Hydrology86

THE RECHARGE OF THE WAIKAPU AQUIFER, MAUI

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ABSTRACT

Recharge to the basal Waikapu aquifer consists of underground discharge from high-level aquifers and direct deep percolation to the Waikapu aquifer.

Water available for deep percolation to the high-level aquifers, and subsequent discharge from them to the basal aquifer is expressed in terms of gauged rainfall less evapotranspiration losses (net rainfall) minus surface-water discharge. While Iao gauged drainage basin has a surplus net rainfall over surface-water runoff (1.6 million gallons per day), Waikapu, South Waiehu, North Waiehu, and Waihee gauged drainage basins have deficits of net rainfall over surface-water discharge.

The deficits of net rainfall over surface-water discharge may be accounted for by augmentation of precipitation beyond the gauged amounts. Considering such augmentation to be a function of valley orientation relative to wind direction, and assuming there is only sufficient augmentation in Waikapu, South Waiehu, North Waiehu, and Waihee gauged drainage basins to balance the estimated deficits of water, then 30.7 million gallons per day may be available for deep percolation in the Iao gauged drainage basin.

Assuming that one half of the ground-water discharge from the Iao segment of the high-level aquifers is tributary to the Waikapu aquifer, then approximately 16.2 million gallons per day is recharged to the Waikapu aquifer from Iao Valley. In addition, precipitation over the high-level aquifers in areas between Iao and Waikapu valleys, as well as south of Waikapu Valley, none of which is tributary to

gauged drainage basins, is estimated to contribute between 0.2 and 0.5 million gallons per day to deep percolation, and subsequent discharge to the Waikapu aquifer. The total recharge to the Waikapu aquifer from the high-level aquifers is, then, estimated to be between 1.0 and 16.7 million gallons per day.

The sources of direct deep percolation to the Waikapu aquifer are: irrigation return water, precipitation over land surfaces directly tributary to the aquifer, and influent stream water.

Based upon varying evapotranspiration rates over a complete crop cycle for sugar cane, actual evapotranspiration losses are estimated to be 0.8 potential evapotranspiration in the irrigated cane areas. If pan evaporation rates represent an approximation of potential evapotranspiration, then between 14.0 and 16.1 million gallons per day is available for deep percolation to the Waikapu aquifer from irrigation. The range in the figures results from alternative assumptions that the long-term total irrigation supply to the cane fields overlying the aquifer is equal to the supply since 1955, including and excluding the water supplied from the Wailuku shaft. Precipitation over areas not planted to cane and directly tributary to the Waikapu aquifer from areas directly tributary is estimated to be between 14.2 and 16.1 million gallons per day. With the relatively low hydraulic conductivity for the lithified alluvium and small areas associated with the Iao and Waikapu stream valleys, the stream water influent available for direct deep percolation to the Waikapu aquifer is negligible.

The total recharge, then, to the basal Waikapu aquifer is estimated to be between 15.2 and 32.8 million gallons per day.

The only measured discharge from the basal ground water aquifer is exerted through draft by the Wailuku shaft and this discharges 4.4 million gallons per day (computed from the mean annual draft between 1955 and 1967). Consequently, the net mean daily recharge to the Waikapu aquifer ranges between 10.8 and 28.4 million gallons per day.

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INTRODUCTION

General

The island of Maui is the second largest island in the northwest-southeast-trending Hawaiian volcanic chain. Maui was built by two distinct volcanic cones: the West Maui Mountains, and Haleakala, to the east. Lavas from Haleakala lapped against the already existing West Maui Mountains, building a saddle known as the Isthmus.

The land area of Maui is 728 square miles. Its 1966 population was 38,316 (Mark, 1967). The principal land use on Maui is agricultural: the principal crops are sugar cane and pineapple. In addition, large areas are utilized for ranching and sizeable areas are presently being developed to meet the demands of the growing tourist industry.

The eastern slope of the West Maui Mountains serves as the source for essentially all the water used for irrigation on the Wailuku Sugar Company plantation, located at the base of the eastern slope of the West Maui Mountains. In addition, domestic water supplies for Wailuku, Waihee, Waiehu, Waikapu, Maalaea, Kahului and Kihei originate on the eastern slope of West Maui. The water supply is derived from both surface and ground-water sources.

The ground-water resources of the eastern slope of West Maui consist mainly of two distinct units: high-level dike water and basal ground water. The ground-water development along the eastern slope of West Maui is mainly from the basal ground water, although there are small drafts on high-level ground water from dike tunnels.

The basal ground-water system associated with the eastern slope of West Maui may be divided into northern and southern units. The southern unit, extending from Iao Valley to Maalaea, comprises the Waikapu aquifer, whose recharge is the principal subject of this report. The northern unit extends from Iao Valley to Waihee Valley and may be termed the Waiehu aquifer. Like most Hawaiian basal ground-water bodies, the Waikapu and Waiehu ground-water bodies are considered to be fresh water lenses floating on top of salt water in accordance with the Herzberg principle (Palmer, 1957).

Figure 1 shows the location of the area under consideration and the approximate boundaries of the Waikapu aquifer, as well as the high-level aquifers.

Water Development

Ground water is developed on the eastern slope of West Maui by two basal water wells and a dike tunnel. Domestic water supplies are developed by the Maui County Board of Water Supply from the Iao Tunnel and Mokuhau well battery and irrigation water is drawn from the Wailuku shaft by Wailuku Sugar Company.

The Iao Tunnel, in Iao Valley, (constructed by Wailuku Sugar Company and Maui County Board of Water Supply) draws water from dike compartments associated with 159 intersected dikes beneath Kahookewa Ridge. The discharge from the tunnel reached a peak of 7.5 million gallons per day in 1945, but decreased asymptotically to a constant discharge of 2.3 million gallons per day.

The Mokuhau well battery, located northwest of Wailuku, consists of three drilled wells. These wells are drilled into the Waiehu basal ground-water aquifer, north of Iao Valley, and are equipped with pumps having a combined capacity 14 million gallons per day. Ordinarily, only one or two of the wells are pumped at any time, with the remaining

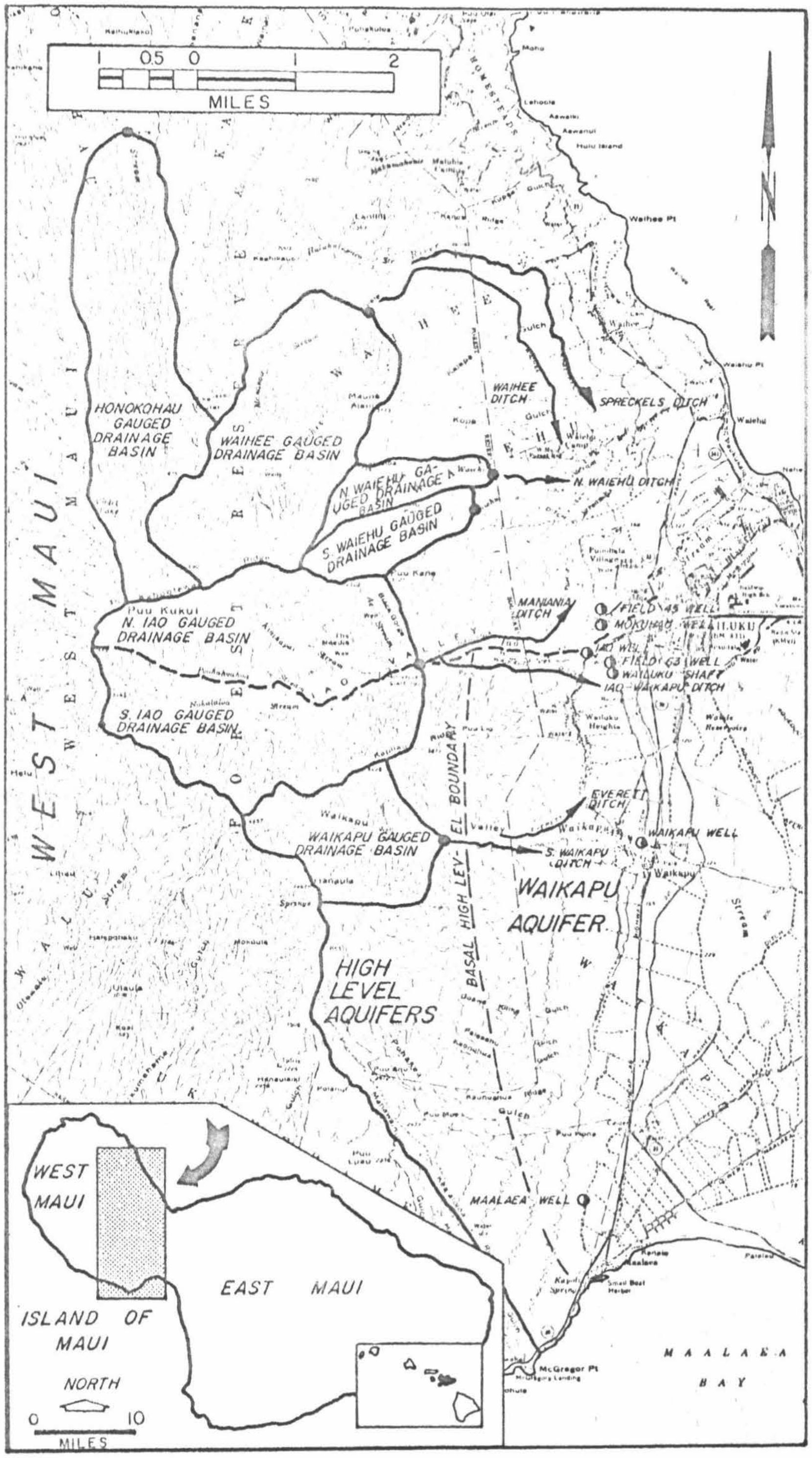

Figure 1. Area of investigation.

wells kept ready for emergency reserves. The mean daily discharge from the Mokuhau wells is less than 5 million gallons per day.

The Wailuku shaft, located southwest of Wailuku, develops water from the Waikapu basal ground-water aquifer. The shaft was originally designed as a skimming Maui-type well, but the design was changed when the inclined shaft reached a level 30 feet above sea level. A large chamber was excavated at the base of the inclined shaft and from it three wells were drilled into the basal water aquifer.

The present pump capacity of the Wailuku shaft is 15 million gallons per day, but Wailuku Sugar Company has recently funded a proposed increase in the capacity to 22 million gallons per day. The shaft is pumped only to satisfy irrigation demands, and the mean daily discharge is less than 5 million gallons per day.

Water levels in the Waikapu aquifer have been lowered from ± 30 feet to ± 15 feet above msl during periods of extensive pumpage, but present water level measurements indicate that the basal water has essentially recovered its static water level. So far no increase in salinity has resulted from the basal water development. However, increases in pumpage from the basal Waikapu aquifer might exceed the recharge to the aquifer and/or have detrimental effects on water quality.

Purpose of this Study

This study has been made in connection with a Water Resources Research Center project concerned with a complete evaluation of the high-level and basal ground water units associated with the eastern slope of West Maui through application of all available geohydrologic methods.

It is the scope and purpose of this study to investigate the water resources of the Waikapu aquifer, and tributary high-level aquifers, to delineate the factors comprising the hydrologic mass balance equation and to evaluate the elements of recharge to the Waikapu aquifer as one approach to the estimation of its potential yield.

Previous Work

The first Hawaiian well outside of Oahu was drilled near Waikapu for W. H. Cornwell about 1881 (McCandless, 1936). No water was found and no log or other information on this well seems to have been preserved. Much early information on the hydrogeology was developed by sugar industry engineers and particularly by the sugar industry geologist, W. O. Clark, who guided ground-water development in the area from the 1920's until 1946. Much of the basis for later published information may be found in Clark's manuscript reports filed at the Experiment Station, Hawaiian Sugar Planters' Association.

A comprehensive study of the geology of Maui was reported by Stearns and Macdonald (1942). The geologic units and the major hydrogeologic concepts referred to in this study were identified in their report. Details of the basal hydrogeology in the vicinity of Iao Valley were reported to the Maui County Board of Water Supply by Cox (1951), and reviewed by Herschler and Randolph (1962).

The only estimate of a water budget for the eastern slope of West Maui was submitted to the Maui County Board of Water Supply by the Hawaii State Division of Water and Land Development (Chuck, 1965).

Geology

The bulk of the West Maui Mountains is comprised predominantly of the Wailuku Volcanic Series basalts, consisting mainly of thin pahoehoe and aa lava flows. These lava flows originate from sub-parallel fissures, which are concentrated in rift zones extending southwestward and northward from the summit. The flows dip in all directions away from the central part of the mountain. Average dips are slightly greater than 15 degrees, but the dips along portions of the eastern slope of West Maui approach 30°. After the main building stages of the West Maui Mountains, collapse of the shield summit formed a caldera in the vicinity of the present head of Iao Valley.

Much of the shield of Wailuku Volcanic Series basalts, but not its eastern slope, was capped by a later series of flows of oligoclase andesite and trachyte named the Honolua Volcanic Series.

Post-dating the Honolua Volcanic Series, stream erosion controlled by a base level much lower than the present sea level resulted in deeply incised stream valleys (Cox, 1951). Following a relative rise in base level and the building of the Haleakala shield, stream downcutting terminated and a period of deposition was initiated. The period of deposition resulted in large alluvial fans that filled the previously incised valleys and, in general, mantled the eastern slope of West Maui from sea level to the present 1000 foot elevation. The fans consist of fanglomerates composed of poorly sorted materials, ranging from room-sized boulders to clay-sized particles, and are most abundant on the eastern slope of West Maui.

The growth of Haleakala continued during the deposition of the West Maui alluvium. Contemporaneous with the ponding of Haleakala lavas against the West Maui shield, alluvium from West Maui sources was lapped against the western slope of Haleakala. These concurrent geologic processes resulted in the interbedding of Haleakala lavas, probably of the Honomanu and Kula Volcanic Series, with the alluvium.

After the formation of the fans, a few scattered eruptions formed flows and cones of picrite basalt and nepheline basanite, comprising the Lahaina Volcanic Series. The Lahaina Volcanic Series is confined principally to the western portion of West Maui, and are therefore of no major concern along the eastern slope of West Maui.

HYDROGEOLOGY

The hydrogeologic environment on the eastern slope of West Maui involves the thin-layered Wailuku basalts, the Honolua trachytes and andesites, feeder dikes associated with both series, partially lithified older Pleistocene alluvium and younger alluvium confined to the stream valleys. Figure 2 shows the distribution of the various rock units on Maui.

The Wailuku basalts, on the whole, form very good aquifers. The lateral hydraulic conductivity parallel to the flows is a result of clinker zones, lava tubes, interfaces between successive flows, and interconnected pores. The hydraulic conductivity normal to the flows is mainly dependent upon the jointing in the lavas, and the juxtaposition of clinker zones in adjacent flows.

The Honolua andesites and trachytes are generally less permeable than the Wailuku basalts. The feeder dikes associated with the Wailuku, Lahaina and Honolua Volcanic Series have hydraulic conductivities that are probably several orders of magnitude less than the Wailuku basalts. The lithified Pleistocene alluvium is relatively impervious with a hydraulic conductivity probably 2 or 3 orders of magnitude less than the Wailuku basalts.

The volcanics of the Honolua Volcanic Series have been almost stripped from the West Maui Mountains by incised stream valleys, but where they remain, on the intra-valley ridges principally on the northern side of West Maui, they greatly retard the infiltration of water and constitute poor aquifer material. For some reason the Honolua Volcanic Series did not mantle the eastern slope of West Maui

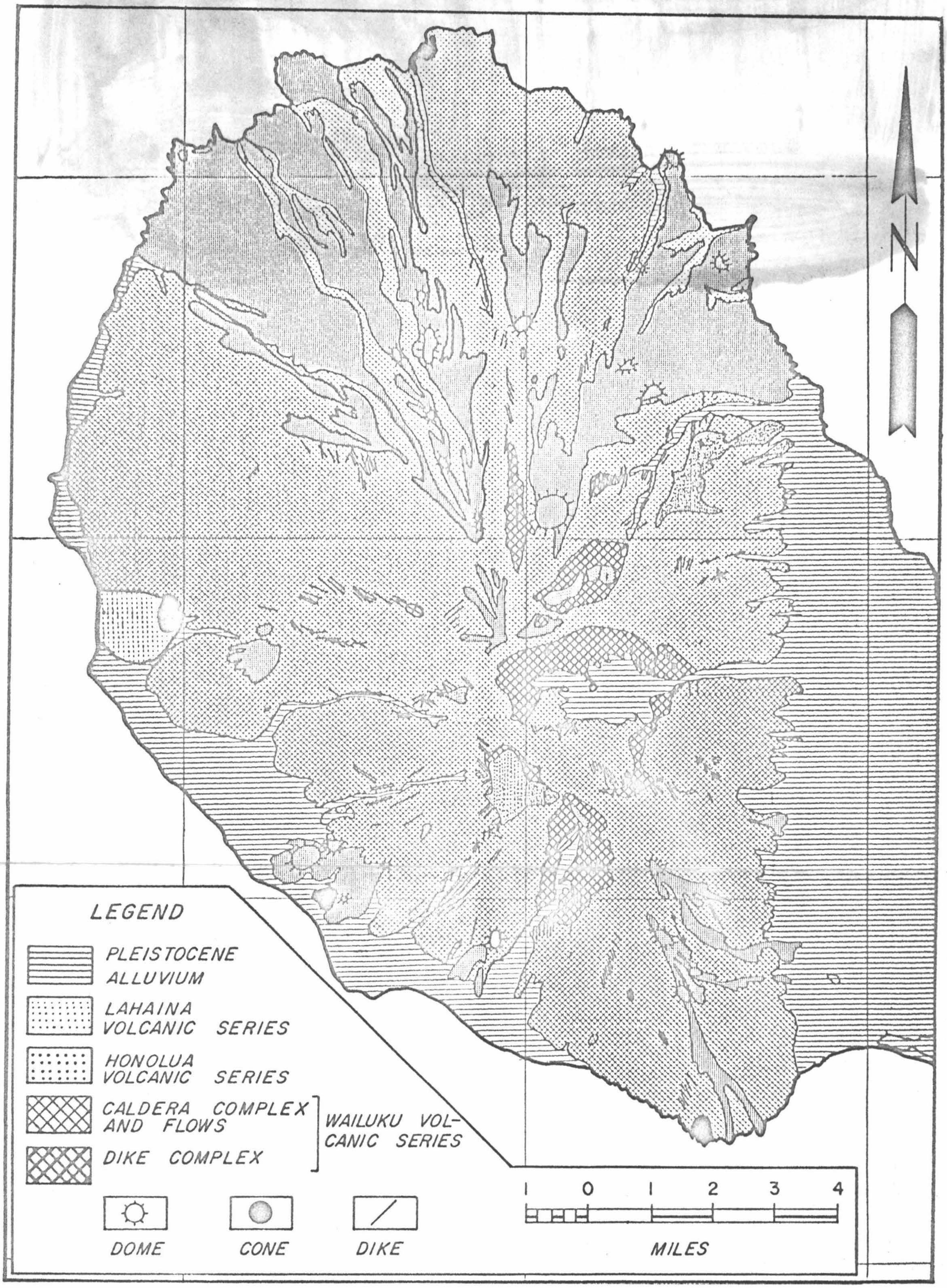

Figure 2. Geologic map of West Maui.

between Waihee and Maalaea, and therefore plays no role in the infiltration of water and transfer of ground water along the eastern slope.

The dikes are responsible for maintaining high-level water within the West Maui Mountain. The dikes are extremely impervious to ground-water flow, and impede the down gradient migration of ground water.

The lithified Pleistocene alluvium, due to its poor sorting, forms a relatively impervious barrier to ground-water flow. Not only does this alluvium impede the downward percolation of water, but it also serves as a north-south trending barrier to eastward discharge of basal ground water from the Waikapu and Waiehu aquifers.

Analysis of the water resources of the eastern slope of West Maui is best carried out recognizing that the ground water system is divided into two distinct units: high-level and basal. The high-level, dike-confined aquifers have an entirely different hydrogeologic and hydraulic environment from the basal Waikapu and Waiehu aquifers. The two units are connected by ground-water transfer from the high-level aquifers to the basal aquifers.

In detail, the hydraulic pattern in the dike zone of the West Maui Mountains must be extremely complicated. In general, the hydraulic conductivity of the dikes is essentially negligible compared to the hydraulic conductivity of the lava flows which they intrude. The dikes therefore form the boundaries of a complex of aquifer compartments. Because of the sub-parallel distribution of the dikes, these compartments are generally tabular, being much thinner in a horizontal direction normal to the locally prevailing dike strike than either vertically or in the horizontal parallel to the prevailing strike. Discharge from any compartment may occur by springs discharging to the surface, by leakage through local discontinuities of a dike or leaky zones in a dike, by ground-water overflow of a dike not reaching the land surface, or by flow around the ends of dikes not intersected by other dikes.

The area of the high-level, dike-compartment aquifers is coincident with the roughly north-south trending West Maui rift zones. Water within the dike aquifers in regions near the northern and southern coasts of West Maui issues along the predominant north-south dike trend to the ocean. High-level water not tributary to the coasts is either discharged to the land surface through springs at dike outcrops or overflows the dikes underground. Leakage through the dikes is, in general, probably insignificant as indicated by the results of the Iao Tunnel. This tunnel penetrated dike compartments several tens, and perhaps hundreds, of feet below the original water tables, and hence reduced greatly the head differentials across many dikes. If there had been much natural leakage through the dikes, the lowering of heads would have materially reduced the rate of leakage and resulted in a tunnel discharge much greater than the original spring discharge in the area. After the storage had been reduced by the tunnel, however, the tunnel discharge was no greater than the original spring discharge (Cox, 1968, per. com.). The flow components normal to the predominant dike trend resulting from spring discharge augmented by any underground overflow must result in the existence of a major north-south trending ground-water divide paralleling and roughly coinciding with the major north-south topographic divide of the West Maui Mountains. For reasons to be explained later, only that part of the high-level aquifers south of the axis of Iao

Valley is under consideration in this study, and therefore the western boundary of the high-level aquifers of interest may be defined by the Kealaloloa Ridge. The eastern boundary of the high-level aquifer system is a poorly defined line running north-south and corresponding to the easternmost dike exposures on the eastern slope of West Maui. By definition, the ground-water system to the west of this boundary is high level while the ground-water system to the east of this boundary is basal.

Water levels measured at the Field 45 test well, Mokuhau wells, MCBWS test well EX-1, Iao well, Field 63 well, Wailuku shaft, Waikapu well, and Maalaea well give evidence by which to define the basal ground-water situation within the Waikapu and Waiehu aquifers. The water level north of Iao Valley is about 25 feet above msl as measured in the Mokuhau wells and slopes slightly (downward) to the north as measured in the Field 45 test well. Directly to the south of Iao Valley the water level is about 30 feet above msl at Iao test well. The water table slopes downward to the south from the Iao well as established by measurements at the Field 63 well and Wailuku shaft. The water level to the south, if projected to Waikapu does not correspond with the measured head in the Waikapu well. Instead the Waikapu well shows a head of about 16 feet above msl, much less than the head projected from the Iao well, Field 63 well and Wailuku shaft. Further south the water table at the Maalaea well is about 3 feet above msl.

The difference in water levels between the Iao and Mokuhau wells indicates a discontinuity between the basal ground-water systems north and south of Iao Valley. To explain the differential water levels north and south of both Iao and Waikapu valleys, there must be some geologic phenomena hampering the transfer of basal-ground water across the valleys. The original valleys cut in bedrock to a base level far below the present sea level are filled with alluvial materials much less permeable than the Wailuku basalts, and therefore act as inverted weirs partially penetrating the aquifer. The presence of these inverted weirs retards the transfer of basal ground water to the north of Iao Valley and southward below Waikapu Valley, resulting in the difference of measured heads. A discontinuity is further indicated because of the fact that short-term pumpage effects are not felt on opposite sides of Iao Valley. These criteria suggest a separation of the Waikapu and Waiehu aquifers, although not an absolute separation (Cox, 1951). Because of this, it is desirable to deal with the Waikapu and Waiehu basal aquifers as separate entities, with Iao Valley serving as the boundary between them.

The Waikapu inverted weir might well act as a barrier as does the Iao inverted weir, however, the water levels south of Iao Valley indicate a major southerly component to the hydraulic gradient. This indicates that the major discharge of ground water is to the south, flowing under the Waikapu inverted weir, and eventually into Maalaea Bay. The coast line at Maalaea, then, constitutes the southern boundary of the Waikapu aquifer.

Considering the relatively low expected hydraulic conductivity for the Pleistocene alluvium which overlies the eastward dipping flows of the Wailuku Volcanic Series which constitutes the Waikapu and Waiehu aquifers, the discharge eastward from the basal lens systems must be relatively small. The intersection between the basal lens within the Wailuku basalts and the confining Pleistocene alluvium forms the eastern boundary of the Waikapu-Waiehu basal water systems. If the mean sea level contour on the alluvium-bedrock contact is projected to the land surface, a line essentially coinciding to the Hononapiilani Highway is traced. For all practical purposes this line may be considered the eastern boundary of the Waikapu aquifer.

Figures 3a and 3b give one interpretation to the hydrogeologic environment in east-west and north-south sections respectively.

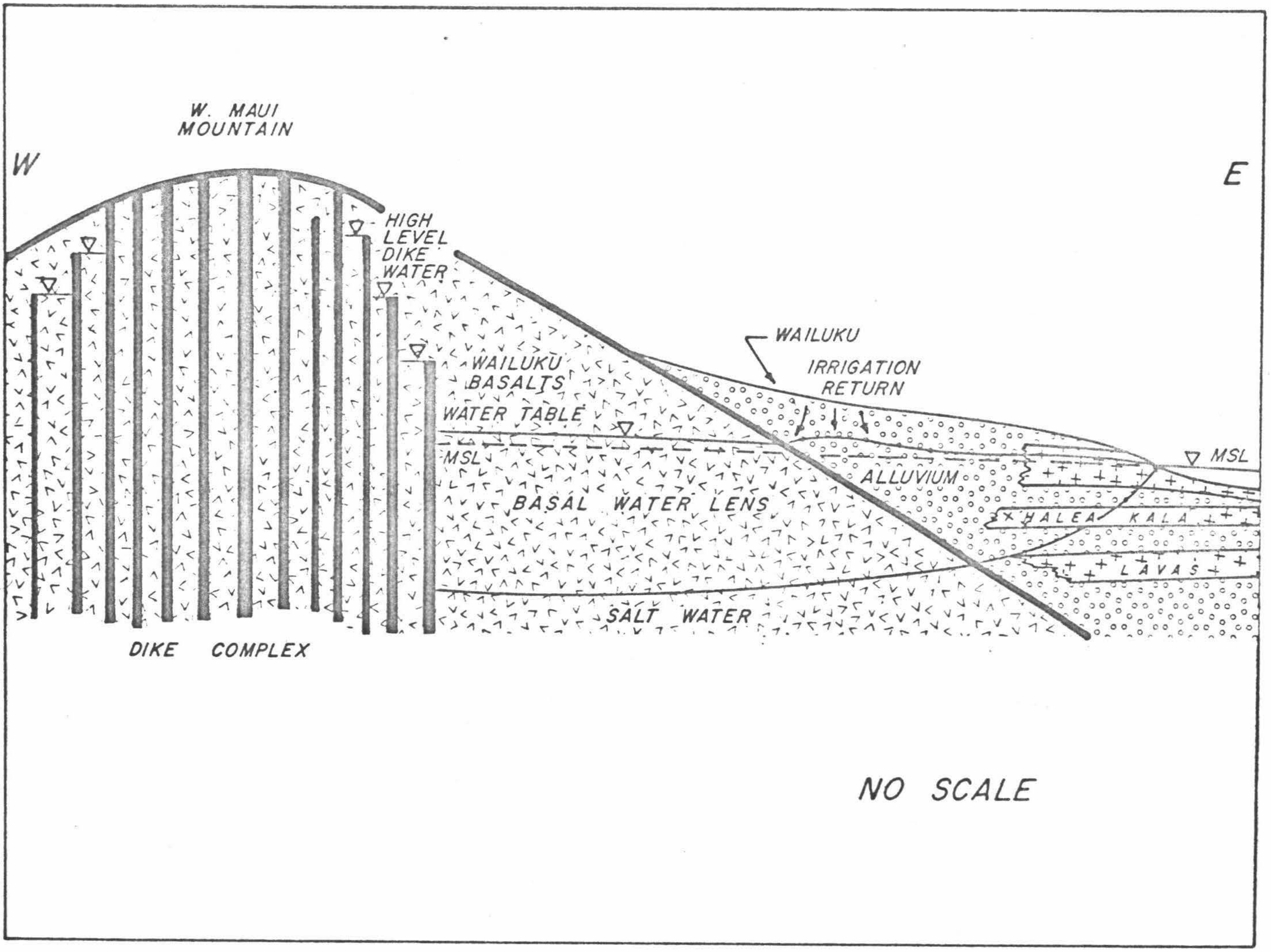

Figure 3a. Idealized east-west section of the high-level and basal aquifers of the eastern slope of West Maui.

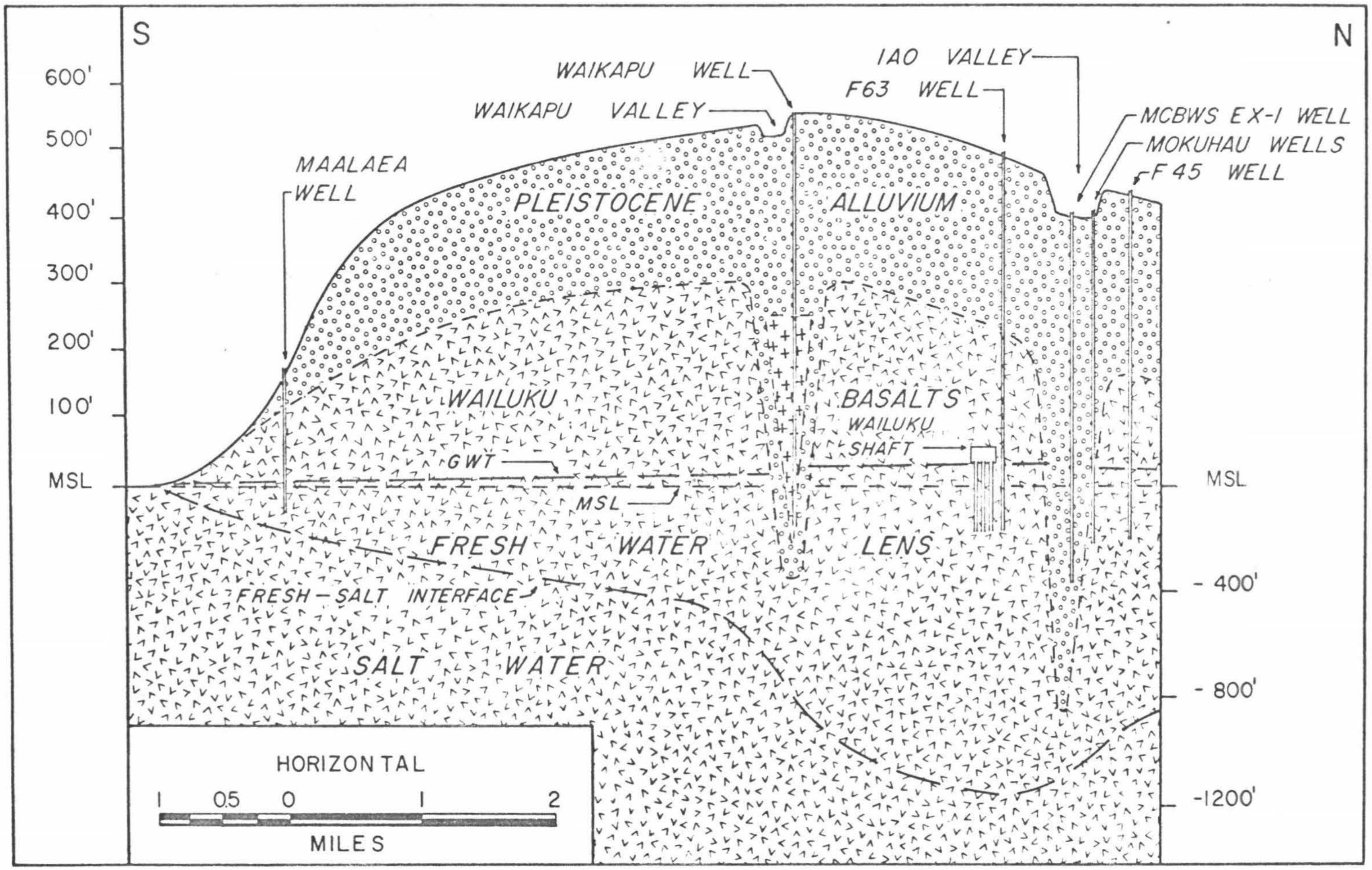

Figure 3b. Idealized north-south section of the basal Waikapu aquifer.

GENERAL ASPECTS OF THE HYDROLOGIC MASS BALANCE

Figure 4 represents idealized schematic diagrams of the hydrologic mass-balance elements for the high-level aquifers and the Waikapu aquifer.

Recharge to the high-level aquifers is represented entirely by precipitation available for deep percolation, i.e. precipitation minus evapotranspiration and overland flow. The debits to the system include spring discharge, ground-water discharge and draft.

In the problem at hand, the important unknown that must be quantified in the high-level aquifers is the ground-water discharge to the basal aquifer and specifically to the Waikapu aquifer. Evapotranspiration is relatively small over the dike compartments, but it must still be estimated. Draft is exerted essentially by tunnels and springs that issue back into surface-water streams. The one exception to this is the Iao Tunnel which furnishes high-level domestic water to Wailuku and Waikapu. However, the stream discharges under consideration in the hydrologic mass balance are dependent upon flow rates established prior to the development of the Iao Tunnel. As a result, the hydrologic mass balance equation may be represented by the following:

$$I_h = O_h + \Delta_h$$

where I_h = inflow into the high-level aquifer system, O_h = outflow from the high-level aquifers, and Δ_h = net changes in storage. Considering the hydrologic mass balance over long periods of time (decades), $\Delta_h = 0$, and I_h and O_h may be defined as:

$$I_h = P_h - E_h - S_{oh} \text{ and}$$

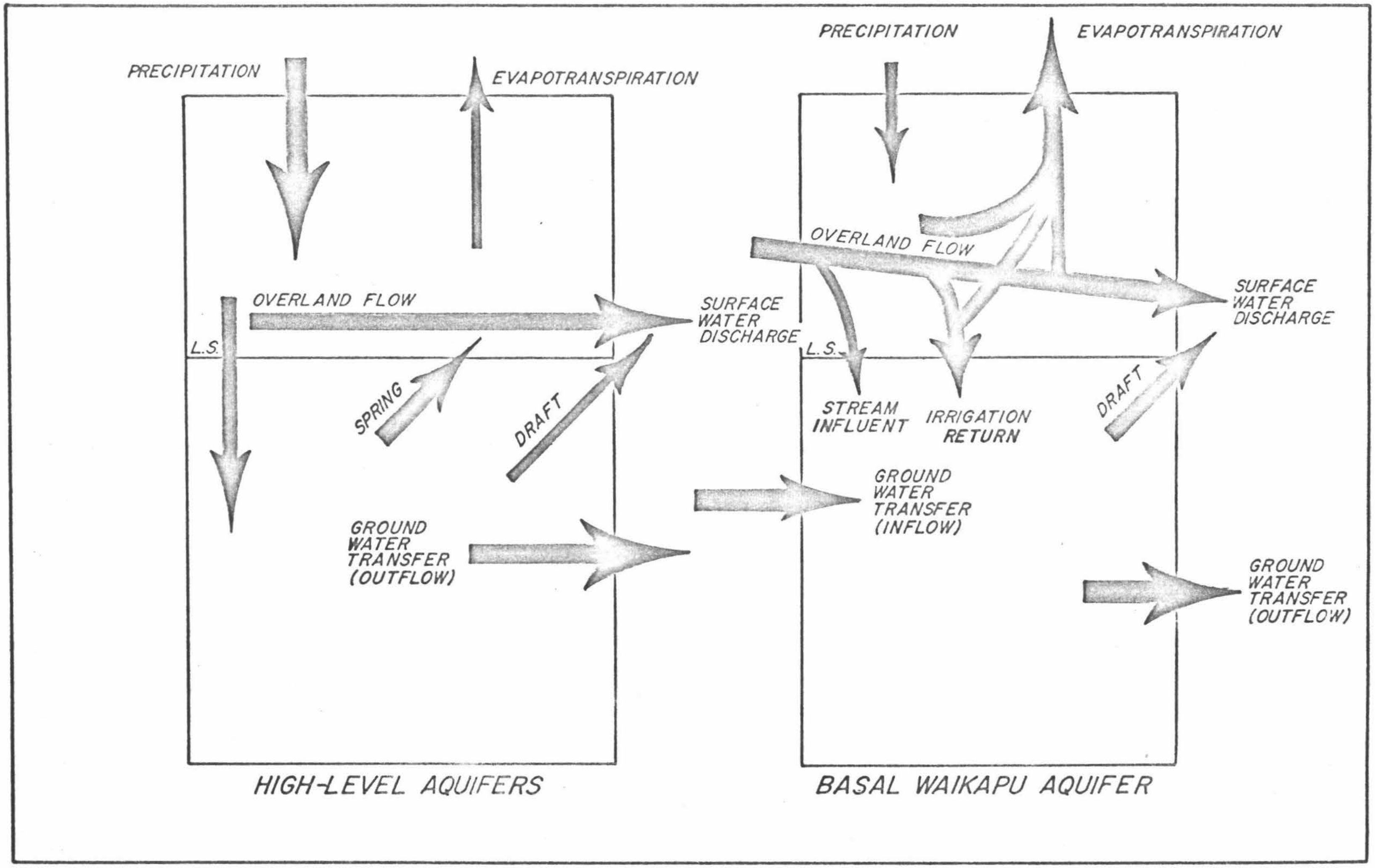

Figure 4. Schematic diagrams showing the hydrologic mass balance units for the high-level aquifers and the basal Waikapu aquifer.

$$O_h = S_{sh} + D_h + G_h$$

where P_h = precipitation over the high-level aquifers, E_h = evapotranspiration over the high-level aquifers, S_{oh} = overland flow from the high-level aquifer system, S_{sh} = spring discharge from the dike compartments, D_h = draft on the high-level aquifers, and G_h = ground water discharge from the high-level aquifers. Since prior to the Iao Tunnel construction, $D_h = 0$, the recharge to the basal aquifers (G_h) is defined as:

$$G_h = P_h - E_h - S_h$$

where $S_h = S_{oh} + S_{sh}$ = total surface discharge.

The terms comprising the hydrologic mass balance for the basal Waikapu aquifer are more numerous than for the dike compartment aquifers. Inflow to the Waikapu aquifer includes deep percolation from precipitation, deep percolation from imported irrigation water, groundwater inflow from the dike complex to the west, and influent seepage from Iao and Waikapu streams. The latter is assumed to be negligible. Outflow from the basal aquifer is represented by draft, ground-water discharge north under Iao Valley to the Waiehu aquifer, south to the ocean, and east through the overlying lithified Pleistocene alluvium to the Haleakala lava aquifers.

The hydrologic mass balance equation for the basal Waikapu aquifer may be represented by the following expression:

$$I_b = O_b + \Delta_b$$

where I_b = inflow into the basal aquifer system (in particular the Waikapu aquifer), O_b = outflow from the basal aquifer, and Δ_b = change in net storage within the aquifer. Considering the hydrologic mass balance over long periods of time (decades), $\Delta_b = 0$, and the remaining elements may be defined as:

$$I_b = G_h + P_b + I_r - E_b \text{ and}$$

$$O_b = G_b + D_b$$

where P_b = precipitation over areas directly tributary to the basal aquifer, I_r = irrigation return water available for deep percolation into the basal aquifer, E_b = evapotranspiration over the basal aquifer, G_b = ground water discharge from the basal aquifer, and D_b = draft upon the basal aquifer. Solving the above equations for G_b:

$$G_b = G_h + P_b + I_r - E_b - D_b$$

The right hand side of this equation represents the net recharge to the Waikapu aquifer and its elements will be quantified in this study.

PRECIPITATION

The predominant feature of air circulation across the tropical Pacific is the trade-wind flow in a general east to west direction. The trade winds of the north Pacific originate in the northeast quadrant of the ocean, flow south-southwestward off the western coast of the North American Continent, and pass southwesterly through Hawaiian latitudes. The zone of northeasterly trade winds moves north and south with the sun in such a manner that between May and September, the central part of the trade-wind zone crosses the eight major Hawaiian Islands. Between October and April, with the sun in a more southerly position, the heart of the trade-wind zone passes to the south of the Hawaiian Islands. According to Blumenstock (1961) the seasons in Hawaii are distinguishable by the degree of predominance of the trade-wind weather, which occurs 80 to 95 percent of the time during the summer months (May through September) and 54 to 69 percent of the time during the winter months (October through April).

The trade winds are accompanied by a well-defined moisture discontinuity between 4,000 and 8,000 feet above mean sea level. This discontinuity is associated with a temperature inversion occuring usually between 5,000 and 7,000 feet altitude. Instead of the temperature decreasing with elevation, in the inversion zone the temperature increases upward and reaches the upper limit for cloud formation from moisture associated with trade winds. Few clouds are able to extend above this inversion layer; consequently, precipitation from trade wind clouds is negligible above the 7,000-foot altitude.

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In addition to the trade-wind precipitation, the Hawaiian Islands receive rainfall attributed to local land-and-sea air circulations and large-scale air circulations associated with major storm systems. The land-and-sea exchange of air is confined to small areas from only a few square miles to at most tens of square miles. These circulation systems are confined to southerly or westerly coastal areas in locations that are in the lee, with reference to the trade winds, of the larger mountains and therefore they are not of importance along the eastern slope of West Maui.

The frequency of major storms (non-trade-wind weather) is greatest between October and March. These storms may be associated with the passage of cold fronts moving from west to east or from northwest to southeast. Also, the storms may be associated with large eddies, or lows, that may be generated in the moving air.

Because land-and-sea air circulations are not of importance along the eastern slope of West Maui, the total precipitation may be discussed in terms of storm and trade-wind precipitation.

The rainfall distribution associated with trade-wind rainfall, as well as storm rainfall, contains an orographic effect. However, the orographic effect associated with the storm rainfall is minimal as compared to the orographic effect as associated with the trade-wind rainfall. Mink (1962) and Leopold (1949) have shown the overall rainfall distribution on both windward and leeward slopes to increase logarithmically with elevation.

As a first approach to the evaluation of precipitation over the eastern slope of West Maui, rainfall data from 25 rain gauge stations (Table 1) are utilized in the construction of an isohyetal map (Plate

TABLE 1. RAIN GAUGE STATIONS UTILIZED.

Station number	Station name	Years of record	Mean annual rainfall (in)
307	Reservoir 9	1930-1950	19.23
387	Hopoi Reservoir	1933-1966	28.14
387.1	Iao Valley	1950-1966	67.78
390.1	Reservoir 1	1950-1966	35.30
391	Hayashi	1933-1966	21.63
386	Wailuku Office	1954-1966	26.79
477	Haelaau	1931-1960	136.76
480	Honokohau	1949-1967	134.43
476	Honokowai	1931-1960	108.78
374	Kahoma Intake	1931-1960	103.25
375	Kauaula	1931-1960	45.69
380	Puu Kukui (Kukui)	1928-1967	400.92
377	Olowalu Gulch	1931-1960	65.07
307.2	Pohakea Bridge	1953-1960	16.69
483	Waihee	1931-1960	32.06
482	Waihee Valley	1931-1960	42.45
481.3	Eke	1913-1933	±260.00
390	Waikapu	1931-1960	31.53
301	Ukumehame	1931-1960	13.34
310	Maalaea	1931-1960	13.51
472	Puu Kukui (Makai)	1931-1960	96.39
392	Wailuku	1931-1960	28.85
484	Waiehu Village	1931-1960	34.70
481.2	Puu Kukui (upper)2	1911-1923	±370.00
481.1	Puu Kukui (upper)1	1923-1939	±270.00

1, appendix). Isohyets at logarithmic intervals were drawn freehand. This procedure has resulted in a set of roughly concentric, more or less equally spaced contours representing the rainfall distribution. Estimates for the rainfall contributed to the land surface were established through the application of a planimeter to measure areas between isohyets. Tables 2 and 3 represent the results of multiplying the area for each interval by the logarithmic mean rainfall for that interval.

Several factors suggest that the gauged precipitation over the eastern slope of West Maui represents only a conservative approximation of the actual precipitation. These include: the probable underregistration of rainfall at the Kukui rain gauge, on which the estimation of the rainfall throughout the high-rainfall area critically depends; the possible non-representativeness of the Kukui rain gauge site; and the addition of cloud droplet interception to the rainfall.

The Puu Kukui (Kukui) rain station is located at the head of Iao Valley at an elevation of 5788 feet. Winds blowing up the Iao Valley corridor attain high velocities as they are channeled over the head of Iao Valley. As a result, the vertical component of raindrop trajectories over the Puu Kukui rain station may, at times, be diverted upward, and many drops may not be caught in a conventional rain gauge such as Kukui. Hence, the rainfall data for Puu Kukui rain gauge probably represents a mean precipitation somewhat less than the actual and, as will be shown, perhaps substantially less than the actual.

If it were possible to estimate the amount by which the actual rainfall at the Kukui gauge exceeded the gauge catch, it would still

TABLE 2. RAINFALL WITHIN GAUGED DRAINAGE BASINS.

Drainage Basin	Waikapu area (mi^2)	Iao area (mi^2)	South Waiehu (mi^2)	North Waiehu (mi^2)	Waihee area (mi^2)	Honokohau area (mi^2)
Isohyet interval (mean annual) (in)						
382+		0.08				0.18
382-306		0.31			0.25	0.58
306-244		0.88			0.68	1.08
244-195		1.17			0.88	0.90
195-156		1.04	0.02	0.07	1.02	1.13
156-125	0.21	0.96	0.21	0.23	0.87	0.23
125-100	0.40	0.84	0.27	0.21	0.49	
100-80	0.60	0.63	0.23	0.17	0.01	
80-64	0.65	0.11	0.05	0.07		
64-51	0.50					
51-41	0.34					
Total area	2.70	6.02	0.78	0.75	4.20	4.10
Total rainfall (mgy)x10^3	3.80	19.21	1.52	1.53	14.21	17.15
Total rainfall (mgd)	10.41	52.63	4.16	4.20	38.92	46.98

TABLE 3. RAINFALL OUTSIDE GAUGED DRAINAGE BASINS SOUTH OF IAO STREAM.

Isohyet interval (mean annual) (in)	Area (mi^2)	Rainfall (mgy)x10^3
100-80	0.04	0.06
80-64	0.40	0.49
64-51	1.23	1.19
51-41	1.63	1.28
41-33	2.90	1.89
33-26	4.06	2.05
26-21	1.66	0.67
21-17	1.51	0.49
17-14	1.30	0.35
less than 14	1.44	0.32
Totals	16.16	8.78
Mean daily rainfall (mgd)		24.05

be questionable whether the Kukui gauge site is representative of the high rainfall area or whether there were differences in rainfall related to topographic exposure. Over the ridges there are much smaller depths of cloud cover contributing to rainfall, and considerable differences in rainfall rates and rainfall patterns may be expected depending on whether a valley opens in the direction from which the prevailing wind blows, in the opposite direction, or in a direction transverse to the prevailing wind.

In addition, above the cloud base level of approximately 2,500 feet in elevation an appreciable quantity of precipitation is contributed to any given land surface by cloud croplet interception. Work carried out on Lanaihale, Hawaii, by Ekern (1964) shows that a Norfork Island pine tree and a wire harp resulted in increases of 30 and 15-20 inches respectively of additional precipitation over the gauged mean annual precipitation of 149 inches. Ekern (1968, per. com.) suggested, in addition, that it is not inconceivable for increases of precipitation to approach 100 inches per year in high rainfall areas such as over the West Maui Mountains.

EVAPOTRANSPIRATION

In discussing the elements of evapotranspiration, actual evapotranspiration and potential evapotranspiration must be distinguished. Potential evapotranspiration is dependent upon radiation and advected heat. Actual evapotranspiration is further limited by the availability of water in the soil for losses by transpiration and evaporation. No direct measurements of either actual or potential evapotranspiration are available for most of the eastern slope of West Maui.

Potential Evapotranspiration

Potential evapotranspiration may be estimated either through estimation of the heat budget (incident radiation less reflection and radiation heat plus net incoming advected heat) or by the use of evaporimeters.

Incident radiation has been measured at various places on the Maui Isthmus, and Chang (1963) shows that it reaches high values of 550 to 600 langleys per day. The areas of high radiation, however, are not characteristic of much cloudier areas such as those found along the eastern slope of West Maui. Even the lower slopes of East Maui are not characteristic of the area under consideration. Therefore, extrapolation of the radiation estimations to even the lower slopes of West Maui (eastern) would be very uncertain and extrapolation to the high rainfall portions of West Maui quite impossible.

Pan evaporation has been measured at a number of sites on the Maui Isthmus as well as on the lower slopes of West and East Maui. Four pan evaporation stations (Wailuku Sugar Company stations III and IV, Hawaiian Commercial and Sugar Company station 310, and

Hawaiian Sugar Planters' Association station 310.1) are located within or near the area under investigation.

Lysimeter experiments on Hawaiian Commercial and Sugar Company plantation (Campbell, Chang, and Cox, 1960) have shown that the actual evapotranspiration of well-watered sugar cane with a completely developed canopy, hence potential evapotranspiration, is on the average equal to pan evaporation from pans maintained in the actively transpiring cane-field environment. Ewart (1967) has criticized this conclusion, but it appears that his criticism pertains to the use of the 1.0 ratio between potential evapotranspiration and pan evaporation as if it were the ratio between average actual evapotranspiration in a commercial cane field, throughout a growth cycle, and average pan evaporation. The pan evaporation rates may, therefore, be considered representative of potential evapotranspiration. However, no pan evaporation data are available for the mountain area of West Maui.

Considering that both evaporation and potential evapotranspiration are limited by cloudiness, and that rainfall is a function of this same cloudiness, evapotranspiration rates may be related to and in a general way indicated by rainfall in Hawaiian regimes of climate. D. C. Cox (1968, per. com.) has suggested that a general relationship applicable in such regimes may be determined between pan evaporation or potential evapotranspiration and rainfall.

Pan evaporation data and lysimeter data are both, unfortunately, very limited in high rainfall areas. As a result, reliance must be put on pan evaporation and evapotranspiration data collected at Luakaha and Kaukonahua, Oahu, for the period 1931-1936 (Stearns and Vaksvik, 1935), evaporation data collected by the U. S. Weather

Bureau at Upper Hoaeae and Maunawili (Stearns and Vaksvik, 1935), pan evaporation data collected at Waikapu and Maalaea by Wailuku Sugar Company (1967, unpublished), Hawaiian Commercial and Sugar Company pan evaporation data for station 310 (Chuck, 1961), and pan evaporation data collected by Hawaiian Sugar Planters' Association at station 310.1 (Chuck, 1961). Table 4 summarizes the data from the above mentioned stations.

From these data, the relationship between pan evaporation, or potential evapotranspiration, and rainfall may be determined graphically as shown by the Line B - B" in Figure 5.

Actual Evapotranspiration

The only published method for estimating actual evapotranspiration in a Hawaiian watershed has been that of Kunesh (1929) long known to be inadequate, especially in high rainfall areas. Kunesh estimated evaporation at 20 percent of total rainfall and transpiration as 30 inches per year where the annual rainfall exceeded that amount and as equal to the annual rainfall where the rainfall was less than 30 inches per year. To obtain total losses, he added these amounts using implicitly, then, the following formulae:

$$\text{for } R<30 \quad E.\ T. = 1.2R \text{ and}$$

$$\text{for } R>30 \quad E.\ T. = 30 + 0.2R$$

where R = annual rainfall (inches per year) and E. T. = annual evapotranspiration (inches per year). Probably because Kunesh was not much concerned with areas of low rainfall, he did not notice that his estimate of evapotranspiration exceeded the rainfall in areas of less than $37\frac{1}{2}$ inches per year mean annual rainfall. Although he cited as the principal reference for his estimate of transpiration, Meyer

TABLE 4. EVAPORATION AND EVAPOTRANSPIRATION DATA.

Station	Elevation (feet)	Year	Rainfall (inches)*	Evaporation (inches)*	E. T.*** (inches)*	E. T.*** (inches)*
Laukaha	890	1931	144.7	47.6		50.0
		1932	180.0	34.2		
		1933	96.9			44.8
Kaukonahua	1250	1932	289.4	16.3	24.5	21.3
		1933	173.2	14.6	24.6	27.6
Upper Hoaeae	705	1921	34.3	69.3		
		1922	25.2	61.8		
		1923	49.5	59.7		
		1925	24.8	59.6		
		1927	67.4	57.7		
		1928	24.1	57.3		
		1929	44.8	58.1		
		1930	37.1	60.1		
		1931	25.3	63.2		
Maunawili	250	1921	98.7	41.7		
		1922	66.3	43.6		
		1923	117.9	50.3		
		1924	73.6	48.1		
		1925	73.8	43.7		
		1926	62.4	44.3		
		1927	140.6	43.6		
		1928	62.4	46.3		
		1929	75.4	44.9		
WSCo. III	500	1967	32.0	70.0		
WSCo. IV	120	1967	20.0	81.7		
HC&SCo. 310	100	1957-1961	13.5	96.3**		
HSPA 310.1	100	1957-1961	15.0	93.7		

*Mean annual **Median annual ***Over fern

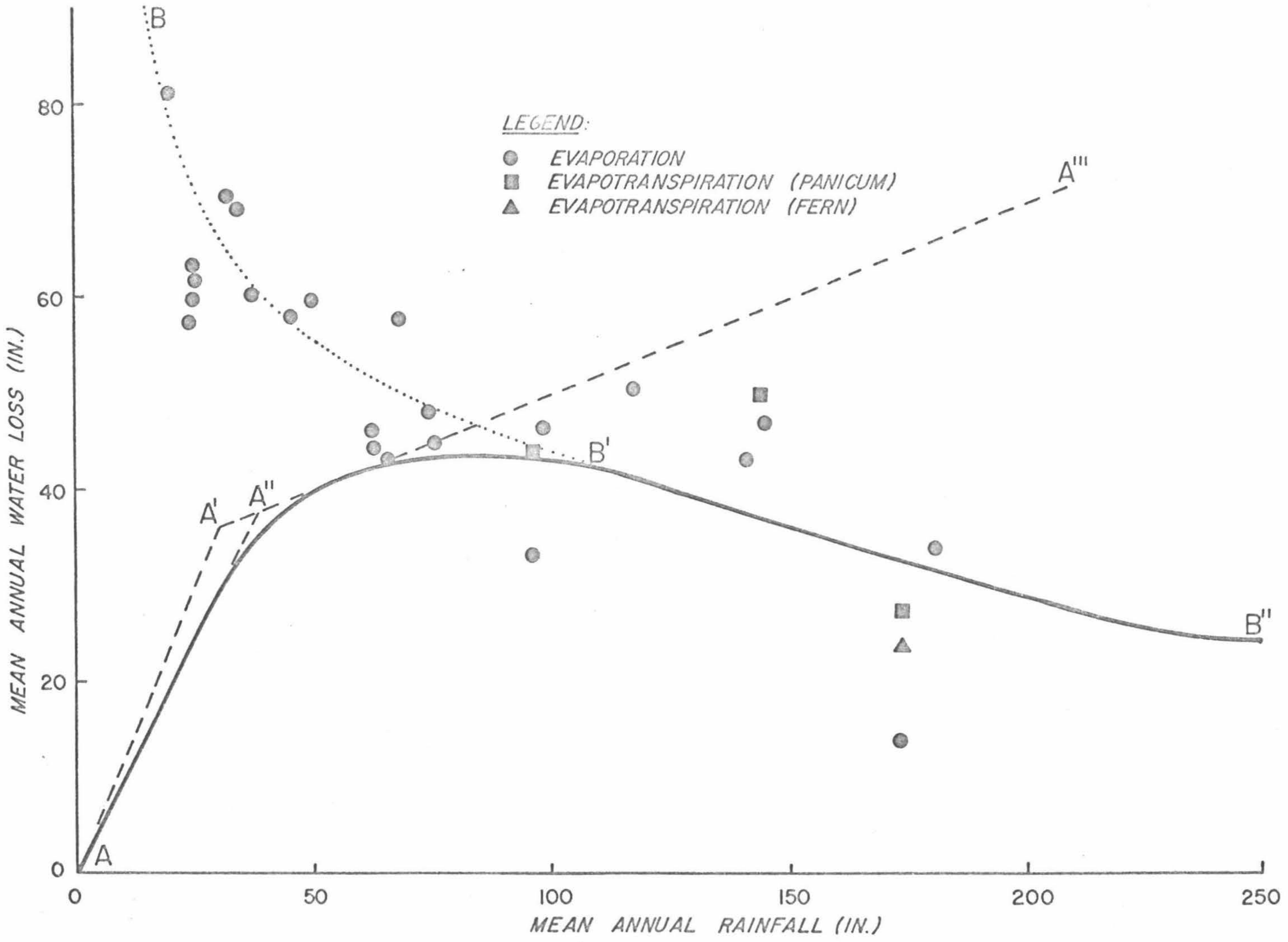


Figure 5. Curves representing some estimates for actual and potential evapotranspiration.

(1915), who provided means for estimating both evaporation and transpiration, the derivation of Kunesh's formulae from Meyer's formulae has proved impossible to follow and, hence, impossible to reconcile the discrepancy at low rainfalls. In Figure 5 have been plotted dashed lines representing both Kunesh's estimate of evapotranspiration (A-A'-A'") and an estimate whereby annual evapotranspiration equals annual rainfall for rainfalls equal to or less than $37\frac{1}{2}$ inches per year (A-A"-A'").

Actually some deep percolation must occur even in dry areas following heavy rainfalls that saturate the soil reservoir, and actual evapotranspiration must be somewhat less than rainfall even in such areas. In high rainfall areas, as previously pointed out, evapotranspiration is limited not by availability of water, but by energy. The actual evapotranspiration cannot exceed the potential evapotranspiration, and as shown by Figure 5, Kunesh's estimate of evapotranspiration is a gross overestimate for high rainfall areas. A more reasonable estimate for actual evapotranspiration is shown by curve A-B'-B" to which the lines A-A", A'-A"', and B-B' are tangential.

Net rainfall, measured rainfall minus evapotranspiration losses, for areas both inside and outside gauged drainage basins, as well as for areas planted to and not planted to sugar cane, is tabulated in Tables 5 and 6.

Ewart (1967) points out that evapotranspiration losses over cane fields for a complete growth cycle can not be expressed as having a ratio of 1.0 with pan evaporation or potential evapotranspiration. Warren Gibson (1968, per. com.) has suggested that a better approximation of the evapotranspiration loss might be 0.8 pan evaporation.

TABLE 5. NET RAINFALL AVAILABLE FOR DEEP PERCOLATION AND SURFACE-WATER RUNOFF WITHIN GAUGED DRAINAGE BASINS.

Drainage Basin				Waikapu	Iao	South Waiehu	North Waiehu	Waihee	Honokohau
Isohyet interval (in)	Logarithmic mean (in)	E. T.** loss (in)	Percent loss	Net Rainfall (mgy)	Net Rainfall (mgy)	Net Rainfall (mgy)	Net Rainfall (mgy)	Net Rainfall (mgy)	Net Rainfall (mgy)
382 plus	390	20*	5		514				1,150
382-306	341	20*	6		1,730			1,385	3,210
306-244	272	20*	7		3,880			3,000	4,760
244-195	218	26	12		3,900			2,964	3,000
195-156	174	33	19		2,560	49	171	2,490	2,762
156-125	139	39	27	372	1,705	372	408	1,540	408
125-100	112	43	38	482	1,013	327	253	581	
100- 80	89	44	49	411	411	158	116	7	
80-64	71	43	61	315	53	24	34		
64-51	57	42	74	129					
51-41	46	39	85	41					
		Total (mgy)		1,750	14,713	930	1,042	11,967	15,290
		Total (mgd)		4.8	40.3	2.5	2.9	32.8	41.6

*Above 250 inches of rainfall the evapotranspiration loss approaches 20 inches.

**Evapotranspiration

TABLE 6. NET RAINFALL AVAILABLE FOR DEEP PERCOLATION AND SURFACE WATER RUNOFF OUTSIDE GAUGED DRAINAGE BASINS.

Areas planted to sugar cane and directly tributary to the basal Waikapu aquifer.

Isohyet* interval (in)	Area (square miles)	Net rainfall (mgy)
41-33	0.962	625
33-26	1.070	542
26-21	0.306	123
21-17	0.306	100
17-14	0.198	52
less than 14	0.192	43
	total (mgy)	1,485
	total (mgd)	4

Areas not planted to sugar cane and directly tributary to the basal Waikapu aquifer.

Isohyet interval* (in)	Logarithmic mean rainfall*(in)	E. T.** loss* (in)	Percent lost*	Net rainfall (mgy)
64-51	57	42	74	48
51-41	46	39	85	81
41-33	37	35	95	40
33-26	29	29	100	0
26-21	23	23	100	0
21-17	19	19	100	0
17-14	15	15	100	0
less than 14	14	14	100	0
			Total (mgy)	169
			Total (mgd)	0.5

TABLE 6 (continued)

Areas tributary to high-level aquifers outside gauged drainage basins.

South of Waikapu gauged drainage basin.

Isohyet interval* (in)	Logarithmic mean rainfall*(in)	E. T.** loss* (in)	Percent lost*	Net rainfall (mgy)
100-80	79	44	56	25
80-64	71	43	61	111
64-51	57	42	74	184
51-41	46	39	85	109
41-33	37	35	95	23
33-26	29	29	100	0
26-21	23	23	100	0
21-17	19	19	100	0
17-14	15	15	100	0
less than 14	14	14	100	0
			Total (mgy)	452
			Total (mgd)	1

Areas between Iao and Waikapu gauged drainage basins.

Isohyet interval* (in)	Logarithmic mean rainfall*(in)	E. T. ** loss* (in)	Percent lost*	Net rainfall (mgy)
80-64	79	44	56	78
64-51	57	42	74	78
51-41	46	39	85	2
			Total (mgy)	158
			Total (mgd)	0.5

*mean annual
**evapotranspiration

Assuming evapotranspiration rates for the first 6 and last 3 months of a cane growth cycle are an average of 0.5 potential evapotranspiration while the remaining 15 months is 1.0 potential evapotranspiration, the calculated average evapotranspiration over a 24 month growth cycle is 0.81 potential evapotranspiration.

Figure 6 illustrates isoevaporation or ios-potential evapotranspiration contours for the sugar cane fields south of Iao Valley along the eastern slope of West Maui.

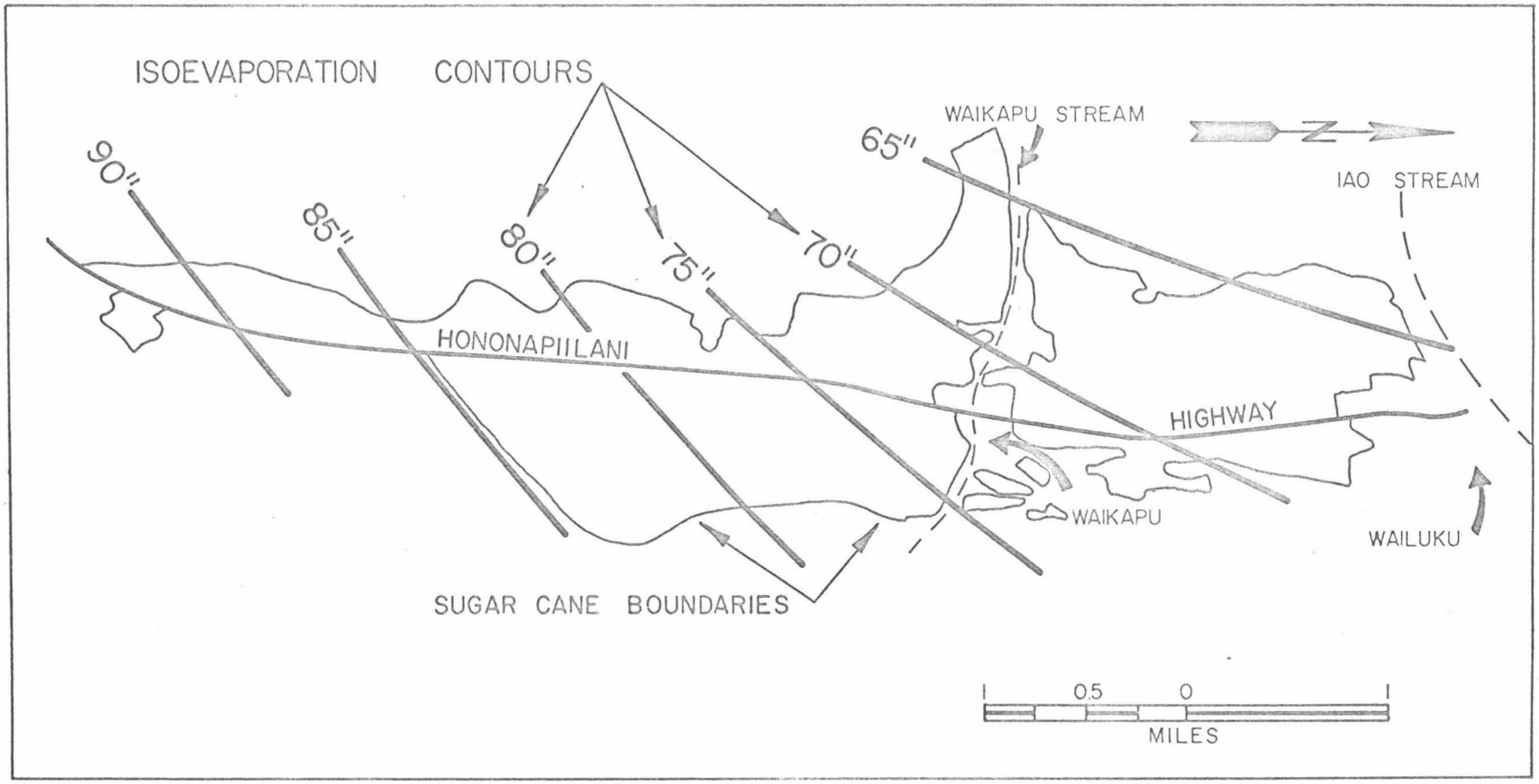


Figure 6. Isoevaporation contours over the sugar cane fields along the eastern slope of West Maui (south of Iao Valley).

SURFACE WATER

The eastern slope of West Maui is drained by six major perennial plus a small number of ephemeral, streams. The major surface-water discharge is from the drainage basins of Waikapu, Iao, South Waiehu, North Waiehu, Waihee and Honokohau streams.

The U. S. Geological Survey established a surface water monitoring network for the island of Maui between 1910 and 1920. However, most of the surface water gauging stations were maintained for only a few years. As a result, surface water records are available only for Waikapu Stream between 1911 and 1917, for Iao Stream between 1910 and 1915, for South Waiehu Stream between 1911 and 1917, for North Waiehu Stream between 1913 and 1916, and for Waihee Stream between 1913 and 1917. The Honokohau gauging station, however, has been continually monitored since its installation in 1912. From this, it is obvious that in an analysis of water resources over long periods of time, the stream discharge records for the eastern slope of West Maui are quite inadequate.

Irrigation needs of the sugar cane industry have led to the development of surface water flowing from the West Maui Mountains. Wailuku Sugar Company and Hawaiian Commercial and Sugar Company have diverted waters from the perennial streams flowing over the eastern slope of West Maui. Waihee and Spreckles ditches (Wailuku Sugar Company, and Hawaiian Commercial and Sugar Company) divert surface water from Waihee Stream, North Waiehu Ditch (Wailuku Sugar Company) diverts surface water from North Waiehu Stream, South Waiehu Ditch (Hawaiian Commercial and Sugar Company) diverts surface water from South Waiehu

Stream, Maniania and Iao-Waikapu ditches (Wailuku Sugar Company) divert surface water from Iao Stream, and Everett and South Waikapu ditches (Wailuku Sugar Company) divert surface water from Waikapu Stream.

Records of the discharges of these ditches are available from Wailuku Sugar Company and Hawaiian Commercial and Sugar Company. The ditches are limited in capacity, and the intakes divert only low to average surface-water discharges. During periods of high surface-water discharge, a large portion of the water flows over the diversions. In addition, during periods of heavy rain the need for irrigation is minimized and little or no water is diverted from the streams. Ditch-flow records are, therefore, entirely inadequate to indicate total surface water discharge.

Because of the inadequacy of both the stream records and the ditch flow records, the average total surface water discharges must be estimated. By flow duration analysis (Searcey, 1959) long-term duration discharge relationship may be estimated for a stream which has only a short-term record, by comparing its short-term duration discharge data with the duration discharge data representing a similar stream with a long-term record.

Even though stream discharges for Honokohau Stream were monitored in 1912, the data collection was intermittent prior to July, 1913 (U. S. Geological Survey, 1961). In flow duration analysis, the long and short-term stream discharge records under consideration must have overlapping records. Therefore, only the Waikapu, Iao, South Waiehu, North Waiehu, and Waihee records monitored after July, 1913 (U. S. Geological Survey, 1917a, 1917b, 1918) are applicable.

Applying the flow duration analysis, the surface discharge records of the Waikapu, Iao, South Waiehu, North Waiehu, Waihee and Honokohau streams were separated into classes of discharge rates. Starting with the class representing the maximum discharges, the class totals were cumulated, and the cumulative total for each class was then converted to a percent of the total occurences for all discharges. The percent representing each class was then plotted against the mean for the corresponding class, with the mean discharge plotted on an arithmetic ordinate and the cumulative percent plotted on a probability abscissa. Such a plot was made for Honokohau (1913-1915, 1913-1916, 1913-1917, and 1913-1950), Waikapu (1913-1917), Iao (1913-1915), South Waiehu (1913-1917), North Waiehu (1913-1916), and Waihee (1913-1917) streams. To establish a correlation between the flow duration curve for each short-term record and the short-term record of Honokohau Stream for the same time period, discharges from each stream corresponding to the same cumulative percentile were plotted against each other on a log-log plot. According to Searcey, if the plot of points results in a random scattering of points, there is not correlation between the two records. If, however, the plot of points results in a smooth curve, as is the case, then there is a correlation between the stream records and the short-term records may be extended with some degree of accuracy.

The following expression represents the relationship between data points for actual flow duration curves, and an unknown data point for the to-be-extended flow duration curve:

$$X_{L_n} = H_{L_n} \cdot \frac{H_{L_n}}{H_{S_n}}$$

where H_{L_n} = long-term Honokohau discharge value for cumulative percentile n,

H_{S_n} = short-term Honokohau discharge value for cumulative percentile n,

X_{S_n} = short-term discharge value (from stream record to be extended) for cumulative percentile n,

X_{L_n} = desired long-term discharge value (for stream record being extended) for cumulative percentile n, with

n = to all cumulative percentiles between 99.999 and 0.001.

Transfering the extended record data to an arithmetic plot (discharge versus cumulative percentile), the resulting locus of points represents a histogram of the extended flow duration. Extrapolating mean discharges for every 5 percent segment, the mean annual discharge may be estimated from the histogram. Table 7 shows the results of the flow duration analysis in terms of the mean discharges of each stream.

TABLE 7. FLOW DURATION ANALYSIS RESULTS.

Drainage basin	Area (mi^2)	Period of record (years)	Actual mean yearly discharge (mgy)x10^3	Extented mean yearly discharge (mgy)x10^3	Mean discharge (mgd)
Honokohau	4.10	1913-1950	9.72		26.6
Waikapu	2.70	1913-1917		4.77	13.1
Iao	6.02	1913-1915		14.13	38.7
South Waiehu	0.78	1913-1916		2.33	6.4
North Waiehu	0.75	1913-1915		2.60	7.1
Waihee	4.20	1913-1917		20.58	56.4

MASS BALANCE OF THE HIGH-LEVEL AQUIFERS

Gauged Drainage Basins

As shown in the section on general aspects of the hydrologic mass balance, the underground discharge of the high-level aquifers is given by the equation

$$G_h = P_h - E_h - S_h$$

where P_h = precipitation in the area of the high-level aquifers,
E_h = evapotranspiration in the area of the high-level aquifers, and
S_h = surface discharge from the area of the high-level aquifers.

If the gauged rainfall represented the total precipitation, the excess of net rainfall (gauged rainfall minus evapotranspiration, Table 5) and surface water discharge (Table 7) should provide an estimate of ground-water discharge from the high-level aquifers to the basal aquifers.

As shown in Table 8, there is a surplus of 1.6 million gallons per day in Iao Valley, about half of which, from the southern side of the valley, might be expected to be tributary to the Waikapu aquifer. However, for Waikapu Valley there is a deficit. This deficit might at first seem explicable by ground-water transfer between the valleys, but over the whole of Iao and Waikapu valleys there is still a net deficit of 7.7 million gallons per day. Table 8 also shows the balance between net rainfall and surface water discharge for South Waiehu, North Waiehu, Waihee, and Honokohau valleys in an attempt to explain the net deficit experienced for Iao and Waikapu valleys. Again, the results indicate a net deficit of water. Since the law of conservation of mass must apply to the ground-water system on the eastern slope of

TABLE 8. A BALANCE OF NET RAINFALL VERSUS SURFACE-WATER DISCHARGE FOR GAUGED DRAINAGE BASINS.

Drainage Basin	Waikapu	Iao	South Waiehu	North Waiehu	Waihee	Honokohau
Net Rainfall (mgd)	4.8	40.3	2.5	2.9	32.8	41.6
Surface Discharge (mgd)	13.1	38.7	6.4	7.1	56.4	26.6
Surface flow minus net rainfall (mgd)	-9.3	+1.6	-3.9	-4.2	-23.6	+15.0

West Maui, it is impossible to have more water running off than is contributed to the system by net rainfall.

The deficits of rainfall over surface-water discharge might be explained by one of the following: overestimates of stream discharges, underestimates of net precipitation, inter-basin ground-water transfers, or precipitation augmentation.

A comparison between the only actual mean annual discharges for Waikapu, Iao, South Waiehu, North Waiehu, and Waihee streams show that the extended mean annual surface discharges in close agreement with actual measurements. Therefore, it is unlikely that the deficit of rainfall over surface-water discharge for the net Iao and Waikapu flow, as well as the deficits found in South Waiehu, North Waiehu, and Waihee, can be explained in terms of overestimates for the surface-water discharge.

If no evapotranspiration losses are subtracted from the gauged rainfall, the remaining estimates of total precipitation are still insufficient to supply the volumes measured as stream discharge. From this it follows that an overestimate of the evapotranspiration is inadequate to account for the deficit of rainfall over surface water along the eastern slope of West Maui.

Table 8 shows that Iao and Honokohau drainage basins are the only systems showing surpluses of mean net precipitation based on gauged rainfall over surface-water runoff. The surpluses measured in Iao and Honokohau drainage basins suggest the possibility of transfers of water to the Waikapu, South Waiehu, North Waiehu, and Waihee drainage basins. However, the hydrogeology suggests such transfers either should be small or should be in the wrong directions.

On the ridge separating Iao from Waihee, the springs discharging into Iao Valley are, on the average, 1000 feet lower in elevation than the springs discharging into Waihee Valley (Stearns and Macdonald, 1942). This indicates that the ground-water drainage divide between Waihee and Iao is most likely north of the surface-water divide and, if anything, ground water is transferred from Waihee to Iao Valley. Furthermore, assuming that at least a few dike compartments are interconnected between the adjacent gauged drainage basins, discharge from the compartments would be to the drainage basin lowest in elevation. Since Iao Valley is more deeply incised than the adjacent Waikapu, South Waiehu, Waihee, and Honokohau valleys, the ground-water flow should be toward Iao Valley and not the reverse. The Honokohau-Waihee intra-basin divide represents the topographic expression of the northern rift zone of West Maui. As a result, even though Waihee Valley is more deeply incised than Honokohau, the ground-water transfer normal to the dikes might well be considered negligible.

Furthermore, if all the surpluses and deficits for all the gauged drainage basins were totaled, the total surplus would still be insufficient to balance the total deficit. The transfer of ground water from the basal Waikapu and Waiehu aquifers to the high-level aquifers is, of course, absurd.

The only remaining explanation for the deficit of rainfall over surface-water discharge is augmentation of the precipitation beyond the amounts indicated by rain gauges.

For the reasons previously discussed, it may be assumed that the augmentation of actual precipitation over gauged rates in valleys such as those of West Maui is a function of the orientation of the valleys relative to the prevailing winds. In Figure 7 is shown the frequency distribution of wind directions at Kahului Airport (Price, 1968, per. com.), 3.7 miles east-northeast of Wailuku. On the figure is also shown the general orientation (down valley) of the several valleys on the eastern slope of West Maui. Figure 8 shows the relationship between the frequency distribution for up-valley winds (from Figure 7) and the deficits of net rainfall over surface-water discharge per unit area for Waikapu, South Waiehu, North Waiehu, and Waihee gauged drainage basins.

Assuming that the precipitation augmentation to Waihee, North Waiehu, South Waiehu, and Waikapu drainage basins is just enough to compensate for the measured deficits, Iao Valley should receive an augmentation of 5.1 million gallons per day per square mile (Figure 8). It is quite likely, however, that the augmented precipitation in Waihee, North Waiehu, South Waiehu, and Waikapu drainage basins more than compensates for the deficits of rainfall over surface-water discharges, and therefore the figure of 5.1 million gallons per day per square mile represents a conservative estimate for Iao Valley.

Over the 6.02 square mile area of Iao Valley, the augmentation amounts to 30.7 million gallons per day, all of which may be assumed to contribute to ground-water discharge because the evapotranspiration and surface water losses have already been subtracted. This, plus the gauged surplus of 1.6 million gallons per day (Table 8), indicates a total underground discharge of 32.3 million gallons per day from Iao Valley to the basal aquifers. Because Iao Valley cuts deeply into the dike system and deeply drains the adjacent dike compartments, discharge to the Waikapu basal aquifer can be expected only from the high-level

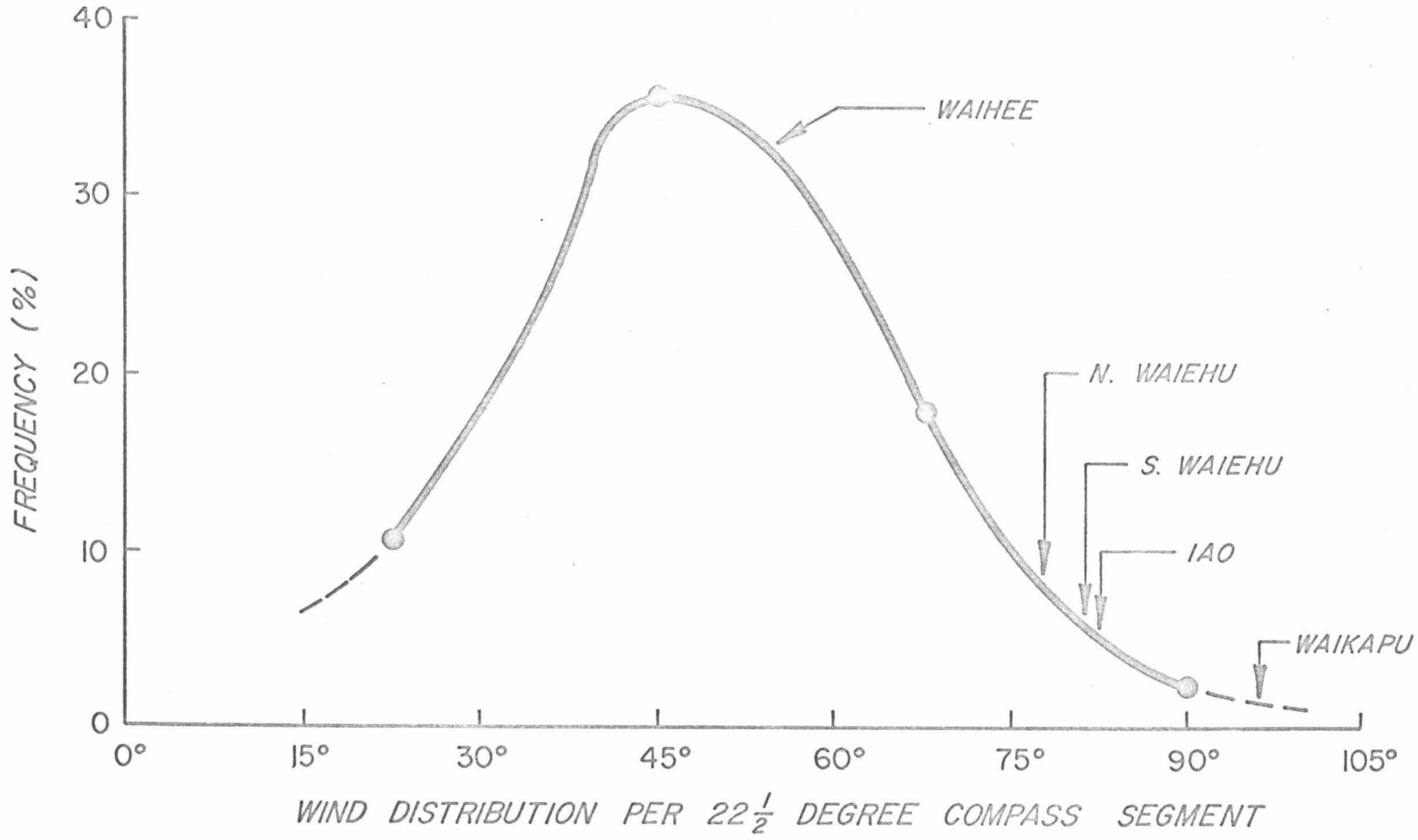


Figure 7. Wind orientation versus frequency.

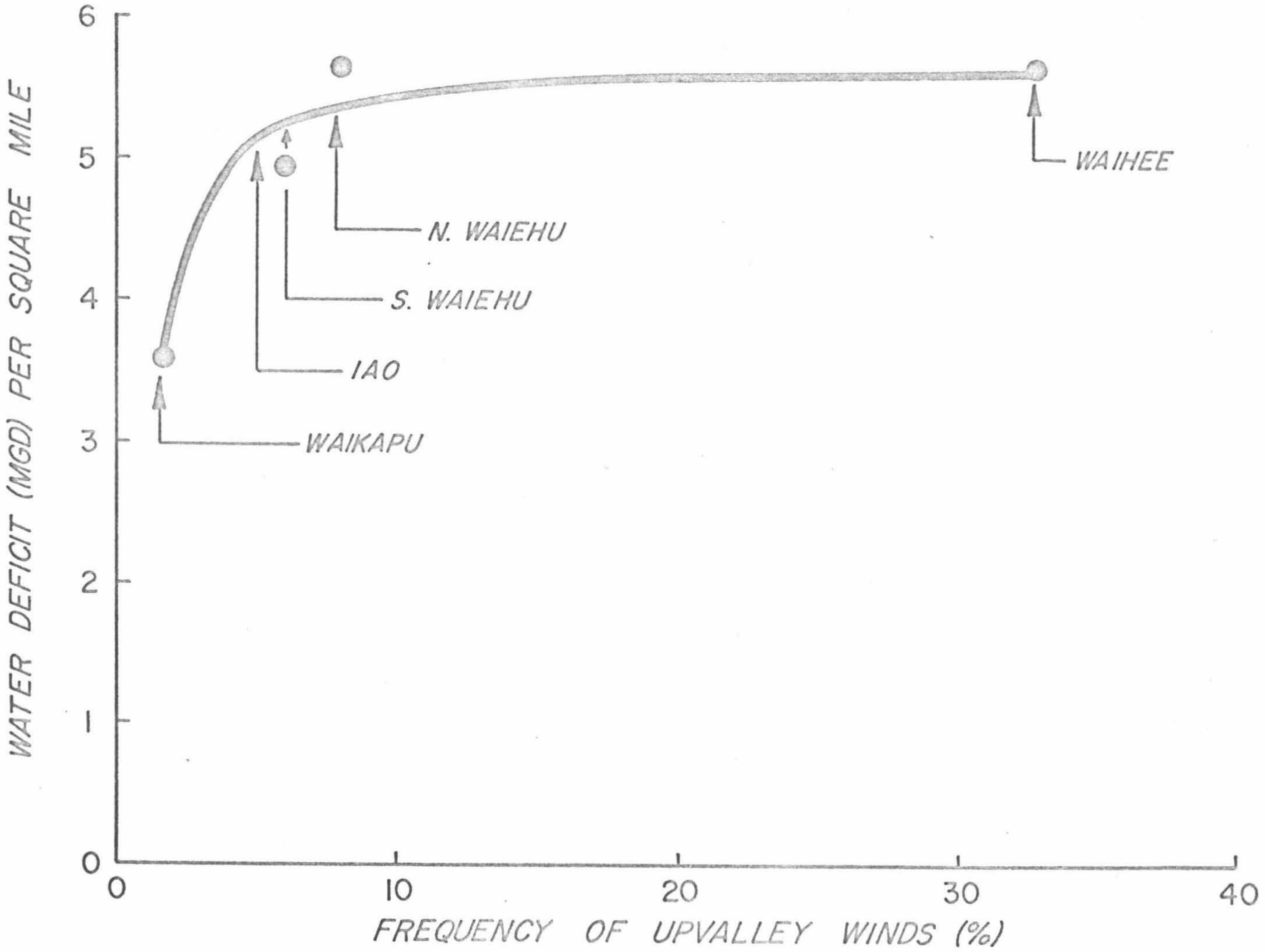


Figure 8. Frequency of up-valley winds versus water deficit.

aquifer systems south of the axis of the valley, and only half of the 32.3 million gallons per day, or 16.2 million gallons per day, can be considered tributary to the Waikapu aquifer.

The State Department of Water and Land Development (DOWALD) has made one estimate for the quantity of water available for recharge to the Waikapu and Waiehu aquifers from Iao drainage basin (Chuck, 1965). Table 9 tabulates the results as estimated by the DOWALD, as well as estimates made in this study. The figures in Table 9 indicate that both estimates are in close agreement. However, the means by which the DOWALD figures were developed are unclear. The DOWALD work is based upon an isohyetal map of Iao Valley that indicates a rainfall much higher than the one based on gauged rainfall presented in this study. If the DOWALD map was drawn with reference to precipitation augmentation, then the DOWALD results are substantiated by this study.

On the assumption that precipitation augmentation just accounts for the deficit in net rainfall over surface discharge in Waikapu Valley, no underground discharge occurs from the high-level aquifers in Waikapu Valley to the Waikapu aquifer.

Outside Gauged Drainage Basins

The surface drainage from a part of the high-level aquifer system between Waikapu and Iao valleys is not tributary to the gauged portion of either valley and has not been included in the above mass balance computations. The net rainfall in this area (Table 6) is 0.5 million gallons per day. No significant precipitation augmentation is expected in this area because it is below cloud base and closer to the lowland gauges where only downward trajectories of raindrops are expected, as opposed to Puu Kukui. Mink (1962) has found that surface runoff in

TABLE 9. ESTIMATES OF DEEP PERCOLATION TO HIGH-LEVEL AQUIFERS WITHIN IAO GAUGED DRAINAGE BASIN, AND SUBSEQUENT RECHARGE TO THE WAIEHU AND WAIKAPU AQUIFERS.

Water Description	Estimated by the State Department of Water and Land Development* (mgd)	Estimated in this study (mgd)
Gauged rainfall	90.0	52.6
Augmented Precipitation	0.0	30.7
Total Precipitation	90.0	83.3
Evapotranspiration losses	10.0	12.3
Surface discharge	42.0	38.7
Total loss	52.0	51.0
Balance available for deep percolation	38.0	32.3

*Chuck (1965)

streams on the leeward areas of the Koolau range of Oahu, not fed by high-level springs, amounts to about 25 percent of the precipitation. On the steep eastern slopes of West Maui a somewhat higher portion of the precipitation may be expected to run off. However, a small amount, perhaps 0.3 million gallons per day, may be expected to percolate to the high-level aquifers and, because it does not show up in springs in the lower parts of either Iao or Waikapu valleys, it may be expected to represent additional discharge to the Waikapu basal aquifer.

On the high-level aquifer area south of Waikapu Valley, there is an additional 1.0 million gallons per day net rainfall (Table 6). Streams draining this area, being intermittent and having no spring flow, are not gauged. On the same basis applied above, about 0.6 million gallons per day may be expected to represent deep percolation to the high level aquifers. However, from this part of the dike system, much of the discharge may occur directly to the ocean, and only a small part, a few tenths of a million gallons per day at the most, may be discharged to the Waikapu aquifer.

DIRECT RECHARGE TO THE WAIKAPU AQUIFER

Irrigated Areas

Wailuku Sugar Company utilizes the water from the Waihee, Spreckels, North Waiehu, Maniania, Iao-Waikapu, South Waikapu and Everett ditches for irrigation of sugar cane on the eastern slope of West Maui. Figure 1 shows, and Table 8 tabulates, the source area for each ditch. During times of low ditch flow and little rainfall, the ditch water is augmented by water pumped from the company's Wailuku shaft.

In compliance with agreements between sugar plantations, Wailuku Sugar Company uses 14/24 of the Waihee daily flow, with the remaining 10/24 going to Hawaiian Commercial and Sugar Company for use east of areas tributary to the Waikapu aquifer. Ditch records for the period 1955-1967 from Field 45 (north of Iao Valley) and Field 63 (south of Iao Valley) show that approximately 90 percent of Wailuku Sugar Company's share of Waihee ditch water is utilized south of Iao Valley. Water from the Spreckels ditch is shared with Hawaiian Commercial and Sugar Company on an equal basis. The Wailuku Sugar Company share of the Spreckels ditch water (50%), Hawaiian Commercial and Sugar Company's share of the Spreckels ditch water, plus all the water from North Waiehu, South Waiehu (Hawaiian Commercial and Sugar Company) and Maniania ditches is utilized in areas either north or east of areas tributary to the Waikapu aquifer.

Of the 2,878.4 (1967) acres (determined by planimeter) south of Iao Stream planted to sugar cane by Wailuku Sugar Company, 1,698.3 acres (determined by planimeter) are located west of Hononapiilani Highway. Since Hononapiilani Highway is assumed to represent the surface expression of the eastern boundary for the Waikapu aquifer, only irrigation west of the highway has any significance in this study. Therefore, 59 percent of all water utilized in irrigation south of Iao Stream on the Wailuku Sugar Company plantation is applied over surface areas tributary to the Waikapu aquifer.

Based upon previous estimates for the ratio between potential evapotranspiration and actual evapotranspiration, Tables 10 and 11 tabulate the amount of water available for deep percolation derived from irrigation water. Prior to the construction of the Wailuku shaft the distribution of the ditch water was, perhaps, different from the present day distribution. Therefore, Tables 10 and 11 carry figures for values inclusive and exclusive of the Wailuku shaft. With an estimate of 25 inches for the mean annual rainfall (Plate 1) over cane fields west of Hononapiilani Highway, Figure 5 yields a potential evapotranspiration rate of 72 inches of water per year. Wailuku Sugar Company irrigates approximately 1,698.3 acres of cane west of Hononapiilani Highway with 21,114.9 acre-feet of water per year. Converting acre-feet per year to inches per year, 149.4 inches of water is applied to cane fields through irrigation. With the actual evapotranspiration losses estimated to be 0.8 potential evapotranspiration (72 inches per year), the evapotranspiration losses are estimated to be approximately 57.6 inches per year, or 38.6 percent of the irrigation water supplied.

Irrigation efficiency is a term that can be defined in at least two ways. First, irrigation efficiency may be defined as the ratio of actual evapotranspiration losses to water applied through irrigation times 100 percent. With this definition, it is obvious that the above

TABLE 10. IRRIGATION WATER USED IN AREAS TRIBUTARY TO THE WAIKAPU AQUIFER.

Water source	Area of origin	Total delivery (mgy)	Delivery south of Iao Valley	
			Mean annual supply* (mgy)	Mean daily supply* (mgd)
Waihee Ditch	Waihee Stream	10,023.4	5,241.6	14.4
Spreckels Ditch	Waihee Stream	3,477.0	0.0	0.0
N. Waiehu Ditch	N. Waiehu Stream	1,020.0	0.0	0.0
Maniania Ditch	Iao Stream	3,805.8	0.0	0.0
Iao-Waikapu Ditch	Iao Stream	3,479.7	3,479.7	9.5
Everett Ditch	Waikapu Stream	552.5	552.5	1.5
South Waikapu Ditch	Waikapu Stream	988.9	988.9	2.7
Wailuku Shaft	Waikapu aquifer	1,587.4	1,587.4	4.4
	Total	24,934.7	11,850.4	32.5
	Irrigation in areas directly tributary to the Waikapu aquifer (59% of all the water delivered south of Iao Valley)			
	Total inclusive of Wailuku shaft		6,991.7	19.2
	Total exclusive of Wailuku shaft		6,055.1	16.6

*Based on means computed for records extending from 1955 to 1967.

TABLE 11. WATER AVAILABLE FOR DEEP PERCOLATION TO THE WAIKAPU AQUIFER FROM AREAS TRIBUTARY TO THE AQUIFER.

Source	Exclusive of the Wailuku shaft (mgd)	Inclusive of the Wailuku shaft (mgd)
Irrigation water	16.6	19.2
Rainfall	4.0	4.0
Total water supply	20.6	23.2
Evapotranspiration loss	6.6	7.4
Total water available for deep percolation	14.0	15.8

mentioned figure of 38.6 percent is one estimate for irrigation efficiency for the cane fields west of Hononapiilani Highway and south of Iao Stream. Second, irrigation efficiency may be defined as the ratio of actual evapotranspiration losses to total water applied (irrigation plus precipitation) times 100 percent. Applying this definition, an irrigation efficiency of 32.1 percent is computed for the same area under consideration.

It has to be estimated that the irrigation for the Hawaiian Islands is, in general, ± 30 percent. Comparing this figure with those computed above, it appears that the irrigation efficiencies for the area under investigation are well within the acceptable range. One implication which follows from this observation is that the extrapolation of the potential evapotranspiration figure from Figure 5, and the subsequent application of the factor of 0.8 potential evapotranspiration for actual evapotranspiration has resulted in relatively accepted figures for irrigation efficiency.

Unirrigated Areas

West of the north-south trending high-level-basal boundary and east of the areas planted to sugar cane, the net rainfall is calculated to be 0.5 million gallons per day (Table 6). Since this area is drained by non-gauged streams, the surface runoff can only be estimated to be approximately 25 percent after Mink (1962). Because the slopes in this area are steeper than the Koolau slopes considered in Mink's work, it is not unreasonable to assume that of the 0.5 million gallons per day net rainfall, approximately 0.3 million gallons per day is available for deep percolation, and directly tributary to the Waikapu aquifer.

CONCLUSIONS

Total Recharge of the Waikapu Aquifer

Table 12 represents a tabulation of the constituents of recharge to the Waikapu basal aquifer. The constituents have been broken down by areas of origin: high-level discharges to the basal aquifer and deep percolation from areas directly tributary to the basal aquifer. Several factors have at least dual values, and this has led to the minimum and preferred estimates of total recharge ranging from 15.2 to 32.8 million gallons per day, respectively. If precipitation augmentation exists, and can be defined as in this study, then the preferred estimate of recharge from the high-level aquifers represents the true picture. If, however, there is no precipitation augmentation, then the recharge to the basal aquifer is actually much smaller, and perhaps approaching the minimal estimate. Another factor that results in dual figures is the pump discharge from the Wailuku shaft. If the water developed from the Wailuku shaft resulted in additional irrigation south of Iao Valley, then the preferred estimate represents the best estimated recharge. But if the development of the Wailuku shaft resulted in a redistribution (north and south of Iao Valley) of ditch water, then the minimal estimate is a better approximation of the recharge from irrigation return water.

Discharge of the Waikapu Aquifer

The Wailuku shaft represents the only artificial draft on the Waikapu aquifer. The mean annual pump discharge of the shaft from 1955 through 1967 was 4.4 million gallons per day. Therefore the net recharge to the Waikapu aquifer ranges between 10.8 and 28.4 million gallons per day. Analysis of irrigation water and amounts returned to the basal

TABLE 12. RECHARGE OF THE WAIKAPU AQUIFER.

Discharge from high-level aquifers

Source	Minimum estimate (mgd)	Average estimate (mgd)
Iao Valley	0.8	16.2
Between Iao and Waikapu valleys	0.2	0.3
Waikapu Valley	0.0	0.0
South of Waikapu Valley	0.0	0.0
Total	1.0	16.7

Direct Recharge

Source	Minimum estimate (mgd)	Average estimate (mgd)
Unirrigated areas	0.2	0.3
Irrigated areas	14.0	15.8
Total	14.2	16.1
Total recharge	15.2	32.8

aquifer points out that approximately half of the Wailuku shaft water is returned to the basal aquifer as irrigation return water. The net-effectual recharge is then computed to range between 13.0 and 30.6 million gallons per day. From this, it follows that the proposed 7 million gallons per day increase in pump capacity for the Wailuku shaft would result in an approximate 3.5 million gallons per day increase in net draft during periods of constant pumping. However, computed as a mean annual figure, based on present day pumping rates, this would result in an approximate mean annual increase in net-effectual draft of only 1.2 million gallons per day.

Although there are few datum points on the basal water table associated with the Waikapu aquifer, the obvious southerly component of the hydraulic gradient indicates that the ground-water discharge (in a north-south section) is principally to the south and into Maalaea Bay. The Iao Valley barrier is not felt to be absolute and as a consequence small discharges to the north are feasible when head differentials dictate. In addition, all the ground-water table datum points are essentially lineated in a north-south fashion so that it is impossible to fully define the sloping water table. With the relatively small hydraulic conductivity of the Pleistocene alluvium forming the eastern boundary of the Waikapu aquifer, the discharge of water through the alluvium to the Haleakala lava aquifers to the east must be small. While it is difficult to quantify the discharge of the Waikapu aquifer at any specified time, the recharge and discharge to the aquifer must be at equilibrium over very long periods of time (decades). In a state of equilibrium the law of conservation of mass must apply, and consequently there is not net change in storage. Therefore, the estimated recharge as given by this study, representing mean figures over approximately 5 decades, may be assumed to be equal to the discharge of the Waikapu aquifer for the same period of time.

Recommendations

Because so many factors involved in this study had to be either estimated or approximated, the data collection network for West Maui could, and should be expanded. Attempts should be made to establish, and maintain, a comprehensive surface-water network for all perennial streams so that between stream records and ditch records, the total stream discharge will be monitored. More rain gauge stations need to be put into operation in intermediate areas: between the lowlands and Puu Kukui. Furthermore, a great deal more research needs to be done on evapotranspiration in the Hawaiian Islands, relationships between actual evapotranspiration and potential evapotranspiration, cloud droplet interception, and precipitation augmentation.

APPENDIX

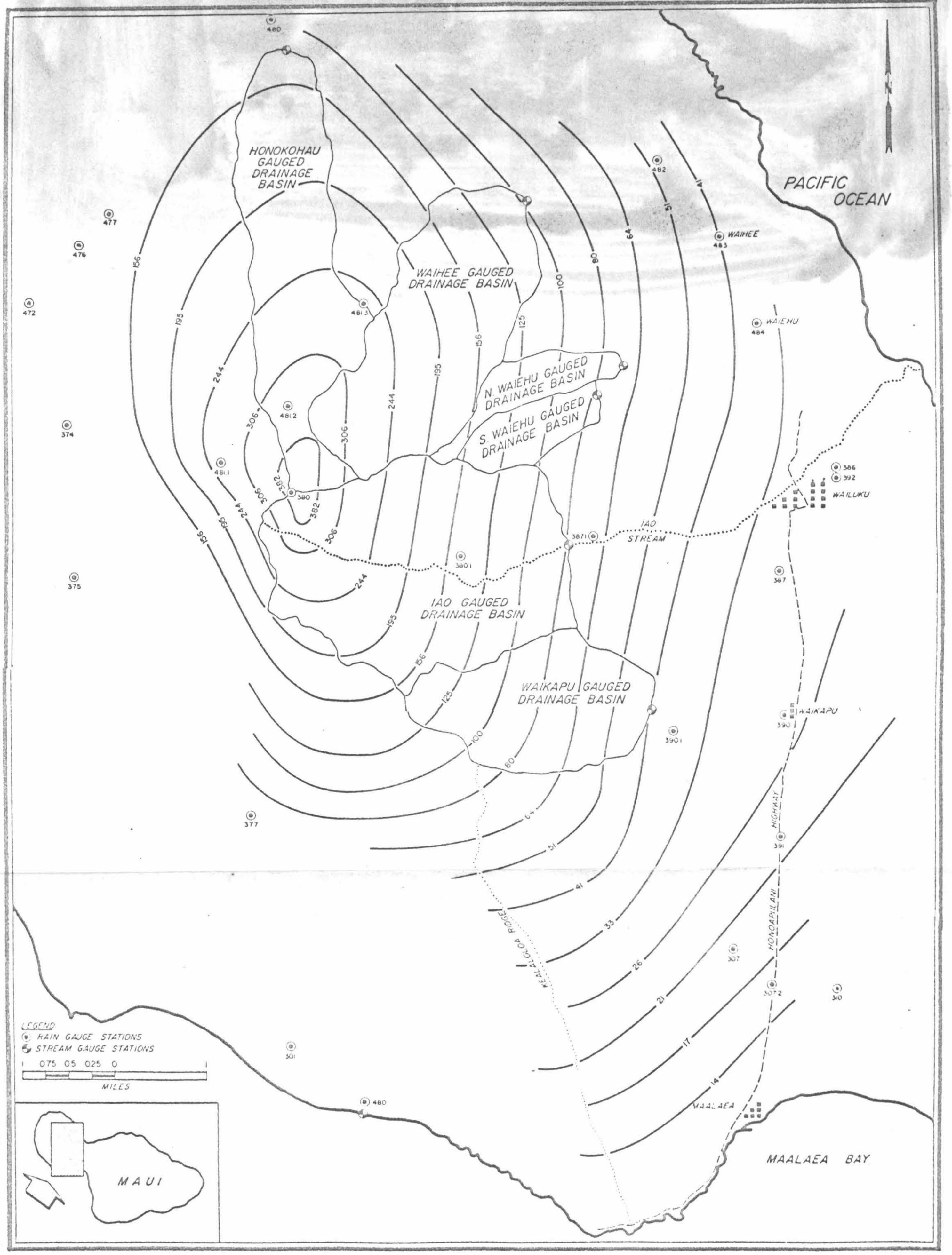


Plate 1. Isohyetal map of the eastern slope of West Maui.

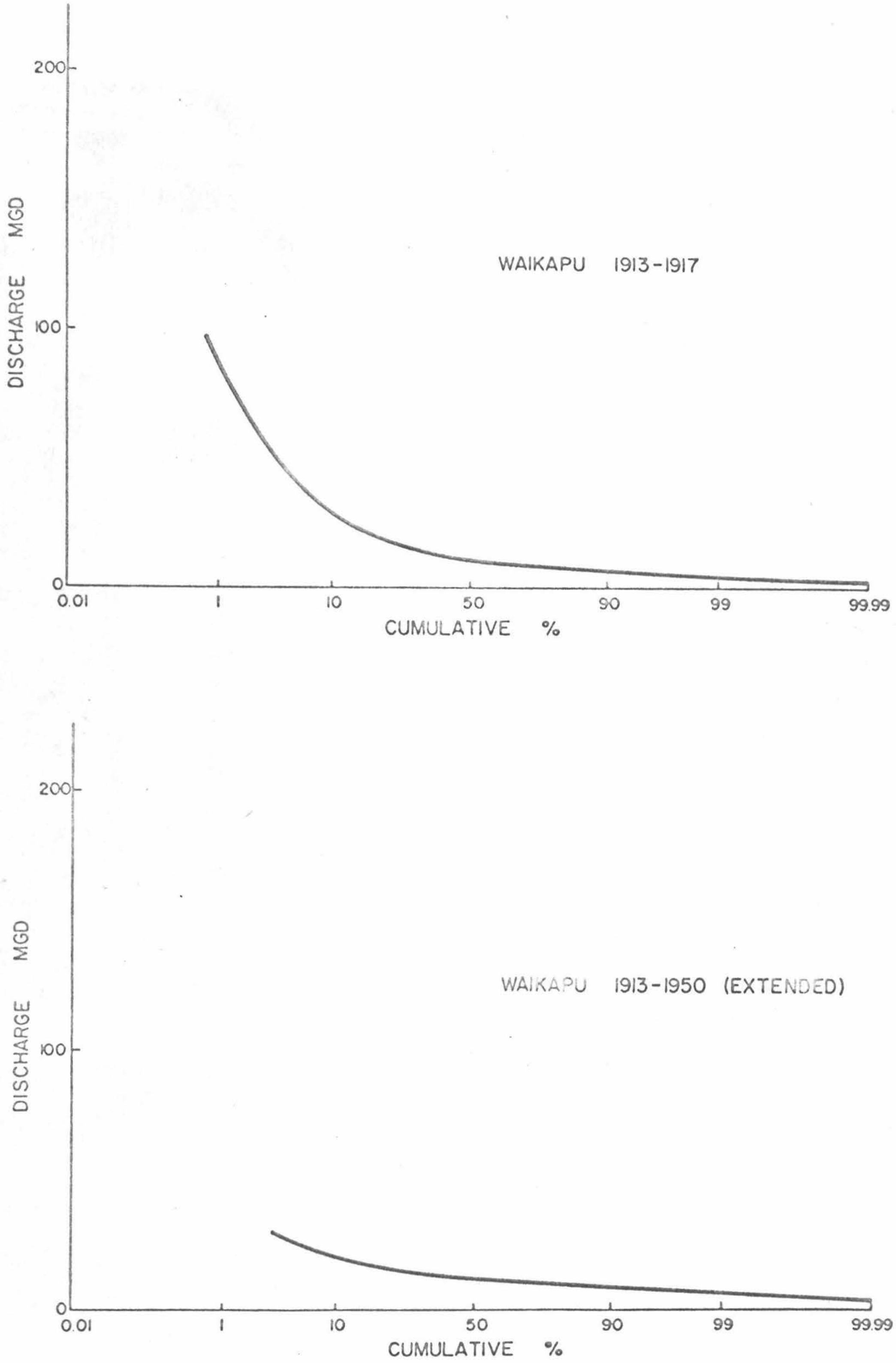
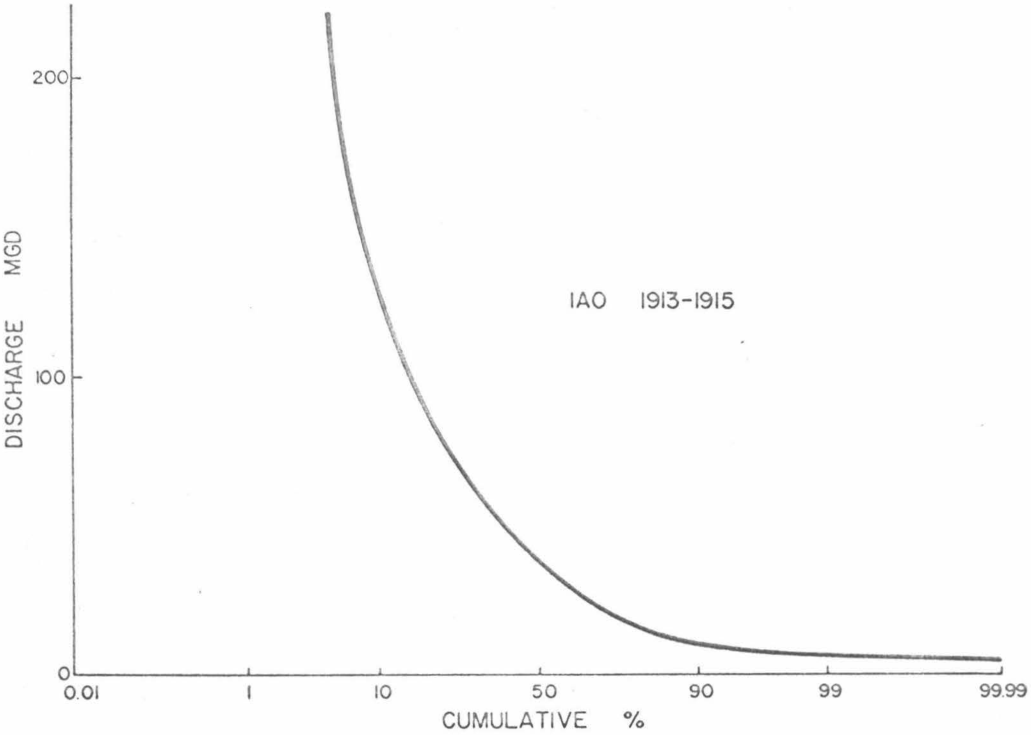
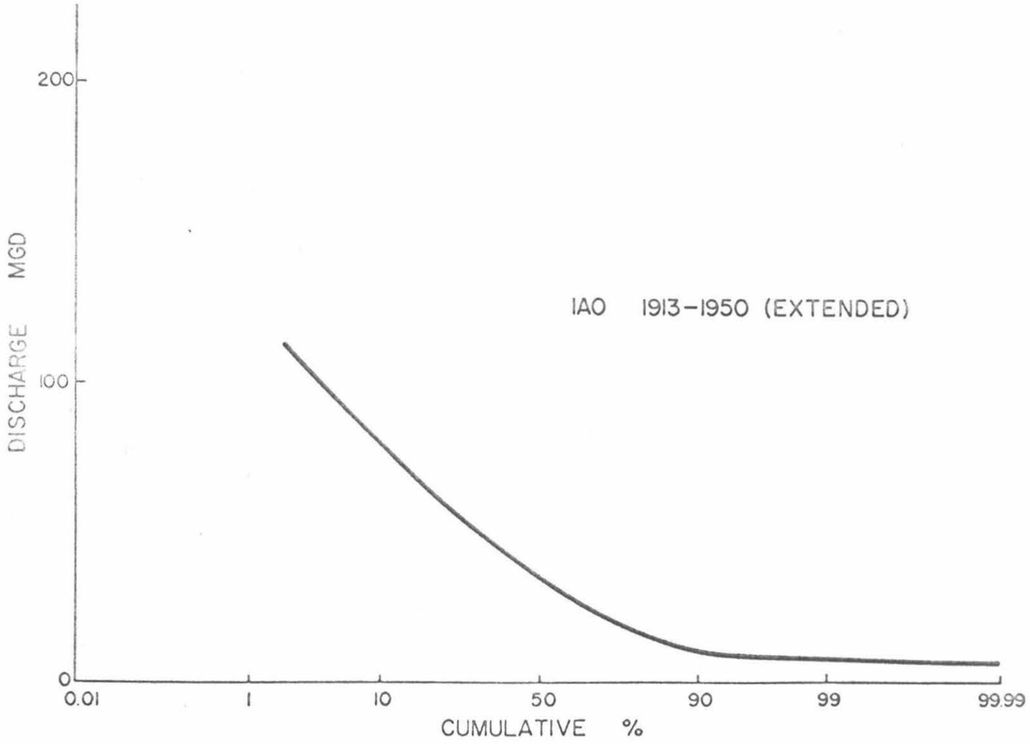


Plate 2. Flow duration curves.





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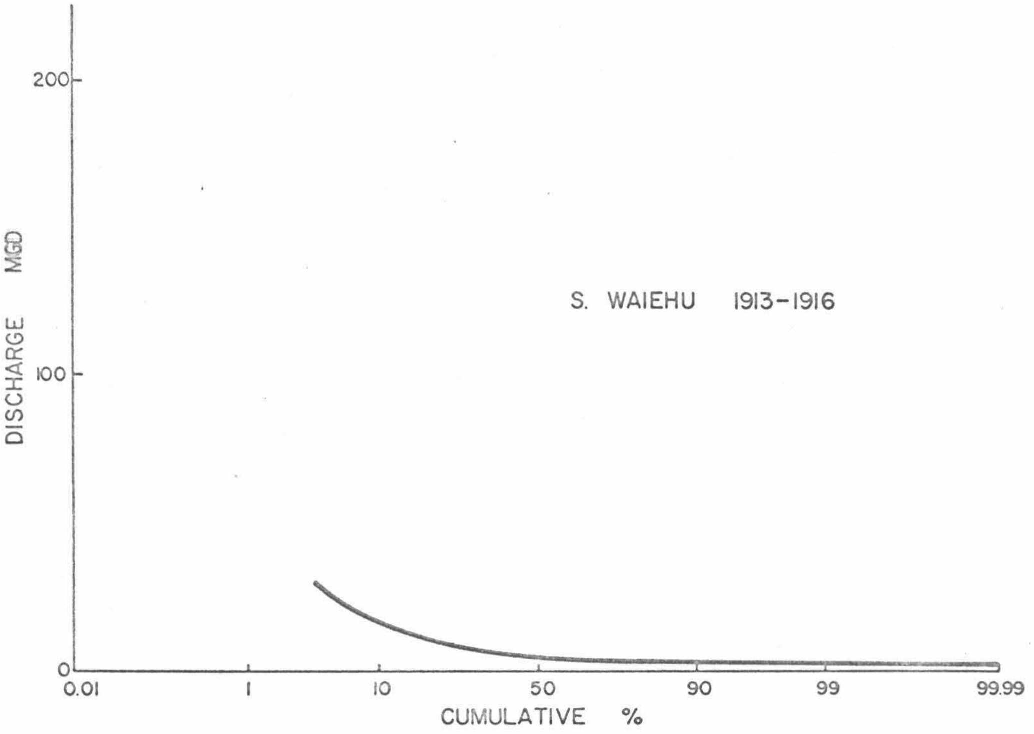

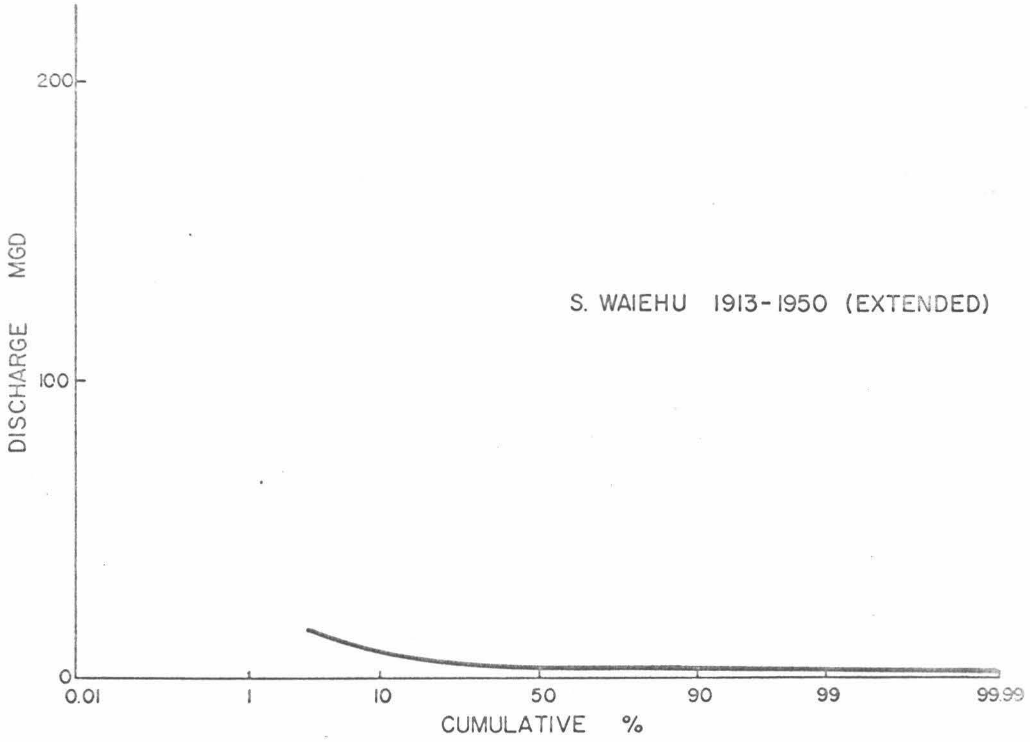

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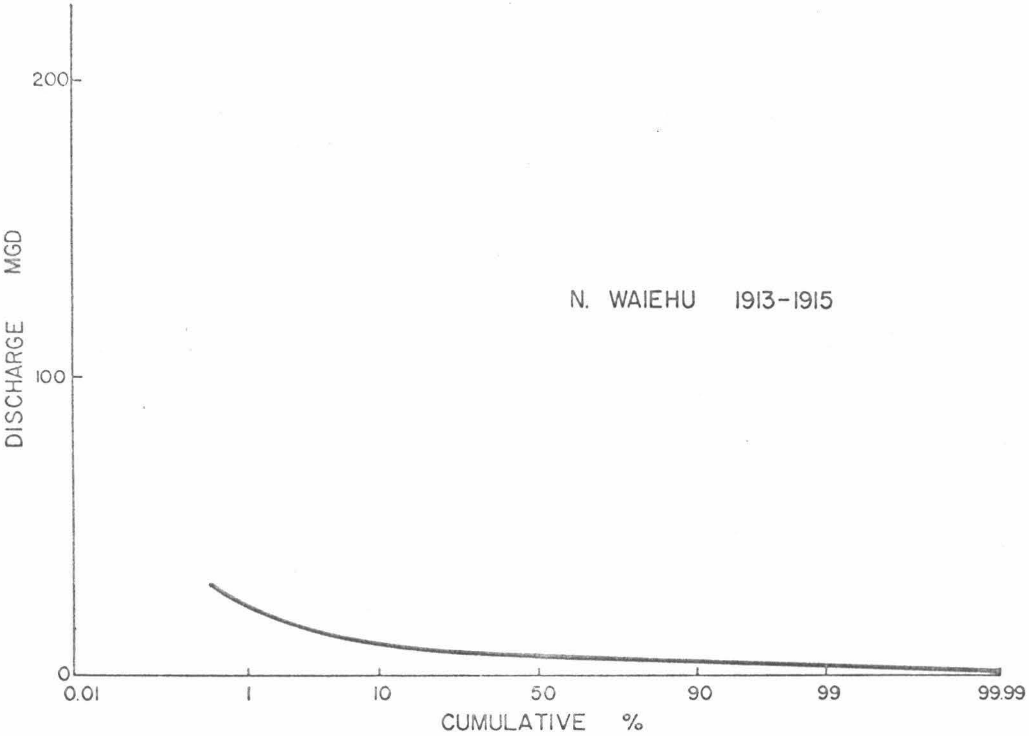

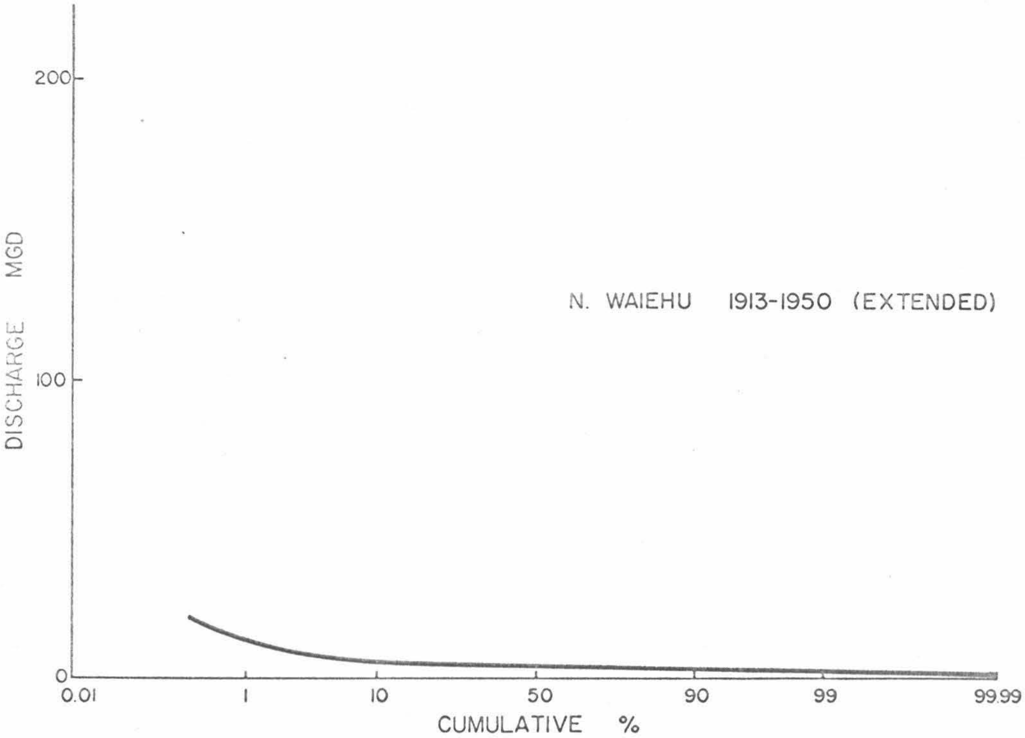

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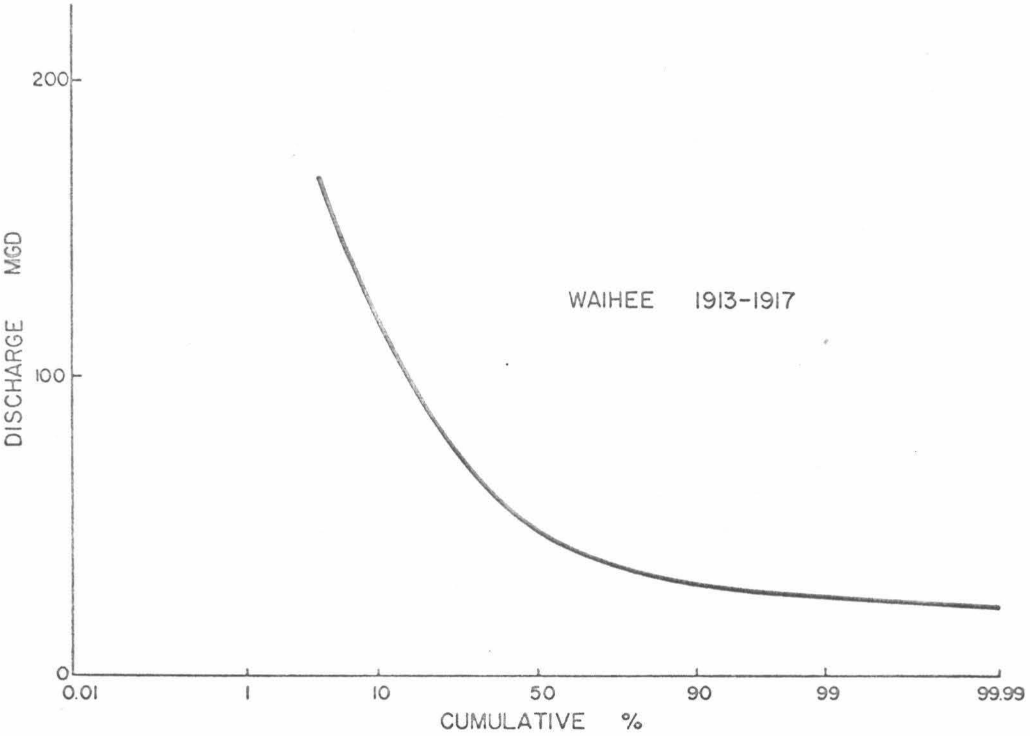

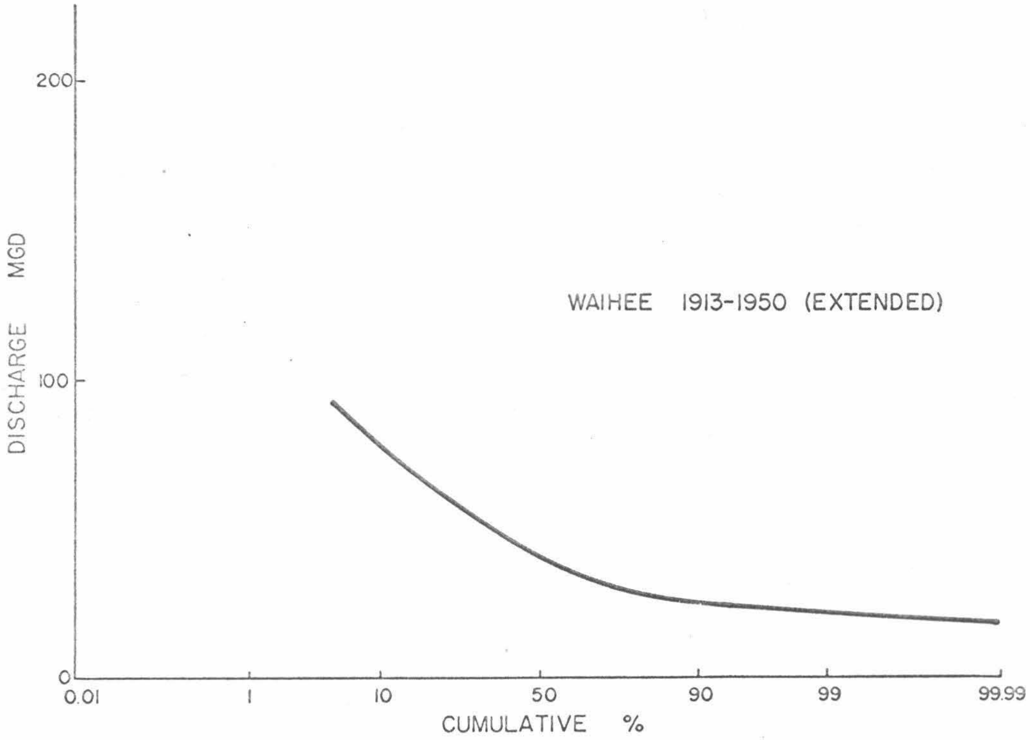

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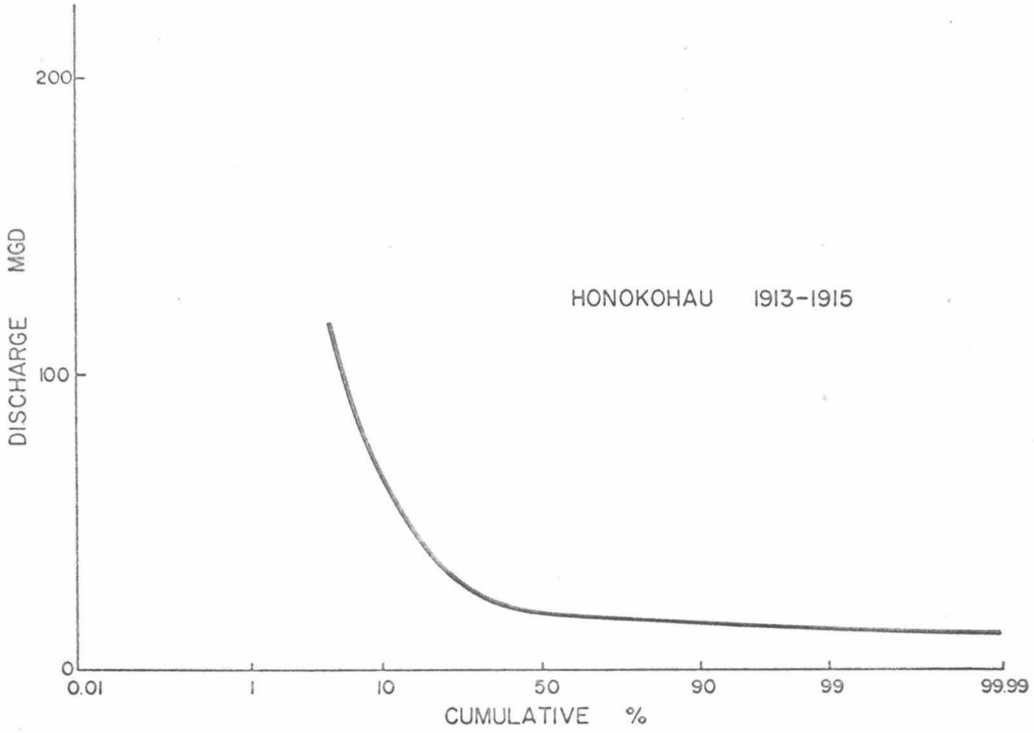

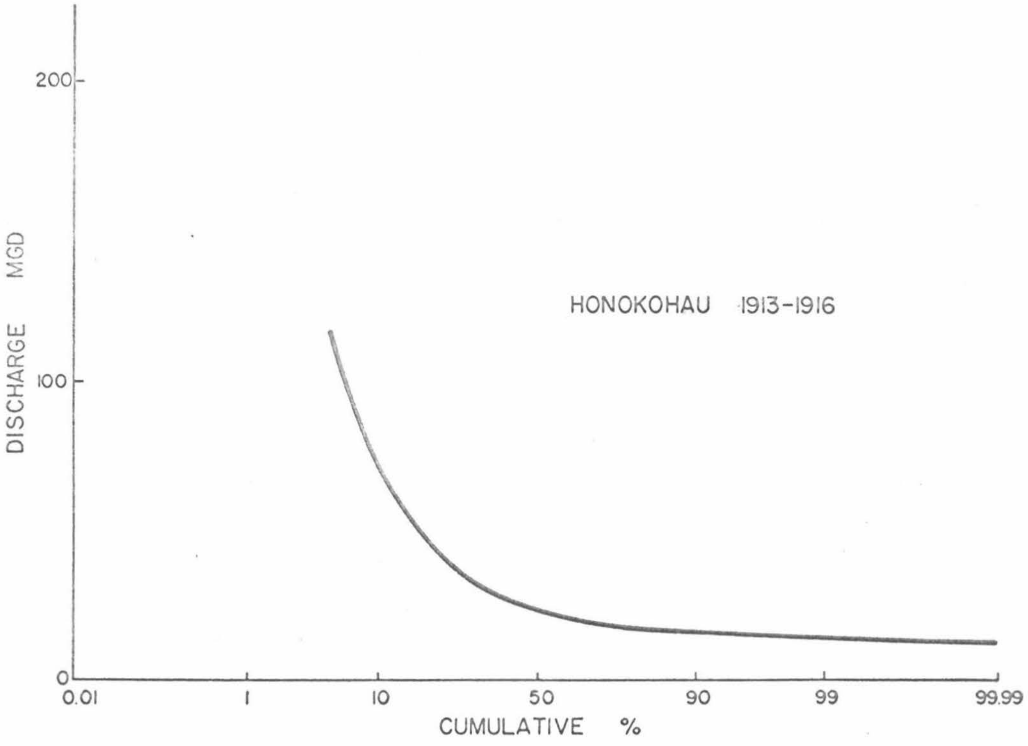

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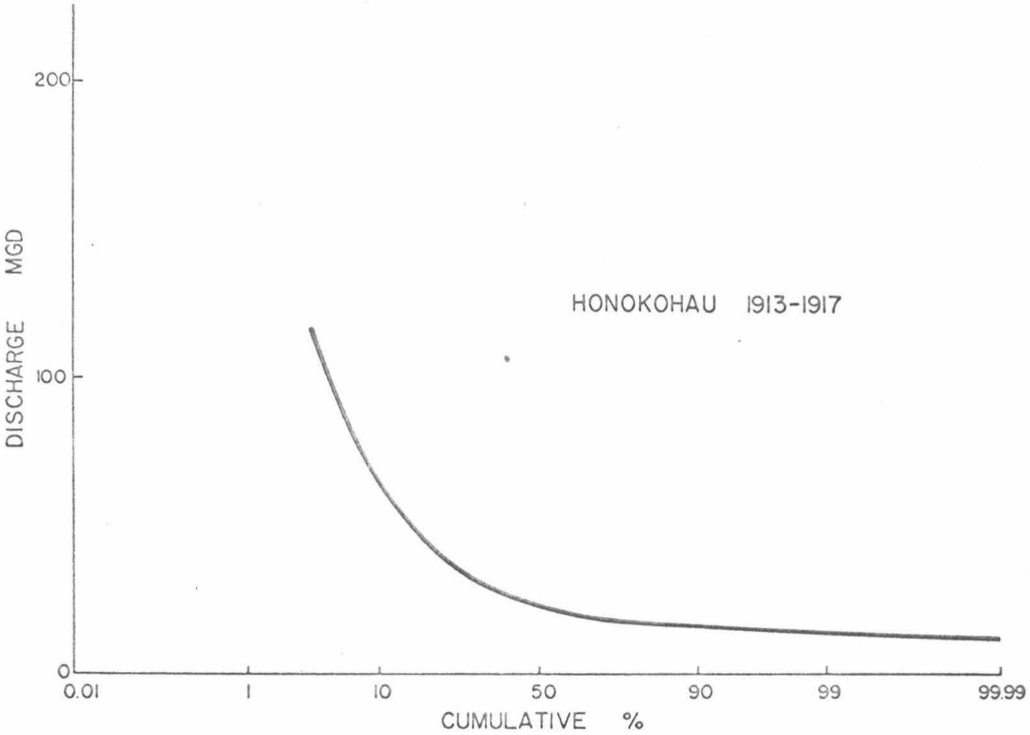

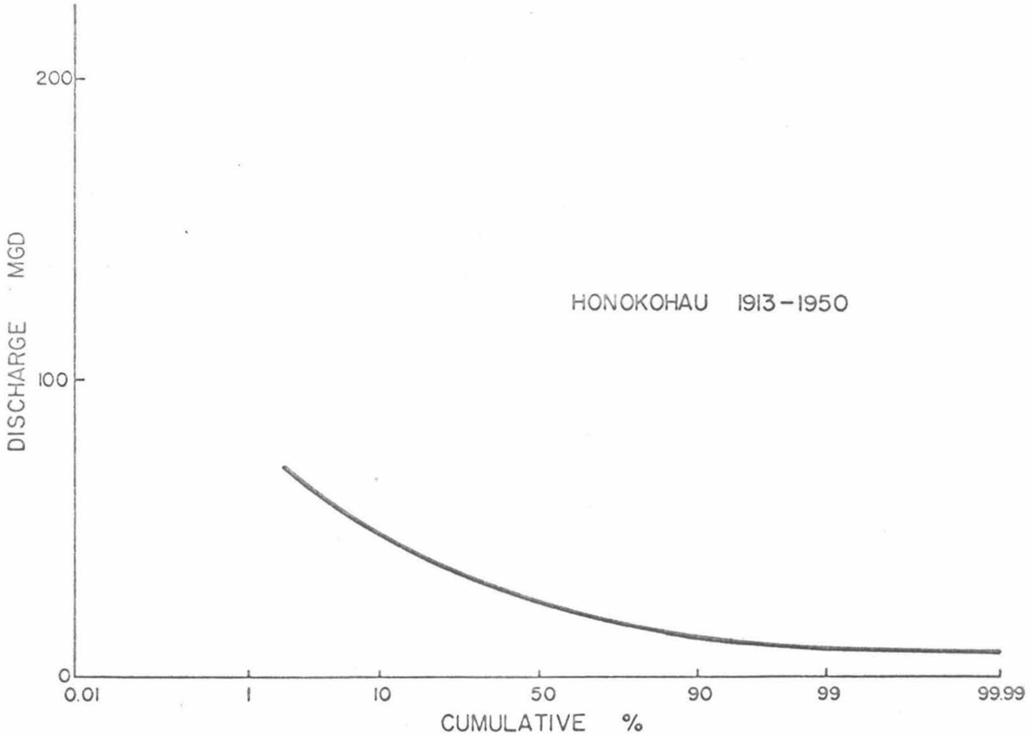

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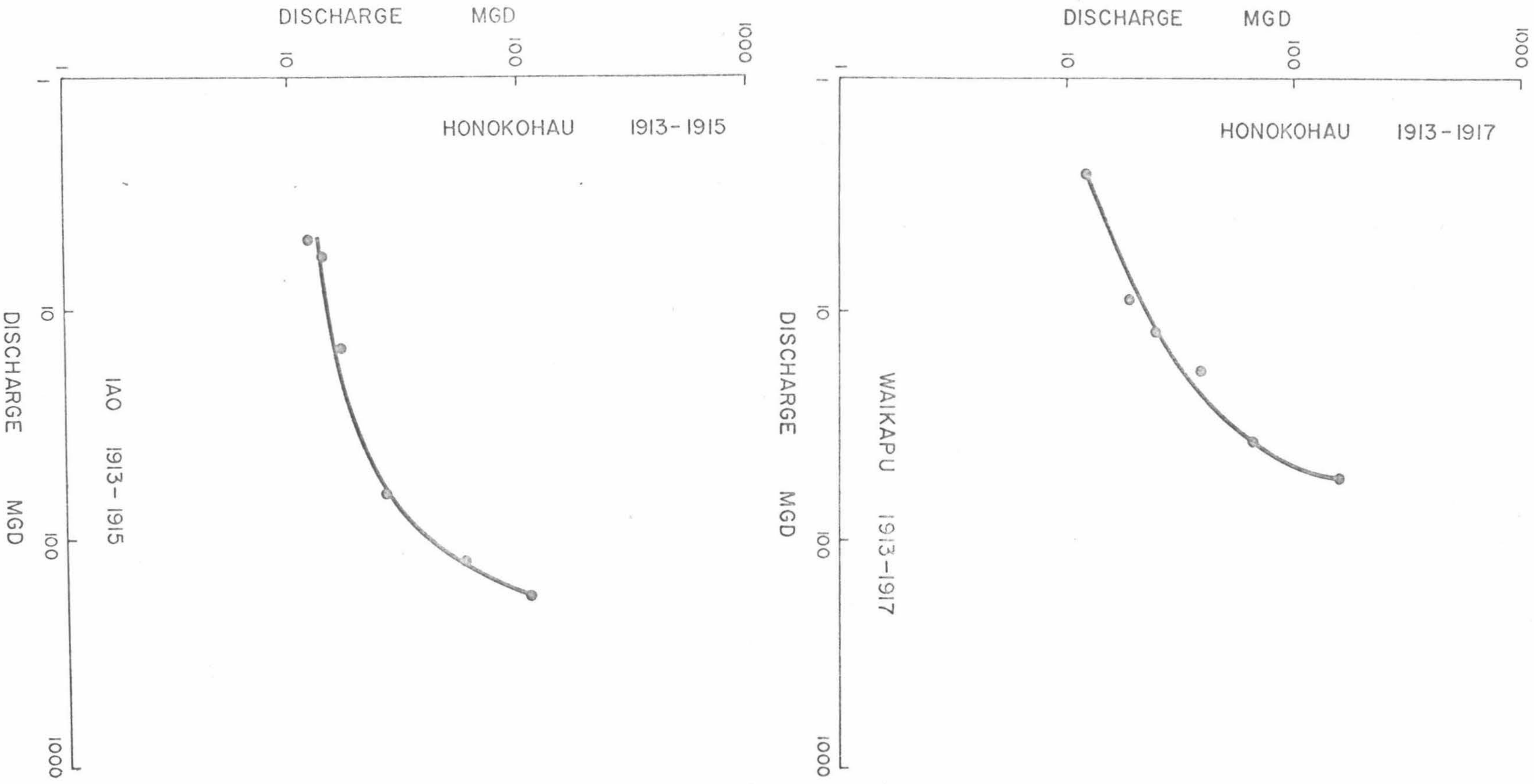
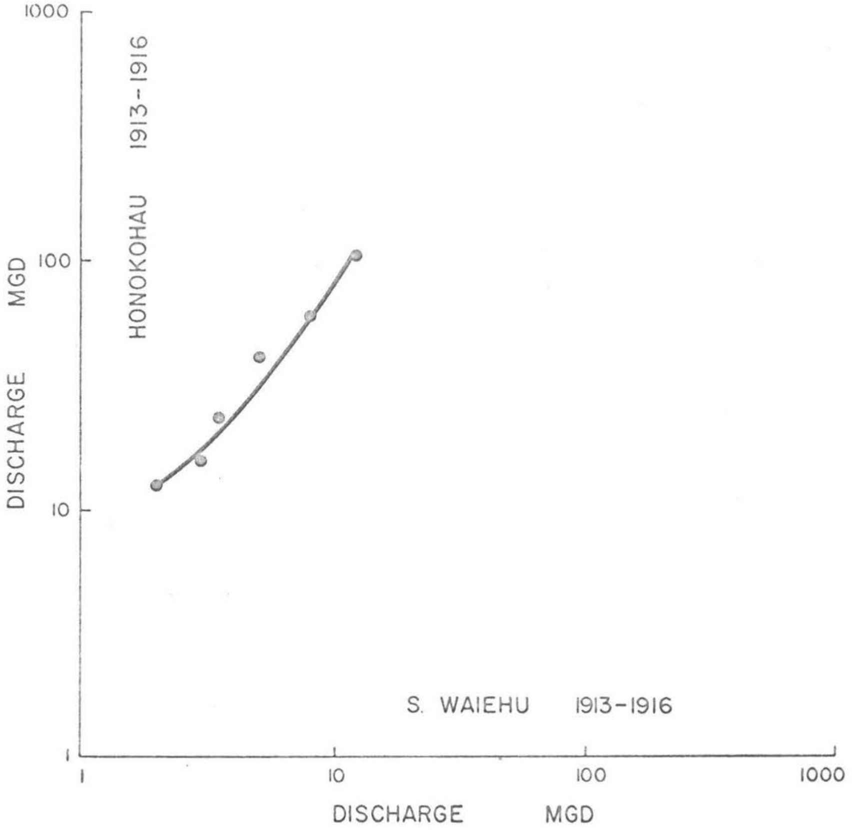
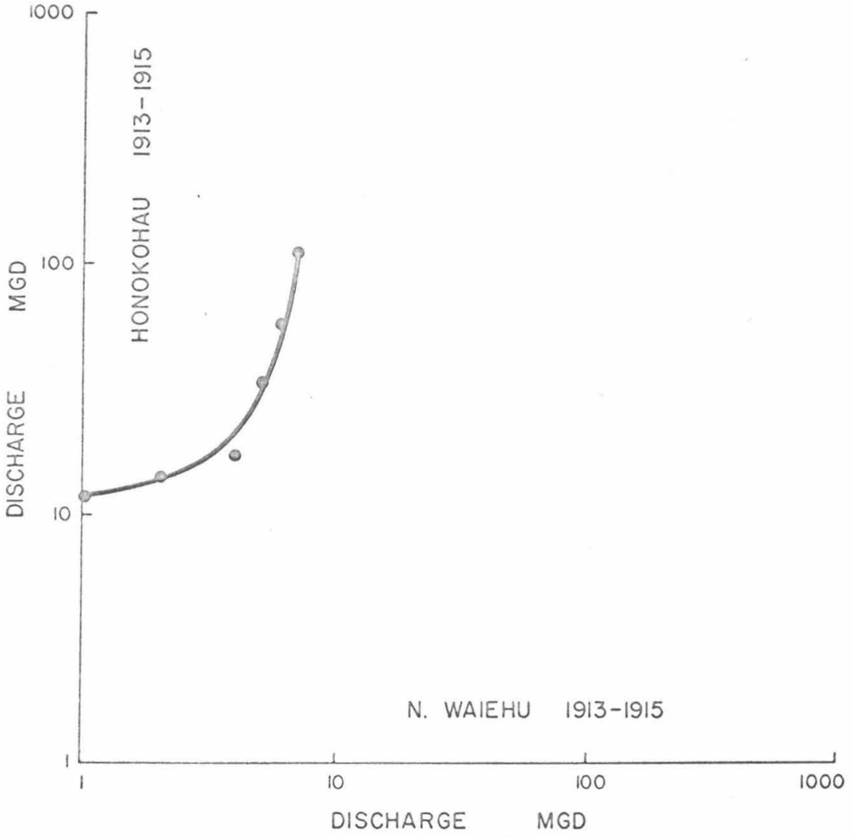


Plate 3. Correlation curves for flow duration analysis.





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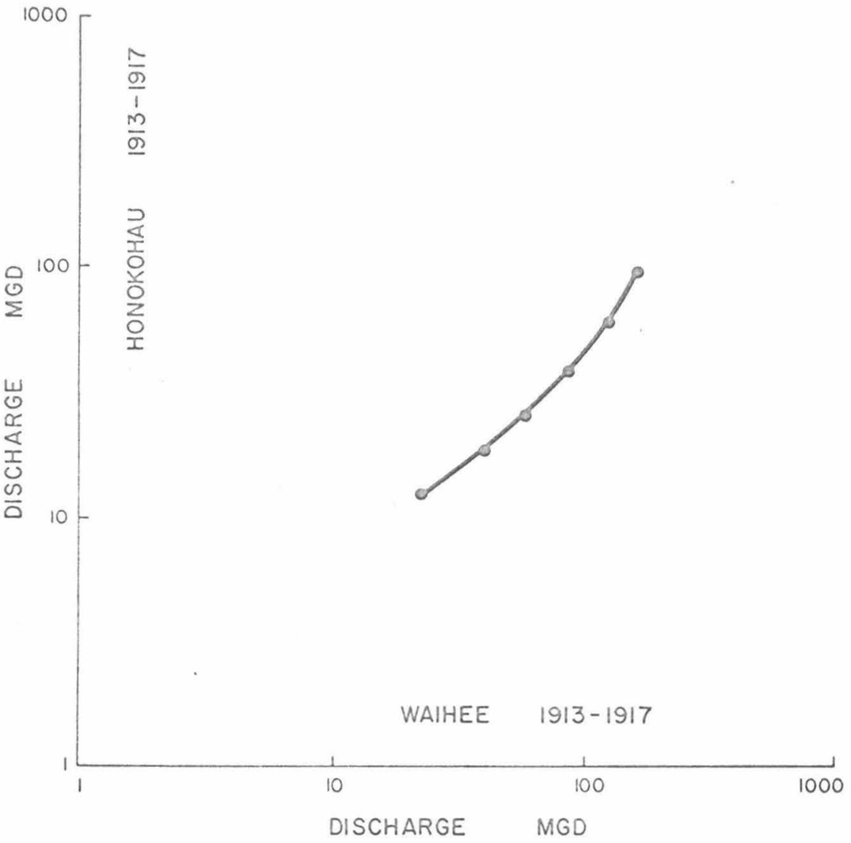

Plate 3. (continued)

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