	12	262	--	--
Soroos/Ewart (1979)	---	--	250	--	--
Mink (1980)	225	45	270	60	--
This study	200†	67	263	64	55

NOTE: mgd × 0.043 81 = m^3/s.
*Adjusted by proportion of areas represented.
†Includes effects of pineapple ET-suppression.

ture conditions. Previous water balance studies typically assumed full pan evaporation and disregarded effects of soil moisture drawdown between irrigations. The inflated ET produced an underestimate of recharge.

The spatial distribution of annual average depth of recharge is shown in Figure 40. Because of the discontinuities created by irrigation and pineapple ET-suppression, sugarcane and pineapple portions are delimited and recharge is represented by point values. The borders should be recognized as having shifted during the study period. The sugarcane and pineapple areas depicted in Figure 40 represent a generalized average of the various configurations during the study period. The chief source areas of recharge are evident: the upper portions of the Ko'olau Range especially toward the northeast section of the study area, and the irrigated sugarcane areas.



NOTE: Point values shown for sugarcane and pineapple areas.
NOTE: Recharge measurements in in.

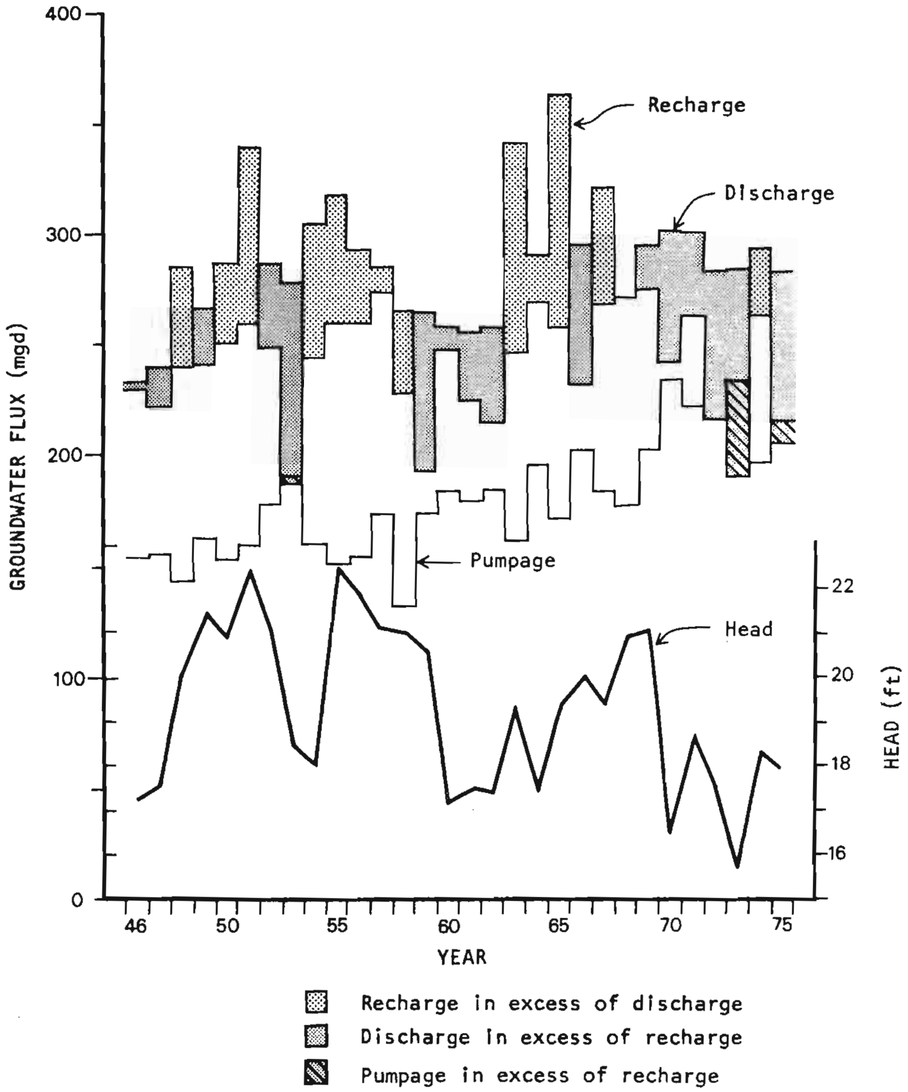
Figure 40. Distribution of annual groundwater recharge

SUMMARY AND CONCLUSIONS

Recharge vs. Discharge

Annual recharge of the Pearl Harbor groundwater body is plotted in Figure 41. Also shown are pumpage, total discharge (pumpage + spring flow), and head level (for well 2300-10 near Waipahu) as presented by Soroos and Ewart (1979).

The Soroos and Ewart discharge figures show that pumpage increased steadily following the advent of statehood in 1959. Total discharge, however, does not show a long-term trend because reduction of spring flow compensated for pumpage increases. Spring flow varies according to head (Visher and Mink 1964) and both were markedly reduced during the study period.



NOTE: mgd × 0.043 81 = m^3/s.
ft × 0.304 8 = m.

Figure 41. Annual groundwater recharge, discharge, and head, Pearl Harbor region

Over the 30-yr study period, the annual difference of recharge minus discharge ranged from +4.56 m^3/s (+104 mgd) in 1965 to -4.25 m^3/s (-97 mgd) in 1953. Discharge exceeded recharge during 16 years. The years 1953, 1973, and 1975 were the driest of the study period in terms of recharge, and were the only years during which recharge was exceeded by pumpage.

Land-Use Effects

Sugarcane cultivation is responsible for more than half of the water usage within the study area. Much of this water (an average of 73%) becomes recharge. Economic factors have raised the question of possible discontinuation of much or all of the Hawaiian sugar industry. Such a land-use shift has important implications for the future of groundwater resources. Since any replacement land use is unlikely to produce an equivalent percentage of return flow, present levels of groundwater withdrawal would exceed sustainable yield. However, alternative land uses are equally unlikely to demand the same level of groundwater withdrawal.

Pineapple cultivation currently provides about 0.48 m^3/s (11 mgd) additional recharge through ET suppression (this figure differs from the 1946 to 1975 average because less area [14.13 $miles^2$] was under pineapple cultivation by 1975). As with the sugar industry, economic feasibility of long-term continuation of pineapple cultivation on O'ahu has been questioned. Conversion of pineapple to alternative land uses carries a penalty for the groundwater resource. Since pineapple is not a major groundwater user, the conversion cost to irrigated or residential land use is exacerbated by new groundwater demands.

Recharge and groundwater usage associated with sugarcane and pineapple cultivation are shown in Table 30. Volumes are based on areas under cultivation as of 1975. Similarly, for vacant and urban land, Table 31 lists recharge and groundwater use values. Per capita urban water use (120 gal/person/day) is based on a graph presented by Yamauchi (1981, Fig. 3) for single family dwellings in Honolulu. At a residential density of 25 persons /acre, urban water demands amount to approximately 1.92 $mgd/mile^2$.

TABLE 30. COMPARISON OF RECHARGE AND GROUNDWATER DEMAND ASSOCIATED WITH SUGARCANE AND PINEAPPLE CULTIVATION, 1975, PEARL HARBOR REGION, HAWAI'I

Land Use	Area ($mile^2$)	Recharge (in.)	Recharge (mgd)	Groundwater Demand (mgd)
Sugarcane				
Non-Caprock	16.86	87	71	49
Caprock	17.31	85	71	84
Total	34.17	172	142	133
Pineapple	14.31	33	23	0

TABLE 31. GROUNDWATER RECHARGE AND DEMAND ASSOCIATED WITH VACANT AND MEDIUM DENSITY RESIDENTIAL LAND, SOUTHERN O'AHU, HAWAI'I

Land Use	Recharge (in.)	Groundwater Demand (gal/p*/day)	(mgd/mile^2)
Vacant			
Present Pine Areas	17	0	0
Present Non-Caprock Cane Areas	11	0	0
Present Caprock Cane Areas	7	0	0
Medium Density Residential			
Present Pine Areas	14	120	1.92
Present Non-Caprock Cane Areas	8	120	1.92
Present Caprock Cane Areas	6	120	1.92

*p = person.

To evaluate the implications of possible replacement of sugarcane and pineapple land, four scenarios, representing the extremes of abandonment or urban development of these areas, were examined.

Scenario 1. Conversion of all 1975 sugarcane land to vacant land. Net effect on groundwater supply, +311 m^3/s (+71 mgd). Reduction of demand for groundwater withdrawal is much greater than loss of recharge from irrigation return flow.

Scenario 2. Conversion of all 1975 sugarcane and pineapple land to vacant land. Net effect on groundwater supply, +2.63 m^3/s (+60 mgd). Reduced recharge resulting from elimination of irrigation return flow and ET-suppression is greatly exceeded by reduction of water demand.

Scenario 3. Conversion of all 1975 sugarcane land to medium density residential land. Net effect on groundwater supply, +0.13 m^3/s (+3 mgd). Based on 25 persons/acre, a maximum of 544,000 persons could be accommodated by future medium density urban development of the area under sugarcane cultivation in southern O'ahu as of 1975. Losses to groundwater supply from increased runoff, elimination of sugarcane irrigation return, in addition to new demands for municipal water implied by this scenario, are nearly equivalent to the 1975 groundwater usage for sugarcane irrigation.

Scenario 4. Conversion of sugarcane and pineapple land to medium density residential land. Net effect on groundwater supply, -1.88 m^3/s (-43 mgd). In this scenario, residential development of more than 129.5 x 10^6 m^2 (50 miles^2), implying a population increase of 816,000, creates new demands for municipal water which exceed net savings from elimination of sugarcane irrigation.

Table 32 summarizes the groundwater recharge and withdrawal volumes implied by each of the above scenarios.

TABLE 32. GROUNDWATER RECHARGE AND GROUNDWATER DEMAND IMPLICATIONS OF FOUR SCENARIOS OF CONVERSION OF SUGARCANE AND PINEAPPLE LAND TO ALTERNATIVE LAND USES

	GROUNDWATER SUPPLY CHANGES			
	Demand		Recharge	Net
	Agric.	Urban		
	(mgd)			
Scenario 1 (Sugarcane to Vacant)				
Non-Caprock	+49	0	-62	-13
Caprock	+84	0	0	+84
Total	+133	0	-62	+71
Scenario 2 (Sugarcane and Pineapple to Vacant)				
Non-Caprock	+49	0	-73	-24
Caprock	+84	0	0	+84
Total	+133	0	-73	+60
Scenario 3 (Sugarcane to Medium-Density Residential)				
Non-Caprock	+49	-33	-64	-48
Caprock	+84	-33	0	+51
Total	+133	-66	-64	+3
Scenario 4 (Sugarcane and Pineapple to Medium-Density Residential)				
Non-Caprock	+49	-66	-77	-94
Caprock	+84	-33	0	+51
Total	+133	-99	-83	-43

It is apparent that present groundwater development is sufficient to support large population increases on southern O'ahu. Given the discontinuation of sugarcane and pipeapple cultivation, the results of this study indicate that a population increase on southern O'ahu of about 450,000 represents the limit imposed by water supply. This is nearly double the population growth for all of O'ahu projected to the year 2000 by the Hawaii State Department of Planning and Economic Development (1978, p. 69).

Of importance in the near future are the effects of conversion to the more efficient drip irrigation technique which is being practiced within the study area. Average irrigation efficiency during the study period for non-caprock areas was 27%. Drip irrigation systems have an average efficiency of about 80 to 95% (Fukunaga 1978) and may reach 100% during the summer (Ekern 1977).

Total conversion to drip irrigation would reduce the recharge and the withdrawal of groundwater. With drip irrigation, ET remains at full PE because soil moisture is kept continuously at or near capacity. For the non-caprock portion, PE averages about 1 397.0 mm (55 in.) annually. At 80% irrigation efficiency, 2.67 m^3/s (61 mgd) would be required for the non-caprock sugarcane area. Of the 2.67 m^3/s, 20% or 0.53 m^3/s (12 mgd) would return to the aquifer. This is a reduction of about 2.45 m^3/s (56 mgd) of recharge. The total irrigation demand for drip is 1.31 m^3/s (30 mgd) less than the average 1946 to 1975 usage for irrigation of the non-caprock portion. Over the caprock, increased efficiency of irrigation reduces demand for withdrawal, but has no effect on recharge since return flow does not reach the basal water. PE in this area averages about 1 676.4 mm (66 in.) annually or 2.41 m^3/s (55 mgd). At 80% efficiency for drip irrigation, 3.2 m^3/s (73 mgd) would be required, a savings of 1.31 m^3/s (30 mgd) compared with average 1946 to 1975 irrigation usage. Thus, conversion of all southern O'ahu sugarcane land to drip irrigation would reduce irrigation return flow (recharge) by 2.41 m^3/s while reducing water demand and presumably groundwater withdrawal by 2.63 m^3/s (60 mgd). The net effect on groundwater supply of total conversion to drip irrigation is a 0.22-m^3/s (5-mgd) gain.

Table 33 summarizes the water balance. Shown are annual average depths and average rates of flux of each component of the water balance by region. Table 33 and the other summaries in this paper condense large amounts of information made available by this study. They are not intended to represent final products, but are selections from among innumerable possible spatial and temporal configurations. The inclusion of the entire raw output in this paper is precluded by space considerations. However, complete data sets of each water balance component are available as described in Appendix B.

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TABLE 33. TOTAL WATER BALANCE SUMMARY, HONOLULU AND PEARL HARBOR REGIONS, HAWAI'I

	Area	Input (I)		Irrigation			Precipitation			Runoff			Evapotransp.			Recharge		
	(mile²)	(in.)	(mgd)	(in.)	(mgd)	(%I)	(in.)	(mgd)	(%I)	(in.)	(mgd)	(%I)	(in.)	(mgd)	(%I)	(in.)	(mgd)	(%I)
HONOLULU																		
Non-Caprock	31.47	95	144	2	2	1	93	142	98	18	27	19	35	53	37	42	64	45
Basalt	(25.09)	(99)	(120)	(1)	(2)	(1)	(98)	(118)	(99)	(18)	(22)	(18)	(36)	(43)	(36)	(46)	(55)	(46)
Alluv./Colluv.	(6.38)	(80)	(25)	(4)	(2)	(6)	(76)	(23)	(94)	(17)	(5)	(22)	(34)	(10)	(42)	(29)	(9)	(37)
Caprock	23.40	30	34	3	3	9	27	31	91	7	8	23	16	18	52	7	8	24
Total	54.87	67	178	2	5	3	65	173	97	13	35	20	27	71	40	27	73	41
PEARL HARBOR																		
Non-Caprock	123.17	88	522	16	95	18	72	427	82	11	63	12	32	192	37	45	268	51
Basalt	(117.72)	(89)	507	(16)	(91)	(18)	(73)	(416)	(82)	(11)	(61)	(12)	(32)	(184)	(36)	(46)	(263)	(52)
Alluv./Colluv.	(5.45)	(55)	(14)	(12)	(3)	(21)	(43)	(11)	(78)	(6)	(1)	(10)	(29)	(8)	(54)	(20)	(5)	(36)
Caprock	42.06	77	156	52	105	67	25	51	33	4	8	5	35	72	46	37	76	49
Total	165.23	85	677	25	199	29	60	478	71	8	71	10	33	264	39	43	344	51
HONOLULU-PEARL HARBOR																		
Non-Caprock	154.64	89	666	13	97	15	76	569	85	12	90	13	33	245	37	44	332	50
Basalt	(142.81)	(91)	(627)	(14)	(93)	(15)	(77)	(534)	(85)	(12)	(83)	(13)	(33)	(227)	(36)	(46)	(318)	(51)
Alluv./Colluv.	(11.83)	(68)	(39)	(7)	(4)	(11)	(61)	(35)	(88)	(12)	(7)	(18)	(32)	(18)	(46)	(25)	(15)	(36)
Caprock	65.46	60	190	34	108	57	26	82	43	5	16	8	28	90	47	27	84	44
Total	220.10	81	856	20	205	24	61	651	76	10	106	12	32	335	39	39	416	49
SUGARCANE (PEARL HARBOR)																		
Non-caprock	18.31	143	126	103	91	72	40	35	28	3	2	2	53	47	37	87	77	61
Caprock	17.20	150	125	124	103	83	26	22	17	2	2	2	63	52	42	85	71	57
Total	35.51	146	251	113	194	77	33	57	23	3	4	2	58	99	40	86	148	59

NOTE: Figures rounded off.
NOTE: Input (I) = Precipitation + irrigation.

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APPENDIX CONTENTS

Tables

A. PRECIPITATION, RUNOFF, EVAPOTRANSPIRATION, AND RECHARGE SUMMARIES

APPENDIX TABLE A.1. AVERAGE PRECIPITATION, 1946-1975, HONOLULU REGION

Month	Whole Basin (in.)	Whole Basin (mgd)	Non-Caprock (in.)	Non-Caprock (mgd)	Basalt (in.)	Basalt (mgd)	Alluv.-Colluv. (in.)	Alluv.-Colluv. (mgd)	Caprock (in.)	Caprock (mgd)
January	7.81	248.30	9.44	172.13	9.75	141.76	8.22	30.37	5.62	76.17
February	5.62	178.56	7.75	141.27	8.06	117.20	6.51	24.07	2.75	37.29
March	7.36	233.90	10.21	186.10	10.75	156.31	8.06	29.80	3.53	47.80
April	5.56	176.82	8.38	152.67	8.80	127.90	6.70	24.77	1.78	24.14
May	4.48	142.32	6.81	124.05	7.18	104.34	5.33	19.71	1.35	18.27
June	3.11	98.90	4.88	88.89	5.10	74.10	4.00	14.79	0.74	10.02
July	4.46	141.90	7.27	132.43	7.71	112.05	5.52	20.39	0.70	9.46
August	3.99	126.79	6.48	118.03	6.87	99.80	4.93	18.24	0.65	8.76
September	3.09	98.31	4.82	87.87	5.11	74.22	3.69	13.65	0.77	10.44
October	4.84	153.86	7.08	129.10	7.45	108.27	5.64	20.83	1.83	24.76
November	7.47	237.35	10.13	184.59	10.57	153.62	8.38	30.97	3.89	52.76
December	7.38	234.70	10.09	183.89	10.43	151.63	8.73	32.27	3.75	50.80
Annual	65.18	172.65	93.32	141.76	97.79	118.44	75.73	23.32	27.35	30.89
Area (mile^2)		54.87		31.47		25.09		6.38		23.40

APPENDIX TABLE A.2. AVERAGE PRECIPITATION, 1946-1975, PEARL HARBOR REGION, HAWAII

Month	Whole Basin (in.)	Whole Basin (mgd)	Non-Caprock (in.)	Non-Caprock (mgd)	Basalt (in.)	Basalt (mgd)	Alluv.-Colluv. (in.)	Alluv.-Colluv. (mgd)	Caprock (in.)	Caprock (mgd)
January	8.08	773.08	8.87	632.83	8.95	610.19	7.17	22.64	5.76	140.25
February	5.34	511.18	6.25	445.77	6.33	431.96	4.37	13.80	2.68	65.41
March	6.56	628.06	7.78	554.85	7.91	539.65	4.81	15.20	3.01	73.21
April	5.15	492.74	6.34	452.01	6.48	441.69	3.27	10.32	1.67	40.73
May	3.87	369.94	4.87	347.58	4.99	340.27	2.31	7.31	0.92	22.36
June	2.69	257.83	3.46	246.81	3.56	242.52	1.36	4.29	0.45	11.02
July	3.82	365.71	4.93	352.05	5.07	345.66	2.02	6.39	0.56	13.67
August	3.69	352.99	4.74	338.24	4.87	331.96	1.99	6.28	0.61	14.76
September	2.88	275.72	3.57	254.35	3.65	248.72	1.78	5.63	0.88	21.37
October	4.43	424.25	5.35	381.50	5.45	371.44	3.19	10.06	1.75	42.75
November	6.86	656.52	7.96	568.03	8.09	551.31	5.29	16.71	3.63	88.50
December	6.62	633.89	7.73	551.37	7.84	534.83	5.24	16.54	3.39	82.52
Annual	59.99	478.48	71.84	427.10	73.18	415.83	42.82	11.26	25.31	51.38
Area (mile^2)		165.23		123.17		117.72		5.45		42.06

APPENDIX TABLE A.3. AVERAGE PRECIPITATION, 1946-1975, SUGARCANE AREA, SOUTHERN O'AHU

Month	Total Sugarcane Area		Non-Caprock		Caprock	
	(in.)	(mgd)	(in.)	(mgd)	(in.)	(mgd)
January	6.76	139.11	7.21	76.47	6.29	62.64
February	3.34	68.73	4.07	43.15	2.57	25.58
March	3.94	80.96	4.70	49.88	3.12	31.09
April	2.44	50.15	3.06	32.42	1.78	17.73
May	1.45	29.85	1.93	20.48	0.94	9.37
June	0.79	16.18	1.13	12.04	0.42	4.14
July	1.10	22.66	1.65	17.54	0.51	5.12
August	1.15	23.73	1.63	17.29	0.65	6.44
September	1.31	27.01	1.69	17.95	0.91	9.05
October	2.37	48.83	2.93	31.12	1.78	17.71
November	4.22	86.85	4.75	50.40	3.66	36.45
December	4.22	86.87	4.88	51.75	3.53	35.12
Annual	33.10	56.75	39.64	35.04	26.15	21.71
Area ($mile^2$)		35.51		18.31		17.20

APPENDIX TABLE A.4. AVERAGE PRECIPITATION, 1946-1975, PEARL HARBOR-HONOLULU BASIN

Month	Whole Basin		Non-Caprock		Basalt		Alluv.-Colluv.		Caprock	
	(in.)	(mgd)	(in.)	(mgd)	(in.)	(mgd)	(in.)	(mgd)	(in.)	(mgd)
January	8.01	1021.38	8.99	804.96	9.09	751.95	7.74	53.02	5.71	216.42
February	5.41	689.73	6.55	587.04	6.64	549.16	5.53	37.87	2.71	102.70
March	6.76	861.96	8.27	740.95	8.41	695.95	6.57	44.99	3.19	121.01
April	5.25	669.56	6.75	604.69	6.89	569.59	5.12	35.10	1.71	64.87
May	4.02	512.26	5.27	471.63	5.37	444.61	3.94	27.02	1.07	40.63
June	2.80	356.73	3.75	335.69	3.83	316.62	2.78	19.07	0.55	21.04
July	3.98	507.61	5.41	484.48	5.53	457.70	3.91	26.78	0.61	23.13
August	3.76	479.79	5.09	456.27	5.22	431.76	3.58	24.51	0.62	23.51
September	2.93	374.04	3.82	342.22	3.90	322.95	2.81	19.28	0.84	31.81
October	4.53	578.11	5.70	510.60	5.80	479.71	4.51	30.89	1.78	67.51
November	7.01	893.88	8.40	752.62	8.52	704.93	6.96	47.69	3.73	141.26
December	6.81	868.59	8.21	735.27	8.30	686.46	7.12	48.81	3.52	133.32
Annual	61.29	651.13	76.21	568.86	77.50	534.27	60.56	34.59	26.04	82.27
Area ($mile^2$)		220.10		154.64		142.81		11.83		65.46

APPENDIX TABLE A.5. ANNUAL PRECIPITATION, HONOLULU REGION

Year	Whole Basin (in.)	Whole Basin (mgd)	Non-Caprock (in.)	Non-Caprock (mgd)	Basalt (in.)	Basalt (mgd)	Alluv.-Colluv. (in.)	Alluv.-Colluv. (mgd)	Caprock (in.)	Caprock (mgd)
1946	57.27	149.61	80.41	120.47	83.35	99.57	68.82	20.91	26.15	29.14
1947	56.24	146.92	87.97	131.80	93.45	111.62	66.44	20.18	13.57	15.11
1948	72.50	189.40	105.71	158.38	110.61	132.12	86.45	26.26	27.85	31.02
1949	54.44	142.21	74.30	111.31	77.89	93.04	60.16	18.27	27.74	30.90
1950	74.69	195.11	104.63	156.76	110.13	131.55	83.01	25.22	34.42	38.34
1951	80.73	210.90	109.36	163.85	115.41	137.86	85.58	26.00	42.23	47.04
1952	54.93	143.50	85.17	127.61	89.80	107.26	66.97	20.34	14.26	15.89
1953	37.77	98.68	57.82	86.63	61.08	72.97	44.99	13.67	10.81	12.05
1954	72.44	189.25	103.94	155.73	108.33	129.40	86.68	26.33	30.09	33.52
1955	78.09	204.00	106.60	159.72	111.37	133.04	87.83	26.68	39.75	44.29
1956	66.64	174.08	97.19	145.62	102.70	122.68	75.53	22.94	25.55	28.46
1957	62.51	163.30	87.85	131.62	91.16	108.89	74.82	22.73	28.44	31.68
1958	69.59	181.80	95.90	143.68	100.08	119.55	79.43	24.13	34.21	38.12
1959	44.72	116.81	65.95	98.80	69.15	82.60	53.34	16.20	16.16	18.01
1960	58.07	151.69	88.30	132.30	92.73	110.77	70.87	21.53	17.41	19.39
1961	52.09	136.09	76.78	115.04	79.76	95.27	65.08	19.77	18.89	21.05
1962	43.48	113.58	64.66	96.88	68.23	81.50	50.65	15.38	14.98	16.69
1963	82.27	214.93	113.05	169.38	119.09	142.25	89.31	27.13	40.88	45.55
1964	69.32	181.08	104.33	156.32	110.09	131.50	81.70	24.82	22.23	24.76
1965	92.51	241.66	127.65	191.25	133.73	159.75	103.73	31.51	45.25	50.41
1966	58.37	152.49	81.93	122.75	85.40	102.02	68.25	20.73	26.70	29.74
1967	82.35	215.13	116.56	174.64	121.81	145.50	95.92	29.14	36.35	40.49
1968	77.54	202.57	107.28	160.73	112.27	134.11	87.62	26.61	37.56	41.84
1969	76.21	199.10	112.73	168.90	118.58	141.64	89.75	27.26	27.10	30.20
1970	64.67	168.94	97.44	146.00	102.34	122.24	78.20	23.75	20.59	22.94
1971	64.28	167.91	89.18	133.62	93.17	111.29	73.49	22.32	30.79	34.30
1972	56.32	147.13	76.17	114.12	79.66	95.16	62.42	18.96	29.63	33.01
1973	58.02	151.57	85.10	127.51	88.38	105.57	72.24	21.94	21.60	24.06
1974	77.63	202.78	111.90	167.66	116.91	139.65	92.22	28.01	31.53	35.12
1975	59.96	156.63	83.94	125.77	87.39	104.39	70.37	21.38	27.70	30.86

APPENDIX TABLE A.6. ANNUAL PRECIPITATION, PEARL HARBOR REGION

Year	Whole Basin (in.)	Whole Basin (mgd)	Non-Caprock (in.)	Non-Caprock (mgd)	Basalt (in.)	Basalt (mgd)	Alluv.-Colluv. (in.)	Alluv.-Colluv. (mgd.)	Caprock (in.)	Caprock (mgd)
1946	52.84	415.70	65.24	382.57	66.52	372.80	37.65	9.77	16.55	33.14
1947	49.90	392.52	62.82	368.39	64.35	360.65	29.81	7.73	12.05	24.13
1948	66.70	524.66	81.20	476.19	82.76	463.82	47.65	12.37	24.21	48.47
1949	56.98	448.25	66.71	391.19	67.78	379.90	43.49	11.28	28.50	57.06
1950	66.06	519.65	78.85	462.39	80.22	449.58	49.36	12.81	28.59	57.26
1951	79.85	628.15	92.41	541.89	93.77	525.55	62.96	16.34	43.08	86.26
1952	48.31	380.06	60.50	354.80	61.93	347.11	29.64	7.69	12.62	25.27
1953	35.49	279.14	44.05	258.29	45.05	252.49	22.35	5.80	10.41	20.85
1954	68.32	537.46	80.99	474.94	82.43	461.98	49.95	12.96	31.22	62.53
1955	71.21	560.17	83.47	489.49	84.72	474.81	56.57	14.68	35.30	70.69
1956	63.72	501.28	75.91	445.16	77.44	434.01	42.96	11.15	28.03	56.12
1957	58.77	462.32	69.54	407.81	70.58	395.59	47.10	12.22	27.22	54.51
1958	64.37	506.40	77.05	451.80	78.47	439.81	46.23	11.99	27.27	54.60
1959	40.23	316.44	48.66	285.33	49.67	278.40	26.72	6.93	15.54	31.11
1960	49.43	388.84	61.78	362.27	63.16	354.01	31.84	8.26	13.27	26.57
1961	47.40	372.88	58.60	343.64	59.95	336.00	29.45	7.64	14.60	29.24
1962	49.36	388.27	58.14	340.95	59.33	332.54	32.43	8.42	23.63	47.31
1963	79.72	627.12	92.89	544.70	94.67	530.60	54.36	14.10	41.16	82.42
1964	62.34	490.43	75.67	443.72	77.38	433.66	38.74	10.05	23.33	46.71
1965	85.51	672.67	100.58	589.80	102.25	573.06	64.49	16.73	41.38	82.87
1966	55.19	434.12	65.97	386.83	67.03	375.69	42.94	11.14	23.61	47.29
1967	73.16	575.49	88.52	519.07	90.00	504.41	56.49	14.66	28.17	56.42
1968	72.02	566.53	83.03	486.88	84.26	472.25	56.38	14.63	39.77	79.64
1969	63.68	500.97	76.69	449.72	78.30	438.85	41.91	10.87	25.59	51.25
1970	51.11	402.06	63.43	371.98	64.80	363.18	33.94	8.81	15.02	30.08
1971	63.52	499.70	74.65	437.72	75.84	425.06	48.81	12.66	30.95	61.97
1972	54.56	429.22	63.46	372.10	64.55	361.76	39.86	10.34	28.52	57.12
1973	42.35	333.12	52.37	307.08	53.59	300.37	25.88	6.71	13.01	26.04
1974	74.74	587.91	89.91	527.25	91.45	512.52	56.79	14.74	30.29	60.66
1975	53.40	420.10	62.64	367.30	63.79	357.49	37.83	9.82	26.36	52.79

APPENDIX TABLE A.7. ANNUAL PRECIPITATION, SUGARCANE AREA, SOUTHERN O'AHU

YEAR	TOTAL SUGARCANE AREA Depth (in.)	Vol. (mgd)	Area (mile^2)	NON-CAPROCK Depth (in.)	Vol. (mgd)	Area (mile^2)	CAPROCK Depth (in.)	Vol. (mgd)	Area (mile^2)
1946	26.46	48.69	38.65	33.57	34.55	21.62	17.44	14.14	17.03
1947	20.92	38.61	38.77	28.24	29.07	21.62	11.69	9.54	17.15
1948	34.75	66.08	39.94	41.12	44.61	22.79	26.29	21.47	17.15
1949	36.21	68.36	39.66	40.83	43.45	22.35	30.23	24.91	17.31
1950	37.29	70.41	39.66	43.26	46.04	22.35	29.58	24.38	17.31
1951	53.53	98.20	38.53	60.29	60.91	21.22	45.25	37.29	17.31
1952	18.47	30.09	34.22	23.54	18.95	16.91	13.52	11.14	17.31
1953	15.38	24.88	33.98	19.82	15.96	16.91	10.98	8.93	17.07
1954	38.67	62.56	33.98	45.35	36.51	16.91	32.05	26.05	17.07
1955	43.62	70.57	33.98	51.99	41.86	16.91	35.33	28.72	17.07
1956	33.94	55.08	34.08	40.28	32.62	17.01	27.63	22.45	17.07
1957	34.06	54.62	33.68	40.34	32.00	16.66	27.92	22.62	17.02
1958	34.45	54.99	33.53	41.98	33.00	16.51	27.14	21.99	17.02
1959	19.12	30.17	33.15	22.87	17.57	16.13	15.55	12.60	17.02
1960	18.88	29.54	32.86	25.02	18.92	15.88	13.14	10.62	16.98
1961	20.96	34.33	34.40	26.52	22.13	17.53	15.19	12.20	16.87
1962	30.18	49.64	34.55	34.55	29.28	17.80	25.53	20.36	16.75
1963	49.63	83.96	35.53	56.07	49.06	18.38	42.74	34.89	17.15
1964	29.71	50.61	35.78	35.75	30.86	18.13	23.50	19.75	17.65
1965	50.95	85.51	35.25	59.47	51.42	18.16	41.90	34.09	17.09
1966	32.28	53.53	34.83	40.40	34.20	17.78	23.82	19.34	17.05
1967	42.13	70.00	34.90	55.25	46.32	17.61	28.76	23.67	17.29
1968	49.06	86.60	37.08	56.41	52.45	19.53	40.87	34.15	17.55
1969	33.03	56.93	36.20	38.27	34.11	18.72	27.43	22.83	17.48
1970	21.47	36.54	35.74	27.57	24.05	18.32	15.06	12.49	17.42
1971	39.63	65.41	34.67	46.66	38.32	17.25	32.67	27.09	17.42
1972	36.14	59.66	34.67	42.20	34.66	17.25	30.15	25.00	17.42
1973	16.80	27.59	34.48	20.76	16.97	17.17	12.88	10.61	17.31
1974	40.49	66.47	34.48	49.68	40.61	17.17	31.38	25.86	17.31
1975	30.42	49.48	34.17	32.92	26.43	16.86	27.97	23.05	17.31

APPENDIX TABLE A.8. ANNUAL PRECIPITATION, PEARL HARBOR-HONOLULU REGION

Year	Whole Basin (in.)	Whole Basin (mgd)	Non-Caprock (in.)	Non-Caprock (mgd)	Basalt (in.)	Basalt (mgd)	Alluv.-Colluv. (in.)	Alluv.-Colluv. (mgd)	Caprock (in.)	Caprock (mgd)
1946	53.95	565.31	68.33	503.04	69.48	472.37	54.46	30.67	19.98	62.27
1947	51.48	539.44	67.94	500.19	69.46	472.27	49.56	27.92	12.59	39.24
1948	68.14	714.06	86.19	634.57	87.65	595.94	68.58	38.62	25.51	79.50
1949	56.35	590.46	68.25	502.50	69.56	472.94	52.48	29.56	28.22	87.96
1950	68.21	714.75	84.10	619.15	85.47	581.13	67.51	38.02	30.67	95.60
1951	80.07	839.05	95.86	705.74	97.57	663.41	75.16	42.33	42.77	133.31
1952	49.96	523.56	65.52	482.41	66.83	454.37	49.78	28.03	13.20	41.15
1953	36.06	377.82	46.85	344.92	47.87	325.46	34.56	19.46	10.56	32.90
1954	69.35	726.71	85.66	630.66	86.98	591.37	69.76	39.29	30.82	96.04
1955	72.93	764.17	88.18	649.20	89.40	607.84	73.43	41.36	36.89	114.97
1956	64.45	675.36	80.24	590.78	81.88	556.69	60.52	34.09	27.14	84.58
1957	59.70	625.62	73.27	539.42	74.20	504.48	62.05	34.95	27.66	86.20
1958	65.68	688.20	80.88	595.48	82.27	559.36	64.13	36.12	29.75	92.72
1959	41.35	433.26	52.18	384.13	53.10	361.00	41.08	23.14	15.76	49.12
1960	51.58	540.53	67.18	494.57	68.36	464.78	52.89	29.79	14.75	45.96
1961	48.57	508.97	62.30	458.68	63.43	431.27	48.66	27.41	16.14	50.29
1962	47.89	501.84	59.47	437.84	60.90	414.04	42.26	23.80	20.54	64.01
1963	80.36	842.05	96.99	714.08	98.96	672.85	73.20	41.23	41.06	127.97
1964	64.08	671.51	81.50	600.03	83.12	565.16	61.91	34.87	22.93	71.47
1965	87.25	914.33	106.09	781.05	107.78	732.81	85.65	48.24	42.77	133.28
1966	55.98	586.61	69.22	509.58	70.26	477.71	56.59	31.87	24.72	77.03
1967	75.45	790.61	94.22	693.71	95.59	649.91	77.76	43.79	31.09	96.91
1968	73.39	769.09	87.96	647.61	89.18	606.37	73.23	41.24	38.98	121.48
1969	66.81	700.06	84.03	618.62	85.38	580.49	67.71	38.13	26.13	81.44
1970	54.49	571.00	70.36	517.98	71.39	485.42	57.81	32.56	17.01	53.02
1971	63.71	667.61	77.60	571.34	78.89	536.35	62.12	34.99	30.89	96.27
1972	55.00	576.35	66.04	486.22	67.20	456.92	52.03	29.30	28.92	90.13
1973	46.25	484.70	59.03	434.59	59.70	405.93	50.88	28.66	16.08	50.11
1974	75.46	790.69	94.39	694.91	95.92	652.16	75.90	42.75	30.73	95.78
1975	55.04	576.73	66.97	493.07	67.93	461.88	55.38	31.19	26.84	83.66

APPENDIX TABLE A.9. AVERAGE RUNOFF, 1946-1975, HONOLULU REGION

MONTH	WHOLE BASIN			NON-CAPROCK			BASALT			ALLUV.-COLLUV.			CAPROCK		
	Depth (in.)	Vol. (mgd)	% Input	Depth (in.)	Vol. (mgd)	% Input	Depth (in.)	Vol. (mgd)	% Input	Depth (in.)	Vol. (mgd)	% Input	Depth (in.)	Vol. (mgd)	% Input
January	2.06	65.57	26.22	2.04	37.23	21.51	2.01	29.19	20.50	2.18	8.04	26.16	2.09	28.34	36.83
February	1.19	37.77	20.92	1.66	30.31	21.29	1.67	24.26	20.58	1.64	6.05	24.69	0.55	7.47	19.55
March	1.78	56.47	23.88	2.25	41.03	21.89	2.27	33.05	21.04	2.16	7.98	26.26	1.14	15.44	31.48
April	1.09	34.51	19.07	1.67	30.52	19.73	1.69	24.60	19.08	1.60	5.92	22.96	0.29	4.00	15.20
May	0.86	27.35	18.57	1.35	24.53	19.40	1.38	20.00	18.95	1.23	4.54	21.65	0.21	2.82	13.50
June	0.46	14.57	13.60	0.68	12.43	13.41	0.68	9.86	13.00	0.70	2.57	15.22	0.16	2.14	14.83
July	0.67	21.27	13.92	1.17	21.25	15.46	1.19	17.35	15.19	1.05	3.90	16.78	0.00	0.03	0.17
August	0.61	19.42	14.15	1.06	19.28	15.70	1.09	15.82	15.53	0.94	3.46	16.54	0.01	0.13	0.92
September	0.36	11.37	10.51	0.61	11.18	12.10	0.64	9.25	12.14	0.52	1.93	11.92	0.01	0.19	1.21
October	0.69	22.02	13.75	1.04	18.95	14.35	1.04	15.13	13.80	1.04	3.83	17.08	0.23	3.07	10.93
November	1.69	53.82	22.31	2.01	36.67	19.66	1.98	28.85	18.66	2.12	7.82	24.51	1.27	17.15	31.34
December	1.70	53.95	22.77	2.18	39.73	21.46	2.15	31.19	20.47	2.31	8.54	26.05	1.05	14.23	27.44
Annual	13.15	34.84	19.54	17.72	26.93	18.64	17.79	21.54	18.00	17.47	5.38	21.76	7.01	7.92	23.39
Area ($mile^2$)	54.87			31.47			25.09			6.38			23.40		

APPENDIX TABLE A.10. AVERAGE RUNOFF, 1946-1975, PEARL HARBOR REGION

MONTH	WHOLE BASIN			NON-CAPROCK			BASALT			ALLUV.-COLLUV.			CAPROCK		
	Depth (in.)	Vol. (mgd)	% Input	Depth (in.)	Vol. (mgd)	% Input	Depth (in.)	Vol. (mgd)	% Input	Depth (in.)	Vol. (mgd)	% Input	Depth (in.)	Vol. (mgd)	% Input
January	1.54	147.17	16.82	1.61	114.97	16.78	1.62	110.75	16.76	1.34	4.22	17.41	1.32	32.20	16.96
February	0.79	75.27	11.92	0.93	66.42	13.30	0.95	64.50	13.33	0.61	1.92	12.39	0.36	8.85	6.69
March	1.17	112.38	13.93	1.38	98.50	15.44	1.41	96.10	15.50	0.76	2.39	13.50	0.57	13.88	8.22
April	0.83	79.16	11.40	1.03	73.80	13.55	1.06	72.43	13.63	0.44	1.38	10.27	0.22	5.36	3.58
May	0.49	46.52	7.78	0.64	45.70	10.03	0.66	44.97	10.11	0.23	0.73	6.68	0.03	0.82	0.58
June	0.19	18.00	3.54	0.25	17.68	4.85	0.26	17.55	4.93	0.04	0.13	1.57	0.01	0.32	0.22
July	0.45	43.05	6.94	0.59	42.25	8.93	0.61	41.85	9.05	0.12	0.39	3.69	0.03	0.81	0.55
August	0.41	39.23	6.37	0.54	38.56	8.33	0.56	38.17	8.43	0.12	0.39	3.71	0.03	0.67	0.44
September	0.19	17.79	3.42	0.24	17.16	4.63	0.25	16.94	4.69	0.07	0.22	2.23	0.03	0.63	0.42
October	0.50	48.15	7.35	0.62	44.35	9.01	0.64	43.49	9.09	0.27	0.86	6.24	0.16	3.79	2.34
November	1.23	117.92	14.16	1.41	100.41	15.34	1.43	97.82	15.39	0.82	2.59	13.41	0.72	17.50	9.83
December	1.10	104.85	13.61	1.29	92.02	14.90	1.31	89.65	14.96	0.75	2.38	12.95	0.53	12.83	8.38
Annual	8.88	70.79	10.45	10.54	62.65	12.01	10.77	61.19	12.06	5.57	1.47	10.21	4.01	8.14	5.22
Area ($mile^2$)	165.23			123.17			117.72			5.45			42.06		

APPENDIX TABLE A.11. AVERAGE RUNOFF, 1946-1975, SUGARCANE AREA, SOUTHERN O'AHU

MONTH	TOTAL SUGARCANE AREA			NON-CAPROCK			CAPROCK		
	Depth (in.)	Vol. (mgd)	% Input	Depth (in.)	Vol. (mgd)	% Input	Depth (in.)	Vol. (mgd)	% Input
January	0.82	16.81	7.02	0.75	7.91	6.21	0.89	8.90	7.96
February	0.21	4.28	2.28	0.28	2.95	3.09	0.13	1.33	1.44
March	0.36	7.46	2.90	0.39	4.13	3.15	0.33	3.33	2.64
April	0.16	3.33	1.34	0.21	2.21	1.80	0.11	1.11	0.89
May	0.05	0.97	0.38	0.08	0.86	0.68	0.01	0.11	0.09
June	0.01	0.15	0.06	0.01	0.13	0.11	0.00	0.01	0.01
July	0.02	0.44	0.16	0.04	0.42	0.31	0.00	0.02	0.01
August	0.02	0.46	0.16	0.04	0.44	0.32	0.00	0.02	0.01
September	0.02	0.35	0.13	0.03	0.33	0.25	0.00	0.02	0.01
October	0.09	1.92	0.70	0.13	1.35	0.97	0.06	0.57	0.42
November	0.39	8.12	3.12	0.40	4.20	3.12	0.39	3.91	3.13
December	0.31	6.38	2.88	0.35	3.73	3.21	0.27	2.65	2.52
Annual	2.46	4.22	1.68	2.70	2.39	1.89	2.21	1.83	1.47
Area (mile²)		35.51			18.31			17.20	

APPENDIX TABLE A.12. AVERAGE RUNOFF, 1946-1975, PEARL HARBOR-HONOLULU BASIN

MONTH	WHOLE BASIN			NON-CAPROCK			BASALT			ALLUV.-COLLUV.			CAPROCK		
	Depth (In.)	Vol. (mgd)	% Input	Depth (In.)	Vol. (mgd)	% Input	Depth (In.)	Vol. (mgd)	% Input	Depth (In.)	Vol. (mgd)	% Input	Depth (In.)	Vol. (mgd)	% Input
January	1.67	212.74	18.91	1.70	152.20	17.73	1.69	139.94	17.42	1.79	12.26	22.31	1.60	60.54	22.69
February	0.89	113.05	13.92	1.08	96.73	15.07	1.07	88.76	14.75	1.16	7.96	19.93	0.43	16.32	9.58
March	1.32	168.85	16.19	1.56	139.52	16.91	1.56	129.15	16.62	1.51	10.37	21.56	0.77	29.33	13.46
April	0.89	113.68	12.98	1.16	104.32	14.92	1.17	97.03	14.70	1.06	7.30	18.63	0.25	9.35	5.31
May	0.58	73.87	9.91	0.78	70.23	12.06	0.79	64.97	11.81	0.77	5.27	16.52	0.10	3.64	2.23
June	0.26	32.57	5.29	0.34	30.11	6.59	0.33	27.40	6.35	0.39	2.70	10.69	0.06	2.46	1.55
July	0.50	64.32	8.32	0.71	63.49	10.40	0.72	59.21	10.27	0.63	4.29	12.68	0.02	0.83	0.51
August	0.46	58.64	7.79	0.65	57.85	9.87	0.65	53.99	9.74	0.56	3.85	12.25	0.02	0.80	0.48
September	0.23	29.16	4.64	0.32	28.34	6.12	0.32	26.19	5.99	0.31	2.15	8.31	0.02	0.82	0.50
October	0.55	70.17	8.61	0.71	63.31	10.14	0.71	58.62	9.97	0.68	4.68	12.95	0.18	6.86	3.60
November	1.35	171.73	15.99	1.53	137.08	16.29	1.53	126.67	16.03	1.52	10.42	20.32	0.91	34.65	14.89
December	1.25	158.80	15.76	1.47	131.75	16.41	1.46	120.83	16.08	1.59	10.92	21.35	0.71	27.05	13.20
Annual	9.94	105.63	12.34	12.00	89.58	13.45	12.00	82.73	13.20	11.99	6.85	17.52	5.08	16.05	8.46
Area (mile²)		220.10			154.64			142.81			11.83			65.46	

APPENDIX TABLE A.13. ANNUAL RUNOFF, HONOLULU REGION

Year	Whole Basin		Non-Caprock		Basalt		Alluv.-Colluv.		Caprock	
	(in.)	(mgd)	(in.)	(mgd)	(in.)	(mgd)	(in.)	(mgd)	(in.)	(mgd)
1946	9.50	24.82	11.68	17.49	11.55	13.79	12.19	3.70	6.57	7.32
1947	9.26	24.19	16.00	23.97	16.90	20.19	12.45	3.78	0.20	0.22
1948	14.28	37.31	19.88	29.78	20.15	24.07	18.81	5.71	6.76	7.53
1949	11.45	29.91	12.65	18.96	12.96	15.48	11.47	3.48	9.83	10.95
1950	15.52	40.54	18.75	28.10	19.20	22.94	17.00	5.16	11.17	12.44
1951	19.57	51.13	22.57	33.81	23.28	27.81	19.76	6.00	15.55	17.32
1952	10.62	27.73	17.19	25.76	18.05	21.56	13.82	4.20	1.77	1.97
1953	4.07	10.62	6.80	10.20	6.95	8.30	6.24	1.89	0.38	0.43
1954	14.02	36.62	19.16	28.71	19.40	23.17	18.24	5.54	7.10	7.91
1955	19.18	50.11	23.45	35.14	23.99	28.66	21.33	6.48	13.44	14.97
1956	13.58	35.48	19.59	29.35	20.27	24.21	16.92	5.14	5.51	6.14
1957	12.54	32.76	15.46	23.17	15.02	17.94	17.20	5.22	8.61	9.59
1958	17.10	44.67	21.85	32.73	22.45	26.82	19.45	5.91	10.72	11.94
1959	6.11	15.95	9.62	14.42	9.74	11.63	9.19	2.79	1.37	1.53
1960	10.66	27.85	16.77	25.13	17.24	20.60	14.93	4.53	2.44	2.72
1961	8.58	22.42	12.98	19.45	13.62	15.62	12.59	3.82	2.66	2.97
1962	5.75	15.03	9.32	13.96	9.41	11.24	8.96	2.72	0.96	1.07
1963	20.27	52.95	24.95	37.38	25.02	29.89	24.65	7.49	13.98	15.57
1964	14.03	36.66	21.36	32.00	21.59	25.79	20.44	6.21	4.18	4.66
1965	24.03	62.77	30.53	45.75	30.26	36.14	31.61	9.60	15.28	17.02
1966	11.57	30.24	14.61	21.89	14.07	16.81	16.70	5.07	7.50	8.35
1967	17.87	46.68	24.58	36.83	24.22	28.94	26.00	7.90	8.84	9.84
1968	19.19	50.12	25.21	37.77	24.93	29.78	26.28	7.98	11.09	12.35
1969	17.00	44.42	24.50	36.71	24.42	29.16	24.85	7.55	6.92	7.71
1970	11.65	30.43	17.84	26.73	17.55	20.97	18.99	5.77	3.31	3.69
1971	12.25	32.01	16.05	24.04	15.80	18.87	17.03	5.17	7.15	7.97
1972	9.07	23.68	10.42	15.60	10.13	12.10	11.55	3.51	7.25	8.08
1973	8.77	22.91	12.43	18.63	11.74	14.02	15.17	4.61	3.84	4.28
1974	15.61	40.79	21.93	32.85	21.31	25.45	24.37	7.40	7.13	7.94
1975	11.58	30.24	13.66	20.47	13.06	15.60	16.06	4.88	8.77	9.77

APPENDIX TABLE A.14. ANNUAL RUNOFF, PEARL HARBOR REGION

Year	Whole Basin (in.)	Whole Basin (mgd)	Non-Caprock (in.)	Non-Caprock (mgd)	Basalt (in.)	Basalt (mgd)	Alluv.-Colluv. (in.)	Alluv.-Colluv. (mgd)	Caprock (in.)	Caprock (mgd)
1946	6.87	54.05	8.66	50.81	8.91	49.96	3.28	0.85	1.62	3.24
1947	6.16	48.49	8.07	47.35	8.39	47.02	1.25	0.33	0.57	1.14
1948	9.85	77.45	12.17	71.37	12.49	69.99	5.34	1.39	3.03	6.08
1949	9.23	72.59	10.06	58.97	10.23	57.31	6.43	1.67	6.80	13.61
1950	10.35	81.43	12.06	70.70	12.32	69.05	6.37	1.65	5.36	10.73
1951	15.10	118.78	16.97	99.49	17.24	96.64	10.97	2.85	9.63	19.29
1952	5.71	44.92	7.37	43.20	7.62	42.69	1.96	0.51	0.86	1.72
1953	2.04	16.07	2.64	15.50	2.71	15.20	1.15	0.30	0.28	0.57
1954	10.18	80.05	11.91	69.85	12.17	68.22	6.26	1.63	5.09	10.20
1955	11.21	88.20	12.64	74.13	12.83	71.90	8.57	2.22	7.03	14.08
1956	8.97	70.58	10.41	61.06	10.69	59.90	4.45	1.15	4.75	9.52
1957	8.38	65.89	9.18	53.80	9.31	52.16	6.34	1.65	6.04	12.09
1958	11.55	90.87	13.63	79.90	13.85	77.62	8.80	2.28	5.47	10.96
1959	2.94	23.16	3.66	21.45	3.78	21.20	0.96	0.25	0.86	1.72
1960	5.51	43.33	7.27	42.64	7.49	42.01	2.43	0.63	0.34	0.69
1961	3.85	30.32	4.93	28.91	5.11	28.65	1.00	0.26	0.70	1.41
1962	4.30	33.86	5.04	29.56	5.21	29.19	1.39	0.36	2.15	4.31
1963	14.08	110.72	15.72	92.19	16.12	90.32	7.22	1.87	9.25	18.58
1964	9.58	75.36	11.68	68.48	12.05	67.53	3.66	0.95	3.43	6.88
1965	16.78	132.00	19.50	114.35	19.86	111.30	11.74	3.05	8.81	17.65
1966	8.20	64.51	9.52	55.83	9.68	54.23	6.18	1.60	4.33	8.68
1967	10.57	83.13	13.02	76.36	13.34	74.77	6.12	1.59	3.38	6.77
1968	14.65	115.26	17.19	100.83	17.36	97.30	13.59	3.53	7.21	14.43
1969	12.28	96.60	14.67	86.03	14.92	83.60	9.37	2.43	5.28	10.57
1970	7.20	56.60	9.18	53.86	9.40	52.69	4.49	1.17	1.37	2.74
1971	9.45	74.30	11.29	66.22	11.50	64.45	6.81	1.77	4.04	8.08
1972	6.08	47.86	7.01	41.12	7.17	40.17	3.66	0.95	3.37	6.74
1973	4.32	33.97	5.45	31.95	5.63	31.55	1.56	0.41	1.01	2.01
1974	12.40	97.55	15.60	91.48	15.90	89.10	9.20	2.39	3.03	6.07
1975	8.52	66.99	9.67	56.69	9.81	54.98	6.59	1.71	5.14	10.29

APPENDIX TABLE A.15. ANNUAL RUNOFF, SUGARCANE AREA, SOUTHERN O'AHU

YEAR	TOTAL SUGARCANE AREA Depth (in.)	Vol. (mgd)	Area (mile^2)	NON-CAPROCK Depth (in.)	Vol. (mgd)	Area (mile^2)	CAPROCK Depth (in.)	Vol. (mgd)	Area (mile^2)
1946	1.12	2.06	38.65	1.37	1.41	21.62	0.80	0.65	17.03
1947	0.34	0.63	38.77	0.59	0.60	21.62	0.03	0.02	17.15
1948	1.88	3.57	39.94	2.25	2.44	22.79	1.39	1.13	17.15
1949	3.92	7.39	39.59	3.55	3.76	22.28	4.40	3.63	17.31
1950	3.04	5.72	39.59	3.05	3.24	22.28	3.02	2.49	17.31
1951	5.77	10.57	38.46	5.77	5.81	21.15	5.77	4.75	17.31
1952	0.47	0.76	34.15	0.56	0.45	16.84	0.38	0.31	17.31
1953	0.16	0.26	33.91	0.28	0.22	16.84	0.05	0.04	17.07
1954	2.76	4.45	33.91	2.99	2.40	16.84	2.53	2.06	17.07
1955	3.88	6.27	33.91	4.18	3.35	16.84	3.60	2.92	17.07
1956	2.05	3.32	34.01	1.95	1.57	16.94	2.16	1.75	17.07
1957	3.26	5.21	33.61	2.83	2.23	16.59	3.68	2.98	17.02
1958	3.58	5.70	33.46	4.16	3.25	16.44	3.02	2.45	17.02
1959	0.15	0.24	33.15	0.26	0.20	16.13	0.05	0.04	17.02
1960	0.35	0.55	32.86	0.65	0.49	15.88	0.07	0.05	16.98
1961	0.29	0.47	34.40	0.31	0.26	17.53	0.26	0.21	16.87
1962	1.04	1.71	34.55	1.02	0.87	17.80	1.06	0.85	16.75
1963	5.34	9.03	35.53	4.59	4.02	18.38	6.14	5.01	17.15
1964	1.72	2.92	35.78	1.84	1.59	18.13	1.59	1.34	17.65
1965	5.51	9.25	35.25	5.91	5.11	18.16	5.08	4.14	17.09
1966	2.72	4.52	34.83	3.19	2.70	17.78	2.24	1.82	17.05
1967	2.19	3.64	34.90	2.74	2.29	17.61	1.63	1.34	17.29
1968	5.57	9.84	37.08	6.97	6.48	19.53	4.02	3.36	17.55
1969	3.99	6.87	36.20	4.34	3.87	18.72	3.61	3.00	17.48
1970	1.15	1.96	35.74	1.69	1.48	18.32	0.59	0.49	17.42
1971	3.01	4.96	34.67	3.44	2.82	17.25	2.58	2.14	17.42
1972	1.76	2.90	34.67	1.80	1.48	17.25	1.72	1.42	17.42
1973	0.46	0.75	34.48	0.51	0.41	17.17	0.41	0.34	17.31
1974	2.46	4.04	34.48	3.93	3.21	17.17	1.01	0.83	17.31
1975	3.13	5.10	34.17	3.06	2.45	16.86	3.21	2.65	17.31

APPENDIX TABLE A.16. ANNUAL RUNOFF, PEARL HARBOR-HONOLULU BASIN

Year	Whole Basin (in.)	Whole Basin (mgd)	Non-Caprock (in.)	Non-Caprock (mgd)	Basalt (in.)	Basalt (mgd)	Alluv.-Colluv. (in.)	Alluv.-Colluv. (mgd)	Caprock (in.)	Caprock (mgd)
1946	7.53	78.87	9.28	68.30	9.38	63.75	8.08	4.55	3.39	10.57
1947	6.94	72.68	9.69	71.32	9.89	67.21	7.29	4.11	0.44	1.36
1948	10.95	114.76	13.74	101.15	13.83	94.05	12.60	7.10	4.37	13.60
1949	9.78	102.50	10.59	77.93	10.70	72.78	9.15	5.15	7.88	24.56
1950	11.64	121.97	13.42	98.80	13.53	91.99	12.10	6.81	7.44	23.17
1951	16.21	169.91	18.11	133.30	18.30	124.45	15.71	8.85	11.75	36.61
1952	6.93	72.65	9.37	68.95	9.45	64.25	8.36	4.71	1.18	3.69
1953	2.55	26.69	3.49	25.69	3.46	23.50	3.89	2.19	0.32	0.99
1954	11.13	116.67	13.39	98.56	13.44	91.39	12.72	7.17	5.81	18.11
1955	13.20	138.31	14.84	109.27	14.79	100.56	15.45	8.70	9.32	29.05
1956	10.12	106.06	12.28	90.41	12.37	84.11	11.17	6.29	5.02	15.66
1957	9.41	98.65	10.45	76.97	10.31	70.10	12.20	6.87	6.96	21.68
1958	12.93	135.54	15.30	112.64	15.36	104.44	14.55	8.19	7.35	22.90
1959	3.73	39.12	4.87	35.87	4.83	32.83	5.40	3.04	1.04	3.25
1960	6.79	71.17	9.20	67.77	9.21	62.60	9.17	5.17	1.09	3.41
1961	5.03	52.73	6.57	48.36	6.51	44.28	7.25	4.08	1.40	4.38
1962	4.67	48.89	5.91	43.51	5.95	40.43	5.47	3.08	1.72	5.37
1963	15.62	163.67	17.60	129.57	17.68	120.21	16.62	9.36	10.94	34.10
1964	10.69	112.01	13.65	100.48	13.73	93.32	12.71	7.16	3.70	11.53
1965	18.59	194.76	21.74	160.09	21.69	147.44	22.46	12.65	11.12	34.67
1966	9.04	94.75	10.56	77.72	10.45	71.04	11.86	6.68	5.46	17.03
1967	12.39	129.81	15.37	113.19	15.25	103.71	16.84	9.48	5.33	16.62
1968	15.78	165.38	18.82	138.59	18.69	127.09	20.43	11.51	8.59	26.79
1969	13.46	141.03	16.67	122.75	16.59	112.77	17.72	9.98	5.86	18.28
1970	8.31	87.03	10.95	80.59	10.83	73.66	12.31	6.93	2.06	6.43
1971	10.15	106.31	12.26	90.26	12.25	83.32	12.32	6.94	5.15	16.05
1972	6.83	71.54	7.70	56.73	7.69	52.27	7.91	4.46	4.75	14.82
1973	5.43	56.87	6.87	50.58	6.70	45.57	8.90	5.01	2.02	6.29
1974	13.20	138.34	16.89	124.33	16.85	114.55	17.38	9.79	4.49	14.00
1975	9.28	97.23	10.48	77.17	10.38	70.58	11.70	6.59	6.44	20.06

APPENDIX TABLE A.17. AVERAGE ACTUAL EVAPOTRANSPIRATION, 1946-1975, HONOLULU REGION

MONTH	WHOLE BASIN Depth (in.)	Vol. (mgd)	% Input	NON-CAPROCK Depth (in.)	Vol. (mgd)	% Input	BASALT Depth (in.)	Vol. (mgd)	% Input	ALLUV.-COLLUV. Depth (in.)	Vol. (mgd)	% Input	CAPROCK Depth (in.)	Vol. (mgd)	% Input
January	2.14	68.10	27.24	2.58	46.96	27.13	2.62	38.06	26.73	2.41	8.90	28.96	1.56	21.14	27.47
February	2.06	65.41	36.23	2.48	45.13	31.70	2.52	36.58	31.03	2.31	8.55	34.92	1.50	20.28	53.09
March	2.23	70.79	29.94	2.73	49.82	26.58	2.75	39.99	25.46	2.66	9.83	32.36	1.55	20.98	42.77
April	2.22	70.64	39.02	2.84	51.74	33.44	2.86	41.50	32.19	2.77	10.25	39.73	1.39	18.89	71.86
May	2.32	73.60	49.96	3.11	56.72	44.84	3.17	46.08	43.68	2.88	10.63	50.72	1.25	16.89	80.89
June	2.14	68.11	63.56	3.08	56.07	60.48	3.12	45.36	59.83	2.90	10.71	63.40	0.89	12.03	83.34
July	2.44	77.41	50.66	3.45	62.96	45.81	3.48	50.58	44.28	3.35	12.39	53.34	1.07	14.45	94.02
August	2.41	76.45	55.71	3.42	62.30	50.73	3.44	49.98	49.06	3.33	12.32	58.88	1.04	14.15	98.20
September	2.23	70.72	65.34	3.09	56.39	61.00	3.11	45.23	59.34	3.02	11.15	68.77	1.06	14.34	90.80
October	2.22	70.68	44.15	2.85	51.92	39.32	2.87	41.76	38.09	2.75	10.15	45.33	1.38	18.76	66.88
November	2.27	72.15	29.91	2.87	52.32	28.05	2.90	42.18	27.28	2.74	10.14	31.78	1.46	19.83	36.24
December	2.15	68.18	28.77	2.65	48.23	26.06	2.71	39.41	25.87	2.39	8.82	26.92	1.47	19.95	38.48
Annual	26.82	71.02	39.84	35.14	53.38	36.96	35.55	43.06	35.97	33.51	10.32	41.74	15.62	17.64	52.14
Area (mile^2)		54.87			31.47			25.09			6.38			23.40	

APPENDIX TABLE A.18. AVERAGE ACTUAL EVAPOTRANSPIRATION, 1946-1975, PEARL HARBOR REGION

MONTH	WHOLE BASIN Depth (in.)	Vol. (mgd)	% Input	NON-CAPROCK Depth (in.)	Vol. (mgd)	% Input	BASALT Depth (in.)	Vol. (mgd)	% Input	ALLUV.-COLLUV. Depth (in.)	Vol. (mgd)	% Input	CAPROCK Depth (in.)	Vol. (mgd)	% Input
January	2.64	252.27	28.83	2.59	184.58	26.94	2.57	175.50	26.55	2.88	9.08	37.51	2.78	67.69	35.64
February	2.71	259.26	41.04	2.66	189.55	37.95	2.66	181.22	37.44	2.64	8.33	53.89	2.86	69.71	52.71
March	2.92	279.66	34.67	2.84	202.64	31.77	2.84	193.86	31.26	2.78	8.78	49.52	3.16	77.01	45.59
April	2.93	280.36	40.37	2.86	204.11	37.47	2.87	195.86	36.87	2.61	8.25	61.62	3.13	76.24	50.89
May	2.85	273.16	45.69	2.79	199.25	43.72	2.81	191.86	43.13	2.34	7.39	67.63	3.03	73.91	51.99
June	2.74	261.81	51.43	2.64	188.38	51.69	2.68	182.46	51.24	1.88	5.92	70.43	3.01	73.43	50.79
July	2.86	273.62	44.13	2.75	196.47	41.53	2.78	189.50	40.97	2.21	6.98	65.86	3.17	77.15	52.52
August	2.85	272.66	44.28	2.74	195.23	42.16	2.76	188.25	41.60	2.21	6.99	66.41	3.18	77.43	50.68
September	2.77	265.18	51.00	2.75	195.86	52.81	2.78	189.41	52.44	2.04	6.45	66.86	2.85	69.32	46.50
October	2.71	258.97	39.56	2.68	190.97	38.80	2.69	183.13	38.28	2.48	7.84	56.94	2.79	68.01	41.86
November	2.55	244.31	29.34	2.49	177.83	27.16	2.48	169.20	26.63	2.73	8.63	44.62	2.73	66.49	37.34
December	2.54	242.84	31.51	2.46	175.77	28.46	2.46	167.55	27.96	2.60	8.22	44.74	2.75	67.07	43.81
Annual	33.06	263.67	38.93	32.25	191.72	36.76	32.38	183.98	36.27	29.41	7.74	53.88	35.44	71.95	46.17
Area (mile^2)		165.23			123.17			117.72			5.45			42.06	

APPENDIX TABLE A.19. AVERAGE ACTUAL EVAPOTRANSPIRATION, 1946-1975, SUGARCANE AREA, SOUTHERN O'AHU

MONTH	TOTAL SUGARCANE AREA Depth (in.)	Vol. (mgd)	% Input	NON-CAPROCK Depth (in.)	Vol. (mgd)	% Input	CAPROCK Depth (in.)	Vol. (mgd)	% Input
January	3.66	75.36	31.48	3.65	38.73	30.39	3.68	36.63	32.73
February	3.88	79.89	42.65	3.73	39.59	41.53	4.04	40.29	43.81
March	4.68	96.19	37.38	4.33	45.95	35.04	5.04	50.24	39.81
April	5.08	104.45	42.03	4.61	48.91	39.85	5.57	55.54	44.15
May	5.38	110.65	43.58	4.89	51.82	41.14	5.90	58.82	45.97
June	5.66	116.51	44.57	5.02	53.29	42.36	6.35	63.22	46.62
July	5.98	123.10	45.72	5.25	55.64	41.63	6.77	67.46	49.76
August	5.99	123.21	44.14	5.24	55.56	40.46	6.79	67.65	47.71
September	5.27	108.33	41.02	4.84	51.30	39.50	5.72	57.03	42.48
October	4.72	97.05	35.35	4.48	47.57	34.30	4.97	49.48	36.41
November	3.96	81.49	31.34	3.77	40.00	29.65	4.16	41.49	33.16
December	3.70	76.19	34.40	3.43	36.35	31.25	4.00	39.84	37.88
Annual	57.97	99.37	39.53	53.24	47.06	37.17	63.01	52.31	41.92
Area (mile^2)		35.51			18.31			17.20	

APPENDIX TABLE A.20. AVERAGE ACTUAL EVAPOTRANSPIRATION, 1946-1975, PEARL HARBOR-HONOLULU BASIN

MONTH	WHOLE BASIN Depth (in.)	Vol. (mgd)	% Input	NON-CAPROCK Depth (in.)	Vol. (mgd)	% Input	BASALT Depth (in.)	Vol. (mgd)	% Input	ALLUV.-COLLUV. Depth (in.)	Vol. (mgd)	% Input	CAPROCK Depth (in.)	Vol. (mgd)	% Input
January	2.51	320.37	28.47	2.58	231.54	26.98	2.58	213.56	26.58	2.62	17.98	32.73	2.34	88.83	33.29
February	2.55	324.67	39.97	2.62	234.68	36.57	2.63	217.80	36.19	2.46	16.89	42.26	2.37	89.98	52.80
March	2.75	350.45	33.59	2.82	252.46	30.59	2.83	233.85	30.09	2.72	18.61	38.69	2.58	97.99	44.96
April	2.75	350.99	40.09	2.86	255.86	36.58	2.87	237.36	35.95	2.70	18.50	47.21	2.51	95.14	54.02
May	2.72	346.76	46.53	2.86	255.97	43.97	2.88	237.94	43.24	2.63	18.02	56.51	2.39	90.80	55.69
June	2.59	329.92	53.54	2.73	244.46	53.47	2.75	227.82	52.75	2.43	16.64	65.73	2.25	85.46	53.74
July	2.75	351.04	45.42	2.90	259.43	42.49	2.90	240.07	41.63	2.83	19.36	57.26	2.42	91.60	56.45
August	2.74	349.11	46.36	2.88	257.53	43.96	2.88	238.23	42.97	2.82	19.31	61.40	2.42	91.58	54.78
September	2.63	335.90	53.47	2.82	252.24	54.45	2.84	234.64	53.64	2.57	17.61	68.06	2.21	83.66	50.74
October	2.59	329.65	40.46	2.71	242.88	38.91	2.72	224.89	38.24	2.63	17.99	49.75	2.29	86.77	45.54
November	2.48	316.46	29.46	2.57	230.15	27.36	2.56	211.37	26.76	2.74	18.77	36.62	2.28	86.32	37.08
December	2.44	311.02	30.87	2.50	224.00	27.91	2.50	206.96	27.54	2.49	17.04	33.32	2.29	87.02	42.46
Annual	31.50	334.70	39.12	32.83	245.10	36.80	32.94	227.04	36.22	31.62	18.06	46.20	28.36	89.60	47.24
Area ($mile^2$)		220.10			154.64			142.81			11.83			65.46	

APPENDIX TABLE A.21. ANNUAL ACTUAL EVAPOTRANSPIRATION, HONOLULU REGION

Year	Whole Basin (in.)	(mgd)	Non-Caprock (in.)	(mgd)	Basalt (in.)	(mgd)	Alluv.-Colluv. (in.)	(mgd)	Caprock (in.)	(mgd)
1946	26.31	68.72	34.80	52.14	35.06	41.88	33.79	10.26	14.88	16.58
1947	26.65	69.61	35.39	53.03	35.69	42.64	34.20	10.39	14.89	16.58
1948	27.82	72.67	36.35	54.47	36.56	43.67	35.56	10.80	16.34	18.20
1949	24.25	63.35	33.45	50.12	33.81	40.38	32.05	9.74	11.87	13.23
1950	27.34	71.41	35.95	53.86	36.16	43.19	35.13	10.67	15.75	17.55
1951	27.08	70.74	35.21	52.76	35.44	42.33	34.34	10.43	16.14	17.98
1952	25.48	66.56	35.00	52.44	35.25	42.11	34.00	10.33	12.68	14.13
1953	23.21	60.63	32.07	48.04	32.42	38.73	30.67	9.32	11.30	12.59
1954	28.48	74.40	36.58	54.81	36.80	43.96	35.71	10.85	17.58	19.59
1955	27.72	72.42	36.16	54.17	36.35	43.42	35.40	10.75	16.37	18.24
1956	27.22	71.12	35.69	53.48	35.85	42.83	35.06	10.65	15.83	17.64
1957	25.52	66.66	34.07	51.05	34.36	41.05	32.94	10.00	14.01	15.61
1958	27.73	72.45	35.83	53.68	36.04	43.04	35.01	10.63	16.85	18.77
1959	25.94	67.75	34.05	51.01	34.27	40.93	33.18	10.08	15.03	16.74
1960	26.44	69.07	35.19	52.73	35.30	42.17	34.77	10.56	14.67	16.34
1961	26.87	70.20	35.82	53.67	36.02	43.02	35.05	10.65	14.84	16.53
1962	24.92	65.11	33.06	49.54	33.52	40.04	31.28	9.50	13.97	15.57
1963	28.09	73.38	35.67	53.45	36.19	43.23	33.65	10.22	17.90	19.94
1964	27.28	71.28	36.13	54.13	36.73	43.88	33.76	10.25	15.39	17.15
1965	28.74	75.09	36.25	54.31	36.99	44.19	33.32	10.12	18.65	20.78
1966	24.51	64.03	32.70	49.00	33.42	39.92	29.87	9.07	13.49	15.03
1967	29.66	77.48	36.65	54.92	37.34	44.61	33.94	10.31	20.26	22.57
1968	27.46	71.73	34.98	52.41	35.66	42.60	32.31	9.81	17.35	19.33
1969	27.33	71.39	36.09	54.07	36.78	43.94	33.36	10.13	15.55	17.32
1970	26.57	69.40	35.16	52.68	35.80	42.76	32.64	9.92	15.01	16.73
1971	27.82	72.67	35.12	52.62	35.70	42.65	32.84	9.98	17.99	20.04
1972	27.21	71.07	34.96	52.38	35.47	42.37	32.95	10.01	16.78	18.69
1973	26.78	69.95	35.54	53.25	36.12	43.15	33.26	10.10	14.99	16.70
1974	28.96	75.64	36.51	54.70	37.20	44.44	33.79	10.26	18.80	20.95
1975	25.13	65.64	33.81	50.66	34.36	41.04	31.65	9.61	13.45	14.99

APPENDIX TABLE A.22. ANNUAL ACTUAL EVAPOTRANSPIRATION, PEARL HARBOR REGION

Year	Whole Basin		Non-Caprock		Basalt		Alluv.-Colluv.		Caprock	
	(in.)	(mgd)	(in.)	(mgd)	(in.)	(mgd)	(in.)	(mgd)	(in.)	(mgd)
1946	30.80	242.27	30.82	180.72	30.90	173.18	29.03	7.53	30.74	61.55
1947	32.62	256.60	32.32	189.54	32.39	181.52	30.89	8.01	33.49	67.07
1948	34.83	274.00	34.54	202.56	34.61	193.95	33.19	8.61	35.68	71.44
1949	31.21	245.48	30.57	179.25	30.74	172.29	26.80	6.95	33.08	66.24
1950	34.36	270.27	34.02	199.49	34.11	191.16	32.10	8.33	35.35	70.78
1951	35.42	278.59	34.41	201.78	34.48	193.26	32.84	8.52	38.36	76.82
1952	31.00	243.90	30.36	178.04	30.49	170.88	27.62	7.17	32.89	65.86
1953	29.10	228.92	28.31	166.03	28.49	159.65	24.58	6.38	31.41	62.89
1954	34.33	270.06	33.30	195.24	33.31	186.70	32.91	8.54	37.36	74.81
1955	33.21	261.24	32.12	188.35	32.12	180.04	32.03	8.31	36.40	72.89
1956	32.83	258.26	31.87	186.91	31.94	179.02	30.40	7.89	35.63	71.35
1957	30.55	240.36	29.65	173.84	29.73	166.61	27.85	7.23	33.22	66.52
1958	32.49	255.60	32.39	189.91	32.50	182.15	29.94	7.77	32.80	65.68
1959	30.72	241.67	29.66	173.92	29.77	166.86	27.22	7.06	33.83	67.75
1960	30.62	240.89	29.92	175.46	29.93	167.75	29.68	7.70	32.68	65.44
1961	32.18	253.16	31.83	186.67	31.99	179.26	28.56	7.41	33.20	66.48
1962	33.74	265.41	33.01	193.59	33.21	186.15	28.67	7.44	35.87	71.82
1963	35.11	276.17	33.93	198.99	34.00	190.53	32.59	8.46	38.54	77.18
1964	32.54	255.95	31.41	184.20	31.47	176.40	30.08	7.81	35.83	71.75
1965	35.35	278.04	34.17	200.38	34.23	191.86	32.83	8.52	38.79	77.67
1966	32.15	252.94	31.15	182.69	31.39	175.95	25.94	6.73	35.08	70.25
1967	36.63	288.13	36.01	211.14	35.98	201.65	36.56	9.49	38.45	77.00
1968	35.48	279.14	33.94	199.02	34.16	191.46	29.15	7.56	40.01	80.12
1969	32.90	258.80	32.26	189.16	32.59	182.66	25.04	6.50	34.78	69.64
1970	31.67	249.12	30.82	180.74	31.08	174.20	25.19	6.54	34.15	68.38
1971	35.91	282.52	34.85	204.34	35.01	196.22	31.29	8.12	39.05	78.19
1972	35.01	275.44	33.81	198.28	34.04	190.76	28.98	7.52	38.53	77.15
1973	30.76	242.00	29.91	175.37	30.18	169.14	24.03	6.24	33.27	66.63
1974	37.24	292.95	36.38	213.32	36.53	204.72	33.15	8.60	39.76	79.62
1975	31.25	245.85	29.97	175.73	30.28	169.69	23.26	6.04	35.02	70.13

APPENDIX TABLE A.23. ANNUAL ACTUAL EVAPOTRANSPIRATION, SUGARCANE AREA

YEAR	TOTAL SUGARCANE AREA Depth (in.)	Vol. (mgd)	Area (mile^2)	NON-CAPROCK Depth (in.)	Vol. (mgd)	Area (mile^2)	CAPROCK Depth (in.)	Vol. (mgd)	Area (mile^2)
1946	52.62	96.83	38.65	48.91	50.35	21.62	57.33	46.48	17.03
1947	57.22	105.61	38.77	52.52	54.06	21.62	63.14	51.55	17.15
1948	57.32	108.99	39.94	52.46	56.93	22.79	63.76	52.06	17.15
1949	55.50	104.79	39.66	49.58	52.75	22.35	63.15	52.04	17.31
1950	57.43	108.43	39.66	52.90	56.29	22.35	63.27	52.14	17.31
1951	57.78	105.99	38.53	53.30	53.85	21.22	63.27	52.14	17.31
1952	59.00	96.12	34.22	54.49	43.87	16.91	63.40	52.25	17.31
1953	58.74	95.03	33.98	53.80	43.31	16.91	63.65	51.72	17.07
1954	59.28	95.91	33.98	55.27	44.50	16.91	63.26	51.41	17.07
1955	58.64	94.87	33.98	54.39	43.79	16.91	62.85	51.08	17.07
1956	58.93	95.62	34.08	55.03	44.57	17.01	62.82	51.05	17.07
1957	58.64	94.02	33.68	54.14	42.94	16.66	63.04	51.09	17.02
1958	53.93	86.09	33.53	51.31	40.33	16.51	56.47	45.75	17.02
1959	58.13	91.75	33.15	53.69	41.23	16.13	62.34	50.51	17.02
1960	58.52	91.56	32.86	54.61	41.29	15.88	62.18	50.27	16.98
1961	58.17	95.27	34.40	54.02	45.09	17.53	62.48	50.18	16.87
1962	57.90	95.23	34.55	53.62	45.44	17.80	62.44	49.79	16.75
1963	59.04	99.86	35.53	54.93	48.07	18.38	63.44	51.80	17.15
1964	58.23	99.19	35.78	53.25	45.97	18.13	63.34	53.22	17.65
1965	58.71	98.53	35.25	54.04	46.73	18.16	63.67	51.81	17.09
1966	58.15	96.42	34.83	52.38	44.34	17.78	64.16	52.08	17.05
1967	60.02	99.72	34.90	55.74	46.73	17.61	64.37	52.99	17.29
1968	58.70	103.62	37.08	53.29	49.55	19.53	64.71	54.07	17.55
1969	58.19	100.30	36.20	52.93	47.18	18.72	63.83	53.12	17.48
1970	58.38	99.33	35.74	52.60	45.88	18.32	64.45	53.45	17.42
1971	59.84	98.77	34.67	54.79	45.00	17.25	64.83	53.77	17.42
1972	58.83	97.11	34.67	53.74	44.14	17.25	63.87	52.97	17.42
1973	58.03	95.26	34.48	52.30	42.75	17.17	63.71	52.51	17.31
1974	59.14	97.09	34.48	54.56	44.60	17.17	63.69	52.49	17.31
1975	57.18	93.02	34.17	51.08	41.00	16.86	63.12	52.02	17.31

APPENDIX TABLE A.24. ANNUAL ACTUAL EVAPOTRANSPIRATION, PEARL HARBOR-HONOLULU BASIN

Year	Whole Basin		Non-Caprock		Basalt		Alluv.-Colluv.		Caprock	
	(in.)	(mgd)	(in.)	(mgd)	(in.)	(mgd)	(in.)	(mgd)	(in.)	(mgd)
1946	29.68	310.99	31.63	232.86	31.63	215.06	31.60	17.80	25.07	78.13
1947	31.13	326.21	32.95	242.56	32.97	224.16	32.68	18.40	26.84	83.65
1948	33.08	346.67	34.91	257.03	34.95	237.16	34.47	19.41	28.76	89.64
1949	29.47	308.83	31.15	229.37	31.28	212.68	29.63	16.69	25.50	79.47
1950	32.61	341.68	34.41	253.35	34.47	234.35	33.73	19.00	28.34	88.33
1951	33.34	349.34	34.57	254.54	34.65	235.59	33.65	18.95	30.42	94.80
1952	29.63	310.46	31.30	230.48	31.33	212.98	31.06	17.49	25.67	79.99
1953	27.63	289.56	29.08	214.07	29.18	198.38	27.86	15.69	24.22	75.48
1954	32.87	344.45	33.96	250.05	33.93	230.67	34.42	19.39	30.29	94.40
1955	31.84	333.66	32.94	242.52	32.87	223.46	33.85	19.06	29.24	91.14
1956	31.43	329.37	32.65	240.39	32.63	221.85	32.92	18.54	28.55	88.98
1957	29.30	307.02	30.55	224.89	30.54	207.66	30.59	17.23	26.35	82.13
1958	31.31	328.05	33.09	243.59	33.12	225.19	32.67	18.40	27.10	84.46
1959	29.53	309.42	30.55	224.93	30.56	207.79	30.44	17.14	27.11	84.49
1960	29.58	309.96	30.99	228.18	30.87	209.92	32.43	18.26	26.24	81.78
1961	30.86	323.36	32.64	240.34	32.69	222.29	32.06	18.06	26.64	83.01
1962	31.54	330.52	33.02	243.13	33.27	226.19	30.07	16.94	28.04	87.39
1963	33.36	349.55	34.29	252.43	34.38	233.76	33.16	18.68	31.16	97.12
1964	31.23	327.23	32.37	238.33	32.40	220.27	32.06	18.06	28.53	88.90
1965	33.70	353.14	34.59	254.69	34.72	236.05	33.09	18.64	31.59	98.45
1966	30.25	316.97	31.47	231.68	31.75	215.88	28.06	15.80	27.37	85.28
1967	34.89	365.62	36.14	266.05	36.22	246.26	35.15	19.80	31.95	99.56
1968	33.48	350.87	34.15	251.43	34.42	234.05	30.85	17.38	31.91	99.44
1969	31.51	330.19	33.04	243.23	33.33	226.60	29.53	16.63	27.90	86.96
1970	30.40	318.52	31.70	233.41	31.91	216.96	29.21	16.45	27.31	85.11
1971	33.90	355.19	34.90	256.96	35.13	238.87	32.13	18.09	31.52	98.23
1972	33.07	346.51	34.05	250.66	34.29	233.13	31.13	17.53	30.75	95.84
1973	29.77	311.96	31.05	228.62	31.22	212.28	29.01	16.34	26.74	83.33
1974	35.17	368.59	36.40	268.02	36.65	249.16	33.49	18.86	32.27	100.57
1975	29.73	311.50	30.75	226.38	30.99	210.73	27.79	15.65	27.31	85.11

APPENDIX TABLE A.25. AVERAGE RECHARGE, 1946-1975, HONOLULU REGION

MONTH	WHOLE BASIN			NON-CAPROCK			BASALT			ALLUV.-COLLUV.			CAPROCK		
	Depth (in.)	Vol. (mgd)	% Input	Depth (in.)	Vol. (mgd)	% Input	Depth (in.)	Vol. (mgd)	% Input	Depth (in.)	Vol. (mgd)	% Input	Depth (in.)	Vol. (mgd)	% Input
January	3.67	116.79	46.71	4.90	89.33	51.60	5.19	75.48	53.02	3.75	13.84	45.04	2.03	27.47	35.69
February	2.50	79.51	44.04	3.74	68.25	47.94	4.00	58.14	49.33	2.74	10.11	41.26	0.83	11.26	29.47
March	3.49	110.90	46.90	5.33	97.17	51.84	5.81	84.50	53.80	3.43	12.66	41.69	1.01	13.74	28.01
April	2.41	76.61	42.33	3.97	72.34	46.76	4.32	62.79	48.70	2.59	9.56	37.05	0.32	4.27	16.25
May	1.60	50.78	34.47	2.66	48.42	38.28	2.90	42.10	39.90	1.71	6.32	30.15	0.17	2.37	11.33
June	0.89	28.14	26.26	1.46	26.60	28.69	1.55	22.56	29.76	1.09	4.04	23.90	0.11	1.54	10.70
July	1.61	51.29	33.56	2.81	51.15	37.22	3.07	44.57	39.02	1.78	6.58	28.35	0.01	0.14	0.89
August	1.33	42.39	30.89	2.30	41.95	34.16	2.53	36.71	36.03	1.42	5.24	25.06	0.03	0.44	3.04
September	0.84	26.58	24.56	1.43	26.08	28.21	1.57	22.75	29.85	0.90	3.33	20.54	0.04	0.50	3.16
October	1.97	62.66	39.14	3.21	58.48	44.29	3.48	50.62	46.17	2.13	7.86	35.09	0.31	4.18	14.90
November	3.56	113.07	46.87	5.29	96.35	51.66	5.69	82.66	53.47	3.70	13.69	42.89	1.23	16.72	30.55
December	3.55	112.73	47.58	5.26	95.87	51.79	5.56	80.80	53.04	4.08	15.07	45.99	1.24	16.86	32.52
Annual	27.42	72.62	40.73	42.35	64.33	44.54	45.67	55.31	46.20	29.31	9.03	36.50	7.34	8.29	24.49
Area (mile^2)		54.87			31.47			25.09			6.38			23.40	

APPENDIX TABLE A.26. AVERAGE RECHARGE, 1946-1975, PEARL HARBOR REGION

MONTH	WHOLE BASIN			NON-CAPROCK			BASALT			ALLUV.-COLLUV.			CAPROCK		
	Depth (in.)	Vol. (mgd)	% Input	Depth (in.)	Vol. (mgd)	% Input	Depth (in.)	Vol. (mgd)	% Input	Depth (in.)	Vol. (mgd)	% Input	Depth (in.)	Vol. (mgd)	% Input
January	4.90	469.09	53.61	5.35	381.80	55.72	5.44	370.75	56.09	3.50	11.05	45.66	3.58	87.29	45.96
February	3.33	318.71	50.45	3.61	257.80	51.62	3.70	252.29	52.13	1.75	5.52	35.67	2.50	60.90	46.06
March	4.43	424.16	52.58	4.81	343.18	53.81	4.94	336.51	54.27	2.11	6.67	37.62	2.32	80.97	47.94
April	3.69	352.72	50.79	3.90	278.58	51.15	4.02	274.37	51.64	1.33	4.21	31.46	3.04	74.13	49.48
May	3.06	293.01	49.01	3.11	221.77	48.66	3.20	218.49	49.12	1.04	3.28	30.03	2.92	71.24	50.11
June	2.51	240.36	47.22	2.34	166.86	45.78	2.41	164.11	46.09	0.87	2.75	32.70	3.02	73.49	50.83
July	3.13	299.85	48.36	3.23	230.14	48.64	3.33	227.27	49.14	0.91	2.87	27.14	2.86	69.71	47.46
August	3.17	303.01	49.20	3.21	229.25	49.51	3.31	225.96	49.93	1.04	3.29	31.27	3.03	73.77	48.29
September	2.45	234.31	45.07	2.23	159.08	42.90	2.29	156.18	43.24	0.92	2.90	30.03	3.09	75.23	50.46
October	3.42	327.13	49.97	3.40	242.31	49.23	3.49	237.94	49.73	1.38	4.37	31.73	3.48	84.82	52.21
November	4.66	445.87	53.54	5.02	358.48	54.75	5.15	350.91	55.22	2.40	7.57	39.14	3.59	87.39	49.08
December	4.33	414.23	53.75	4.81	343.34	55.60	4.93	335.87	56.06	2.37	7.47	40.67	2.91	70.89	46.30
Annual	43.07	343.50	50.71	45.02	267.68	51.32	46.20	262.52	51.76	19.63	5.16	35.95	37.35	75.82	48.66
Area (mile^2)		165.23			123.17			117.72			5.45			42.06	

APPENDIX TABLE A.27. AVERAGE RECHARGE, 1946-1975, SUGARCANE AREA, SOUTHERN O'AHU

MONTH	TOTAL SUGARCANE AREA			NON-CAPROCK			CAPROCK		
	Depth (in.)	Vol. (mgd)	% Input	Depth (in.)	Vol. (mgd)	% Input	Depth (in.)	Vol. (mgd)	% Input
January	7.13	146.68	61.29	7.65	81.17	63.70	6.58	65.51	58.54
February	5.32	109.34	58.37	5.20	55.14	57.83	5.44	54.20	58.93
March	7.46	153.39	59.61	7.60	80.66	61.51	7.30	72.73	57.62
April	7.05	145.06	58.37	6.94	73.59	59.96	7.17	71.47	56.82
May	7.09	145.90	57.46	7.07	75.02	59.56	7.12	70.88	55.40
June	7.17	147.40	56.39	6.98	74.09	58.90	7.36	73.31	54.06
July	7.08	145.56	54.07	7.22	76.55	57.28	6.93	69.01	50.90
August	7.52	154.76	55.44	7.68	81.50	59.34	7.35	73.26	51.67
September	7.42	152.67	57.80	7.32	77.62	59.76	7.53	75.05	55.90
October	8.26	169.98	61.91	8.19	86.83	62.61	8.35	83.15	61.20
November	8.06	165.87	63.79	8.35	88.63	65.69	7.75	77.24	61.74
December	6.69	137.59	62.11	7.10	75.36	64.79	6.25	62.23	59.16
Annual	86.26	147.86	58.82	87.31	77.18	60.96	85.13	70.68	56.65
Area (mile^2)		35.51			18.31			17.20	

APPENDIX TABLE A.28. AVERAGE RECHARGE, 1946-1975, PEARL HARBOR-HONOLULU BASIN

MONTH	WHOLE BASIN Depth (in.)	WHOLE BASIN Vol. (mgd)	WHOLE BASIN % Input	NON-CAPROCK Depth (in.)	NON-CAPROCK Vol. (mgd)	NON-CAPROCK % Input	BASALT Depth (in.)	BASALT Vol. (mgd)	BASALT % Input	ALLUV.-COLLUV. Depth (in.)	ALLUV.-COLLUV. Vol. (mgd)	ALLUV.-COLLUV. % Input	CAPROCK Depth (in.)	CAPROCK Vol. (mgd)	CAPROCK % Input
January	4.60	585.88	52.07	5.26	471.13	54.89	5.39	446.23	55.55	3.63	24.90	45.32	3.03	114.75	43.00
February	3.12	398.22	49.03	3.64	326.06	50.80	3.75	310.43	51.58	2.28	15.62	39.10	1.90	72.16	42.34
March	4.20	535.06	51.29	4.92	440.35	53.36	5.09	421.02	54.18	2.82	19.33	40.20	2.50	94.71	43.46
April	3.37	429.33	49.04	3.92	350.93	50.18	4.08	337.16	51.07	2.01	13.77	35.14	2.07	78.40	44.52
May	2.70	343.79	46.13	3.02	270.19	46.41	3.15	260.59	47.35	1.40	9.60	30.11	1.94	73.60	45.14
June	2.11	268.50	43.57	2.16	193.46	42.32	2.26	186.67	43.22	0.99	6.79	26.83	1.98	75.04	47.19
July	2.75	351.14	45.44	3.14	281.29	46.07	3.29	271.84	47.13	1.38	9.46	27.97	1.84	69.85	43.04
August	2.71	345.40	45.87	3.03	271.20	46.29	3.18	262.66	47.38	1.25	8.53	27.14	1.96	74.21	44.38
September	2.05	260.89	41.53	2.07	185.16	39.97	2.16	178.93	40.91	0.91	6.23	24.08	2.00	75.73	45.93
October	3.06	389.79	47.84	3.36	300.79	48.18	3.49	288.57	49.07	1.78	12.23	33.81	2.35	89.00	46.72
November	4.38	558.93	52.04	5.08	454.83	54.06	5.24	433.57	54.88	3.10	21.26	41.48	2.75	104.10	44.72
December	4.13	526.96	52.30	4.90	439.22	54.72	5.04	416.67	55.45	3.29	22.55	44.08	2.31	87.74	42.82
Annual	39.17	416.12	48.63	44.48	332.01	49.85	46.10	317.82	50.70	24.85	14.19	36.30	26.62	84.11	44.35
Area ($mile^2$)		220.10			154.64			142.81			11.83			65.46	

APPENDIX TABLE A.29. ANNUAL RECHARGE, HONOLULU REGION

Year	Whole Basin (in.)	Whole Basin (mgd)	Non-Caprock (in.)	Non-Caprock (mgd)	Basalt (in.)	Basalt (mgd)	Alluv.-Colluv. (in.)	Alluv.-Colluv. (mgd)	Caprock (in.)	Caprock (mgd)
1946	23.49	61.36	35.53	53.23	37.77	45.12	26.70	8.11	7.30	8.14
1947	22.37	58.44	38.18	57.20	41.88	50.02	23.64	7.18	1.11	1.24
1948	32.45	84.78	51.08	76.52	54.93	65.61	35.93	10.91	7.41	8.26
1949	20.78	54.27	29.83	44.69	32.17	38.42	20.64	6.27	8.60	9.58
1950	33.82	88.35	51.48	77.12	55.77	66.62	34.59	10.51	10.07	11.22
1951	36.11	94.34	53.19	79.69	57.72	68.94	35.39	10.75	13.15	14.65
1952	21.21	55.40	34.92	52.31	37.88	45.24	23.28	7.07	2.77	3.09
1953	12.19	31.84	20.21	30.28	22.38	26.74	11.67	3.54	1.40	1.56
1954	31.95	83.47	49.77	74.56	53.14	63.48	36.49	11.08	7.99	8.91
1955	33.26	86.90	48.66	72.91	52.11	62.25	35.10	10.66	12.56	13.99
1956	27.87	72.81	43.52	65.21	47.58	56.83	27.59	8.38	6.82	7.60
1957	26.56	69.38	40.03	59.98	42.77	51.09	29.29	8.90	8.43	9.40
1958	26.94	70.38	40.07	60.04	42.71	51.01	29.71	9.02	9.28	10.34
1959	14.90	38.94	24.05	36.03	26.16	31.25	15.73	4.78	2.61	2.91
1960	22.92	59.88	37.99	56.92	41.13	49.13	25.66	7.80	2.66	2.96
1961	18.84	49.21	29.80	44.64	31.74	37.92	22.15	6.73	4.10	4.57
1962	14.94	39.03	24.11	36.12	26.32	31.44	15.41	4.68	2.61	2.91
1963	36.13	94.38	54.31	81.36	58.95	70.42	36.03	10.94	11.68	13.01
1964	30.11	78.66	48.65	72.89	52.77	63.04	32.45	9.86	5.18	5.77
1965	41.93	109.53	62.75	94.02	67.55	80.69	43.87	13.33	13.92	15.51
1966	24.50	63.99	36.52	54.72	39.00	46.59	26.76	8.13	8.32	9.27
1967	37.03	96.74	57.24	85.76	61.34	73.28	41.09	12.48	9.86	10.98
1968	33.13	86.54	49.04	73.48	52.81	63.09	34.23	10.40	11.72	13.06
1969	34.07	89.00	54.00	80.91	58.44	69.81	36.56	11.10	7.26	8.09
1970	28.66	74.88	46.36	69.46	50.09	59.83	31.68	9.62	4.87	5.42
1971	26.44	69.07	39.96	59.87	42.79	51.11	28.82	8.75	8.26	9.21
1972	22.25	58.13	32.68	48.97	35.16	42.00	22.95	6.97	8.22	9.16
1973	24.68	64.47	39.02	58.47	41.59	49.68	28.92	8.78	5.39	6.00
1974	35.36	92.38	55.39	82.99	59.51	71.09	39.18	11.90	8.43	9.39
1975	25.49	66.58	38.40	57.54	41.11	49.10	27.78	8.44	8.11	9.04

APPENDIX TABLE A.30. ANNUAL RECHARGE, PEARL HARBOR REGION

Year	Whole Basin		Non-Caprock		Basalt		Alluv.-Colluv.		Caprock	
	(in.)	(mgd)	(in.)	(mgd)	(in.)	(mgd)	(in.)	(mgd)	(in.)	(mgd)
1946	37.55	295.38	39.74	233.03	40.62	227.68	20.64	5.35	31.14	62.35
1947	36.33	285.76	38.02	222.96	39.17	219.54	13.18	3.42	31.36	62.80
1948	46.06	362.31	48.75	285.88	50.04	280.47	20.84	5.41	38.17	76.43
1949	41.51	316.56	41.21	241.65	41.98	235.26	24.63	6.39	42.40	84.91
1950	45.54	358.22	49.03	287.50	50.21	281.40	23.50	6.10	35.32	70.72
1951	53.12	417.85	57.77	338.79	58.82	329.65	35.25	9.15	39.48	79.06
1952	40.63	319.60	42.46	248.99	43.59	244.29	18.12	4.70	35.26	70.61
1953	32.37	254.64	32.00	187.64	32.65	182.97	18.00	4.67	33.46	67.00
1954	48.58	382.15	52.27	306.49	53.48	299.76	25.94	6.73	37.79	75.66
1955	50.26	395.38	54.17	317.67	55.20	309.39	31.90	8.28	38.81	77.72
1956	45.62	358.83	49.88	292.51	51.15	286.69	22.43	5.82	33.12	66.32
1957	46.02	362.03	48.55	284.71	49.43	277.02	29.64	7.69	38.62	77.33
1958	40.67	319.90	45.31	265.70	46.55	260.88	18.59	4.82	27.07	54.20
1959	32.58	256.31	33.13	194.29	33.86	189.76	17.47	4.53	30.97	62.02
1960	39.97	314.40	42.41	248.69	43.70	244.91	14.57	3.78	32.82	65.72
1961	37.27	293.16	38.64	226.61	39.76	222.83	14.55	3.78	33.24	66.56
1962	36.36	286.05	36.89	216.32	37.85	212.13	16.16	4.19	34.82	69.73
1963	53.32	419.41	58.18	341.16	59.61	334.06	27.33	7.09	39.08	78.25
1964	47.03	369.96	49.61	290.92	51.00	285.83	19.61	5.09	39.47	79.05
1965	57.34	451.03	61.75	362.11	63.22	354.30	30.09	7.81	44.41	88.92
1966	42.02	330.55	39.68	232.66	40.59	227.51	19.84	5.15	48.89	97.89
1967	49.86	392.23	54.68	320.65	56.19	314.93	22.05	5.72	35.75	71.58
1968	45.75	359.87	46.36	271.85	47.62	266.89	19.12	4.96	43.96	88.02
1969	45.11	354.84	47.25	277.06	48.72	273.08	15.34	3.98	38.84	77.78
1970	41.19	324.04	41.34	242.42	42.71	239.36	11.79	3.06	40.76	81.62
1971	45.33	365.59	44.95	263.61	46.36	259.83	14.58	3.78	46.43	92.97
1972	38.19	300.46	37.14	217.82	38.36	215.01	10.81	2.80	41.27	82.64
1973	33.77	265.68	32.57	190.98	33.89	189.92	4.06	1.05	37.30	74.70
1974	46.56	366.26	50.13	293.94	51.62	289.33	17.75	4.61	36.12	72.32
1975	34.99	275.22	35.22	206.51	36.34	203.66	10.98	2.85	34.31	68.71

APPENDIX TABLE A.31. ANNUAL RECHARGE, SUGARCANE AREA, SOUTHERN O'AHU

YEAR	TOTAL SUGARCANE AREA Depth (in.)	Vol. (mgd)	Area (mile^2)	NON-CAPROCK Depth (in.)	Vol. (mgd)	Area (mile^2)	CAPROCK Depth (in.)	Vol. (mgd)	Area (mile^2)
1946	66.70	122.73	38.65	61.10	62.90	21.62	73.80	59.83	17.03
1947	66.63	122.99	38.77	58.91	60.64	21.62	76.35	62.34	17.15
1948	74.08	140.86	39.94	62.76	68.09	22.79	89.12	72.77	17.15
1949	80.68	152.34	39.66	71.04	75.59	22.35	93.13	76.75	17.31
1950	75.10	141.81	39.66	73.54	78.26	22.35	77.11	63.55	17.31
1951	91.22	167.33	38.53	98.11	99.12	21.22	82.77	68.21	17.31
1952	94.24	153.53	34.22	105.00	84.53	16.91	83.72	69.00	17.31
1953	92.45	149.56	33.98	102.99	82.92	16.91	82.00	66.64	17.07
1954	96.05	155.39	33.98	106.85	86.03	16.91	85.35	69.37	17.07
1955	93.52	151.30	33.98	103.51	83.33	16.91	83.63	67.96	17.07
1956	85.81	139.22	34.08	98.41	79.70	17.01	73.25	59.53	17.07
1957	98.44	157.84	33.68	112.30	89.07	16.66	84.86	68.77	17.02
1958	72.68	116.02	33.53	86.54	68.02	16.51	59.24	48.00	17.02
1959	87.56	138.19	33.15	100.81	77.42	16.13	74.99	60.77	17.02
1960	93.36	146.06	32.86	107.14	81.00	15.88	80.48	65.06	16.98
1961	84.58	138.52	34.40	87.46	72.99	17.53	81.59	65.53	16.87
1962	88.84	146.14	34.55	92.81	78.65	17.80	84.62	67.48	16.75
1963	87.43	147.89	35.53	91.47	80.04	18.38	83.10	67.85	17.15
1964	93.38	159.08	35.78	96.98	83.71	18.13	89.69	75.37	17.65
1965	96.15	161.36	35.25	96.50	83.43	18.16	95.78	77.93	17.09
1966	96.25	159.60	34.83	79.00	66.87	17.78	114.23	92.73	17.05
1967	90.74	150.77	34.90	99.52	83.44	17.61	81.80	67.33	17.29
1968	88.08	155.49	37.08	83.29	77.45	19.53	93.41	78.05	17.55
1969	87.30	150.47	36.20	89.33	79.62	18.72	85.13	70.85	17.48
1970	92.33	157.10	35.74	89.03	77.66	18.32	95.79	79.45	17.42
1971	102.66	169.45	34.67	99.89	82.04	17.25	105.40	87.41	17.42
1972	90.82	149.91	34.67	86.64	71.15	17.25	94.96	78.76	17.42
1973	82.58	135.57	34.48	75.91	62.05	17.17	89.21	73.52	17.31
1974	75.72	124.30	34.48	70.03	57.24	17.17	81.37	67.06	17.31
1975	70.23	114.25	34.17	63.35	50.85	16.86	76.93	63.40	17.31

APPENDIX TABLE A.32. ANNUAL RECHARGE, PEARL HARBOR-HONOLULU BASIN

Year	Whole Basin		Non-Caprock		Basalt		Alluv.-Colluv.		Caprock	
	(in.)	(mgd)	(in.)	(mgd)	(in.)	(mgd)	(in.)	(mgd)	(in.)	(mgd)
1946	34.04	356.74	38.88	286.26	40.12	272.79	23.91	13.46	22.62	70.48
1947	32.85	344.20	38.05	280.16	39.65	269.56	18.82	10.60	20.55	64.04
1948	42.67	447.09	49.22	362.40	50.90	346.08	28.98	16.32	27.17	84.69
1949	36.34	380.83	38.89	286.34	40.25	273.68	22.48	12.66	30.32	94.49
1950	42.62	446.57	49.53	364.62	51.19	348.02	29.48	16.60	26.29	81.95
1951	48.88	512.19	56.84	418.48	58.62	398.59	35.33	19.90	30.07	93.71
1952	35.79	375.01	40.93	301.31	42.58	289.53	20.90	11.77	23.65	73.70
1953	27.34	286.48	29.60	217.92	30.84	209.71	14.59	8.22	22.00	68.56
1954	44.43	465.62	51.76	381.05	53.42	363.24	31.63	17.81	27.14	84.57
1955	46.02	482.28	53.05	390.57	54.66	371.63	33.63	18.94	29.43	91.71
1956	41.19	431.64	48.59	357.72	50.52	343.52	25.21	14.20	23.72	73.92
1957	41.17	431.41	46.82	344.69	48.26	328.10	29.45	16.59	27.83	86.72
1958	37.24	390.28	44.24	325.74	45.87	311.89	24.59	13.85	20.71	64.54
1959	28.18	295.25	31.28	230.32	32.51	221.01	16.53	9.31	20.83	64.93
1960	35.72	374.29	41.51	305.61	43.25	294.03	20.55	11.57	22.04	68.68
1961	32.67	342.38	36.84	271.25	38.35	260.75	18.65	10.50	22.82	71.12
1962	31.02	325.08	34.29	252.44	35.82	243.57	15.76	8.87	23.31	72.63
1963	49.03	513.78	57.39	422.52	59.49	404.48	32.02	18.04	29.28	91.26
1964	42.81	448.63	49.42	363.81	51.31	348.86	26.54	14.95	27.22	84.82
1965	53.49	560.56	61.95	456.13	63.98	435.00	37.52	21.13	33.51	104.43
1966	37.65	394.55	39.03	287.38	40.31	274.10	23.57	13.28	34.39	107.17
1967	46.66	488.97	55.20	406.41	57.10	388.21	32.32	18.20	26.49	82.56
1968	42.60	446.42	46.91	345.34	48.53	329.98	27.27	15.36	32.43	101.08
1969	42.36	443.85	48.62	357.97	50.43	342.89	26.78	15.09	27.55	85.87
1970	38.07	398.92	42.36	311.88	44.01	299.20	22.52	12.68	27.93	87.04
1971	40.62	425.66	43.94	323.48	45.73	310.94	22.26	12.54	32.79	102.18
1972	34.22	358.59	36.24	266.79	37.80	257.01	17.36	9.78	29.46	91.80
1973	31.51	330.15	33.88	249.45	35.24	239.61	17.47	9.84	25.89	80.70
1974	43.77	458.64	51.20	376.93	53.01	360.43	29.31	16.51	26.22	81.71
1975	32.62	341.80	35.87	264.05	37.18	252.77	20.04	11.29	24.95	77.74

APPENDIX B. OUTPUT DATA

The output data sets of monthly wb-zone precipitation, sugarcane irrigation, runoff, evapotranspiration, and groundwater recharge are stored on magnetic tape as follows:

TAPE NO.: X12863

PRECIPITATION

FILE NO. 1	DSN: ZONE.PRECIP.DATA BLKSIZE: 6600 RECFM: FB STANDARD LABEL	LRECL: 132 N OF BLOCKS: 171 DEN: 1600 BPI

IRRIGATION

FILE NO. 2	DSN: ZONE.IRR.DATA BLKSIZE: 6600 RECFM: FB STANDARD LABEL	LRECL: 132 N OF BLOCKS: 77 DEN: 1600 BPI

RUNOFF

FILE NO. 3	DSN: ZONE.RO.DATA BLKSIZE: 6600 RECFM: FB STANDARD LABEL	LRECL: 132 N OF BLOCKS: 171 DEN: 1600 BPI

EVAPOTRANSPIRATION

FILE NO. 4	DSN: ZONE.AE.DATA BLKSIZE: 6600 RECFM: FB STANDARD LABEL	LRECL: 132 N OF BLOCKS: 171 DEN: 1600 BPI

RECHARGE

FILE NO. 5	DSN: ZONE.RCHG.DATA BLKSIZE: 6600 RECFM: FB STANDARD LABEL	LRECL: 132 N OF BLOCKS: 171 DEN: 1600 BPI

READ FORMAT: (//,30(/,5X,13F8.2)

AVAILABILITY

Printouts and tape may be seen at the Water Resources Research Center Library:

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Honolulu, Hawaii 96822