Water Resources on the Island of Kauai
Territory of Hawaii

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Territory of Hawaii

The island of Kauai is one of the principal islands making up the Hawaiian group; it is fourth in size in the Hawaiian archipelego. Kauai lies 2100 miles south-west of San Francisco and 100 miles northwest of Honolulu. The center of the island may be located at approximately 22° 00' north latitude and 159° 30' west longitude.

The island is deeply eroded, roughly circular in shape with a mean diameter of twenty seven miles. There is a total land area of 555 square miles. The highest elevations, located near the center of the island, are about 5000 feet. Except for the eleven miles of Napali Cliffs which rise 1000 to 3000 feet directly from the ocean, a coastal plain surrounds the island.

Population

The population of Kauai is comparatively constant with a population of 35,636 in 1940. Figure 1 shows the plotted growth of population on the island. The figure shows a tremendous growth between the years 1878 and 1938 reaching a high of 39,914 in 1938. It is an arithmetic increase of approximately 5500 in each ten years. The decrease in population since 1938 is due to unsettled pre-war conditions. A very slow growth is anticipated in the future, being due principally to the excess of births over deaths.

The principal towns are all small and are summarized with their populations in Table 1. In general the population is located on the plains surrounding the mountainous center of the island.

Figure 1

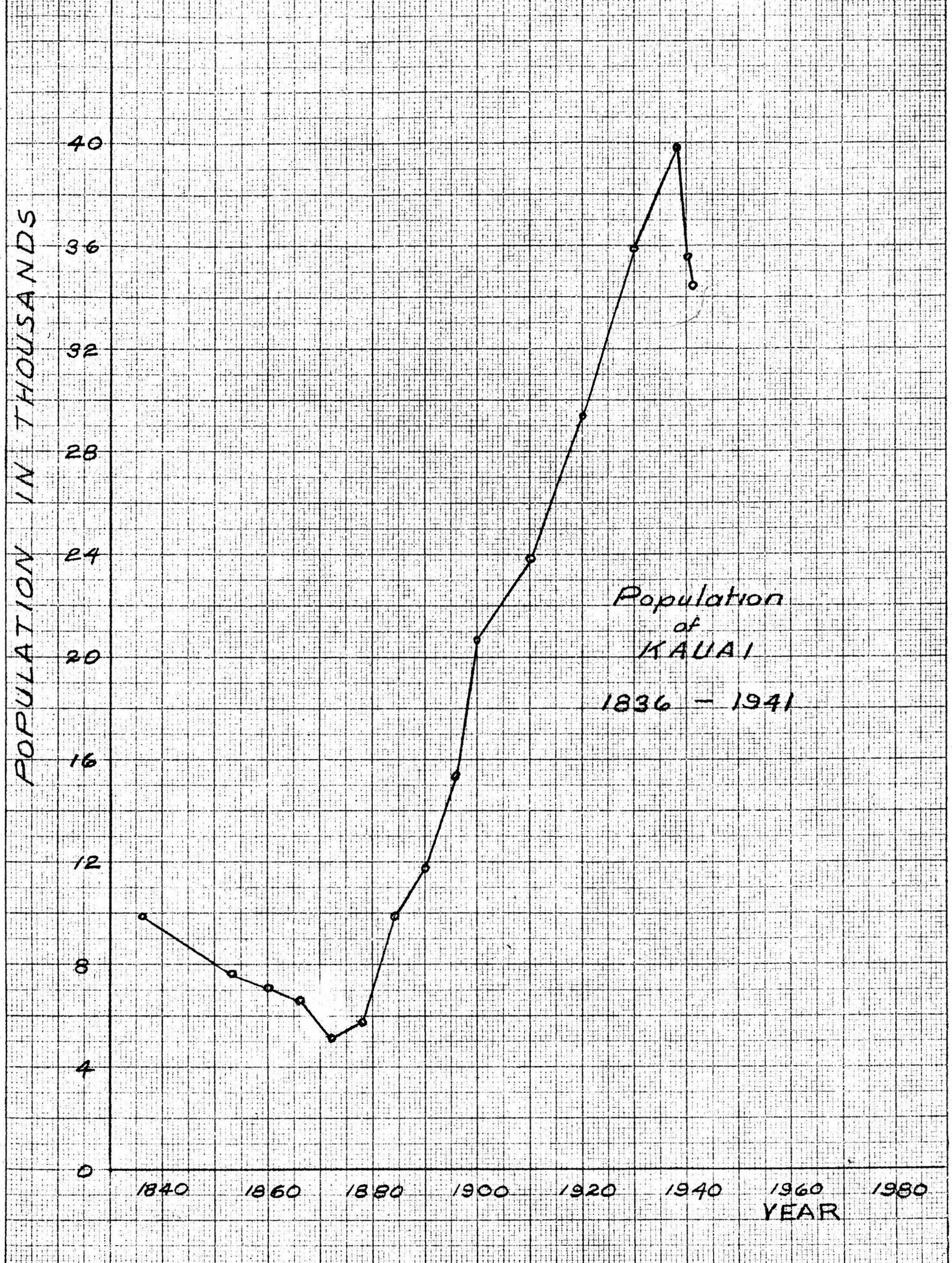

POPULATION IN THOUSANDS
40
36
32
28
24
20
16
12
8
4
0
1840
1860
1880
1900
1920
1940
1960
1980
YEAR
Population of KAUAI
1836 - 1941

Table 1

Population of Principal Towns on Kauai in 1930 and 1940 (1)

Town	Population 1930	Population 1940
Kapaa	2818	2828
Lihue	2400	4254
Waimea	2091	1921
Koloa	1844	1903
Hanapepe	1088	1166

While the rate of growth of population in the territory of Hawaii has exceeded that of the mainland because of immigration and also due to the higher birth rate and lower death rate than on the mainland as shown in Table 2, the population of Kauai has dropped since 1938. However, it may be expected to grow slowly with the end of the war at a rate primarily dependent on the excess of births over deaths.

Table 2

Birth and Death Rate, Territory of Hawaii (2)

	1930	1935	1940	1942
Births	10,814	9196	9414	10,422
Deaths	3865	3306	3089	3397
Births minus Deaths	6949	5890	6325	7025
Birth Rate/1000	29.4	23.6	22.2	23.6
Death Rate/1000	10.5	8.5	7.3	7.7
Birth Rate-Death Rate/ 1000	18.9	15.1	14.9	15.9

The population of Kauai is generally dependent on agriculture for employment. Forty percent of the territorial population was employed in agriculture in 1930. On Kauai an even larger percentage are employed in agriculture. The percentage employed in trade and transportation in the territory is small amounting to only thirteen percent in 1930.

The racial origins of the population in the territory of Hawaii are diverse.. The make-up of the population in 1938 is shown in Table 3.

The following points may be summarized as to the future population of Kauai:

1. The future growth of population will be mainly the difference between births and deaths.

2. Statistics of births and deaths in the Territory reveal:

   a. a high birth rate among all nationalities

   b. a general decline in birth rate

   c. an increase in birth rate among "other Caucasian" and Hawaiian stock.

   d. a very low death rate

   e. the approaching of a gradually increasing death rate due to an aging population

   f. a quite stationary rural population

   g. a density of 64.2 persons per square mile or one and a half times greater than for that of the United States as a whole

   h. a decreasing net alien migration

Table 3

Racial Origins of Population of Hawaii in 1938 (3)

Racial Origin		Percent of Total Population
Japanese		37.31
Caucasian		
Portugese	7.39	
Puerto Rican	1.86	
Spanish	0.30	
Other Caucasian	16.45	
Total Caucasian		26.00
Hawaiian and part Hawaiian		15.10
Filipino		12.83
Chinese		6.90
Korean		1.64
All Others		0.22
	Total	100.00

i. an average family size larger than that of the average for the United States (4.8 vs. 3.4 in 1930)

Industry and Agriculture

The island of Kauai is an agricultural community and its chief industries are those common to the other islands. Of the lands in agriculture, 59,000 acres or 16.6% are improved while 135,200 acres or 38.1% are unimproved. The utilization of land is shown in Table 4 and Figure 2.

Sugar

The sugar industry in the territory of Hawaii had its beginnings on the island of Kauai in 1835. Since then it has expanded until it is the major industry of the islands. Sugar exports in 1941 amounted to $47,266,417. for the territory and about one-fifth of which came from Kauai. At the present time there are eight plantations on Kauai with a total area under cultivation of 47,272 acres. (5)

In general the lands planted in sugar cane are all below an elevation of 1100 feet on Kauai because of the difficulties of transportation and irrigation at higher levels. The cane grows best with large quantities of water in hot weather. Consequently while the leeward side of the island is warmer the problems of supplying water are greater in that area as all the land must be irrigated. On the cooler, windward side of the island most of the water is supplied directly to the fields as rainfall. The effect of climate is taken up in a later section of this report.

Table 4

Land Utilization, Island of Kauai, 1900, 1920, 1937 (4)

Utilization	1900	1920	1937
Sugar Cane	23,000 acres	42,800 acres	47,000 acres
Pineapple	0	1,050	2,900
Grazing	164,600	143,600	135,600
Forest	142,000	147,000	149,000
Wet (rice, taro,etc.)	5,090	2,720	1,170
Macademia Nuts	0	3	200
Vegetables	200	272	335
Fruit	10	614	75
Federal	0	74	80
Field Crops	3,600	65	40
Parks	0	1,200	1,900
Other	17,100	16,200	17,300
Total	355,200	355,200	355,200

Pineapples

Before the birth of the pineapple agriculture as an industry there are records of pineapple fruits in the commerce records of Hawaii. In 1850 pineapples were exported from a number of points among which Waimea, Kauai is listed by the Royal Hawaiian Agriculture Society. In 1892 a cannery was established on Oahu and the industry developed rapidly. Using the acreage of lands as an index of the growth of the pineapple industry Table 5 shows this development..

Table 5

Acreage in Pineapples (6)

	1900	1910	1920	1930	1940	
Island of Kauai	0	50	1,900	2,945	2,950	acres
Territory of Hawaii	600	5360	46,895	50,124	49,598	acres

The present value of pineapples packed in the territory amounts to almost fifty million dollars annually with twelve to thirteen million cases of pineapples being packed. On Kauai there are two canneries, located at Kalaheo, and Kapaa respectively. They pack all the pineapples raised on the island.

Other Industries

The sugar and pineapple agricultural industries are developed in large economic units, the average plantation being 6000 acres in size. Probably seventy percent of the employed persons on the island are employed on these plantations. They are provided with their homes and other prerequisites in the form of fuel, water, hospital and medical service as well as cash earnings.

The other industries include the growing and processing of rice and taro, fishing, cattle raising and other small ventures. There is practically no manufacturing or mining industry on the island..

Economic Need for Water

In an agricultural area water and soil resources are the basis of economic wealth. In Hawaii this is particularly true because cane and pineapples are the only industries utilizing Hawaii's only resources--soil and water. The available water is one of the measures of wealth of Kauai and the development of water is an indication of the development of the resources of the island. There are two uses of water; for growing crops and for domestic use. Water for agriculture can be divided into two groups; that provided by rain, and that provided by irrigation. The windward side of the Hawaiian Islands all have a high rate of rainfall that is spread reasonably consistently throughout the year. Sugar cane is often grown just by this rainfall. On the leeward side of the islands the rainfall is not plentiful enough or spread throughout the year to provide the necessary water. Pineapples, generally, are raised without irrigation as they need much less water than sugar cane..

Irrigation

The growing of cane demands large quantities of water.

The value of water is illustrated by the following report of cost for Maui by H. T. Stearns. (7) "The gross water requirement excluding rainfall to raise a ton of sugar on the Pioneer Mill Company's plantation is 737,000 gallons, or 1,000,000 gallons for each 1.35 tons of sugar. Data regarding the value of water for growing sugar on the Pioneer Mill Company's plantation is given in Table 6."

Shaw (8) computed the value of irrigation water as a growth factor during months of low rainfall to be about $120. per million gallons, even at the low price of sugar in 1936. Soils require a minimum application of three to four acre-inches per acre for a thirty inch penetration. Only 38.7% of the gross water supply is utilized by the cane, the rest is consumed by transpiration, evaporation, deep percolation, and conveyance seepage. (9)

Sugar cane is raised on lateritic soils, alluvial soils, ash soils, and boulder deposits on Maui. Some of the rockiest fields farmed anywhere in the world grow large crops of cane near Olowalu. Shaw (10) has aptly expressed the part played by water and nutrients in the following: "Agricultural text books for the past century have glorified the fertile, mellow loam, and have implied that the farmer who cannot sink his plow into a deep friable soil is indeed destitute. The present school of agricultural workers look upon soil as a mass of inert rock fragments of various shapes, sizes, and chemical composition, but with no other function than as a physical support for the plants, and as a reservoir for water and nutrients from

Table 6

Average water needs, rainfall excluded, 1935-1940 for Pioneer Mill Company Plantations (12)

On 10,000 acres of cane:	Water
Annual amount used	34,107,874,000 gallons
Monthly amount used	2,842,322,500 gallons
Amount per acre per crop (21.57 mon)	6,130,884 gallons
Amount per acre per annum	3,410,787 gallons
Amount per acre per month	284,232 gallons
Amount per acre per annum	10.4 feet
Amount per acre per month	10.4 inches
Amount per acre per crop	18.7 feet
Amount per 1.35 tons of sugar (96°H.S.)	1,000,000 gallons
Amount per 1 ton of sugar (96°H.S.)	737,000 gallons
Amount per 1 ton of sugar (96°H.S.)	3,070 tons

which the plants may draw. The capacity of this subterranean reservoir may vary with the physical nature of the soil particles but essentially there should not be a great difference in the inherent productivity of soils so long as the soil reservoir is filled with the proper amounts and combinations of raw materials from which the plant is manufactured.

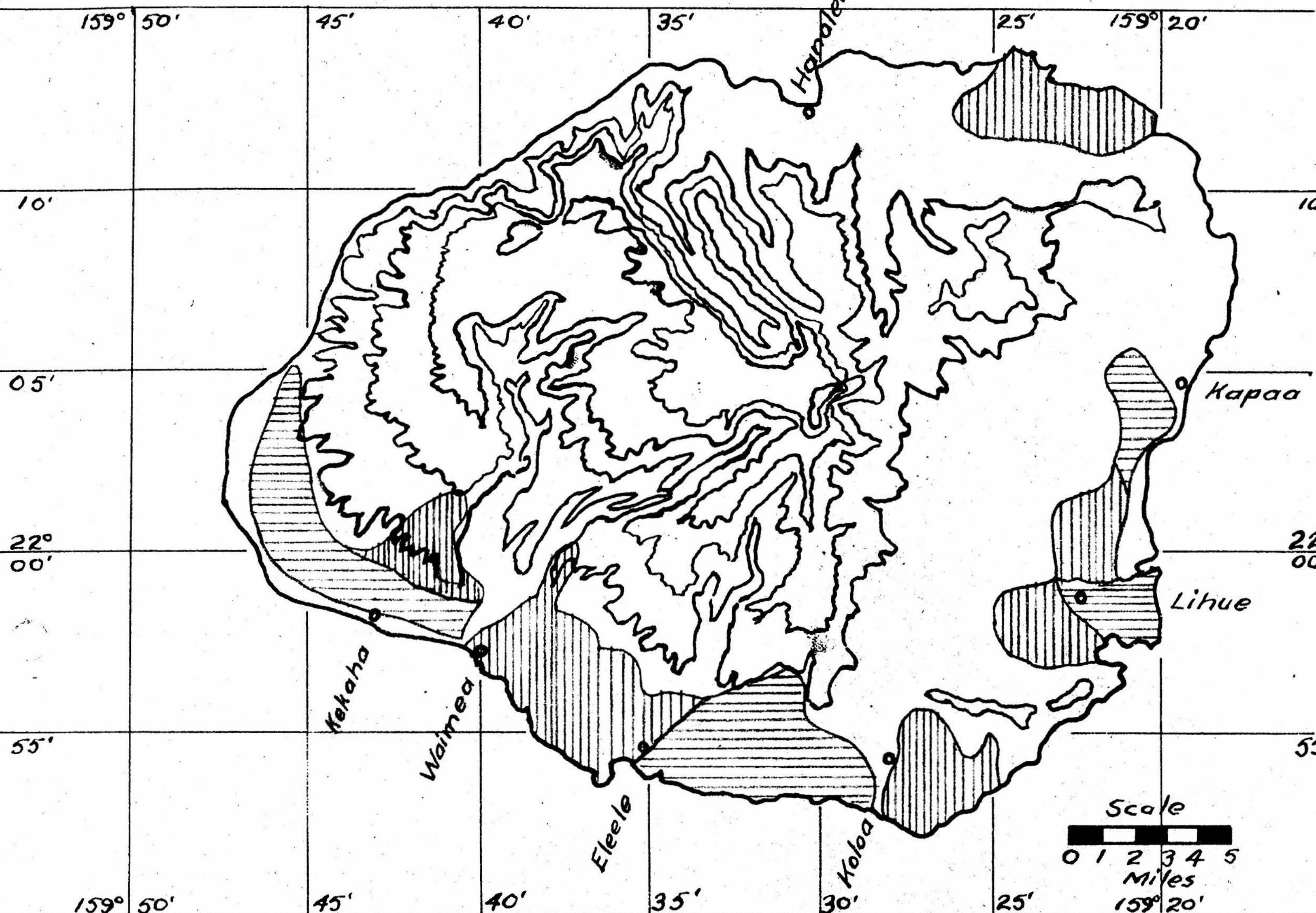
We need not look far for examples of such heretical theory, for no place in the world better illustrates this conception than on the Hawaiian Islands. Many of the fields in which Hawaii consistently establishes high-production records are tight black adobes, thin sheets of top soil over a base of coral rock, or boulder-strew flats in which cultivation is performed with pick and shovel. In all of these cases, the factors that cause record yields are not the beautiful farming loams, but a fortunate combination of ideal climatic conditions, and a skillful forced feeding of water and artificial fertilizers."

Mr. J. H. Foss, manager of the East Maui Irrigation Company, estimates that the value of a continuous low flow of one million gallons a day from water-development tunnels at the ditch level in the Nahiku area of East Maui is $16,000. (11)

Despite the heavy rainfall on many of the plantations irrigation water obtained from surface and ground supplies must be supplied. Figure 3 shows the irrigated lands on Kauai using ground and surface water supplies. The total irrigated lands amounted to 39,480 acres in 1938. Of this total, 38,384 acres were planted in sugar cane, 982 acres in rice and 114 acres in taro. (13) Only the island of Oahu contains more irrigated

Figure 3

Map of Kauai Showing Irrigated Land



Topography: 1000' contour interval
Scale 1" = 5 mi.

IRRIGATED SUGAR CANE

Surface Water [vertical hatching] Ground Water [horizontal hatching]

Irrigated Land	Acres
Sugar Cane	38,384
Rice	982
Taro	114

Average Quantity
Daily 374 m.g.

Investment in Ditches
Wells, & Pumps
& power $5,841,135

Source Terr. Planning Board 1939

land on any one island in the Hawaiian group. An annual average of 374 million gallons per day is supplied for irrigation. The investment in ditches, wells, pumps, and power amounted to $5,841,000 in 1938. This total amounted to one-fifth the territorial total of $29,891,000 investment and amounts to an average investment of $178 for ditches, wells, pumps, and power per acre. (14) An idealized seasonal variation curve is shown in Figure 4. This is based on the requirements of the McBryde Sugar Company. This shows the peak demand lasting for about three or four of the driest summer months when irrigation must be depended upon for all the water supplied to the sugar cane. The power demand is relatively constant throughout the year. It is the seasonal demand for irrigation that makes storage of surface flows necessary as this demand comes during months of relatively low stream flow. The great advantage of ground water lies in the fact that surface storage facilities are relatively expensive as impermeable reservoir sities are almost nonexistant. Ditch systems have been constructed in nearly all the valleys between the Waimea and Wainiha Rivers to carry waters from the upper reaches of the streams to the cane fields on the lowlands.

One example of a reservoir supply is Alexander Dam, built and maintained by McBryde Sugar Company. This dam is a hydraulic earth fill structure 140 feet in height with a crest length of 620 feet. It has a total volume of 540,000 cubic yards of fill and cost approximately $16,000 although there was a partial failure during construction. The dam backs up a reservoir of

810,000,000 gallons or 2500 acre feet of water. The dam is situated at an elevation of 1485 feet above sea level on the Wahiawa stream. The stream drains an area of 2.64 square miles at the position of the dam which has an average rainfall of 180 inches per year. (15)

The reservoir of the Koloa Sugar Company at Koloa is the largest on the island and has a capacity of two and one half billion gallons. The pumping plant raises 3,000,000 gallons every twenty four hours..

Domestic Water

The demand for domestic water supply is small. The towns on the island are all small. A good number of the people live on plantations and are provided water by the plantation for their homes. Figures for the county water system are quite complete. Service is made to 2143 connections with an annual consumption of 558 million gallons or 715 gallons per connection per day. (16) Table 7 gives the data on the domestic water supply in 1938. Figure 5 gives the location of the county mains.

Probable Future Needs

Further development of water would be demanded by increased domestic, irrigation, or industrial use. The population of Kauai is not expected to increase at any large rate and industries are non-existant so than any increased demand will be for irrigation.

At the present sugar production in Hawaii is limited by law, the Jones-Castigan Act of 1934. Accordingly, the acreage was cut back in 1934 by 24,238 acres and has remained that way

Table 7

County Water Works, Island of Kauai, 1938 (17)

No.	Locality	No Serv.	Miles Mains	Cons. MGD	Storage Capacity MG	Value
1	Kawaihau	509	8.2	.46	04	$ 66,799.
2	Wailua House-Lots	59	14.4		.4	118,250.
3	Lihue	317	12.9	.27	.2	86,339.
4	Kalaheo	185	5.8	.13		14,595.
5	Lawai	71	2.4			10,533.
6	Waimea	324	3.1	.29	.10	20,840.
7	Kekaha*	73	3.1	.01		7,323.
8	Wahiawa-Omao-Koloa	None	6.0		.30	66,989.
9	Hanalei	78	2.8	.10		7,189.
10	Haena	11		.01		934.
11	Hanapepe	204	7.0	.07	.06	40,091.
12	Puukapele	25	2.3	[illegible]	.01	6,886.
13	Wanini-Kalihikai	7		.01		481.
14	Anahola	65	3.1	.01		8,084.
15	Moloaa	12		.01		209.
16	Kalihiwai	14	.6	.02	.005	1,839.
17	Koloa*	189	5.1	.13		11,477.
18	Omao	30				259.

* Plantation source where plantation and county utilize the water.

Table 7a

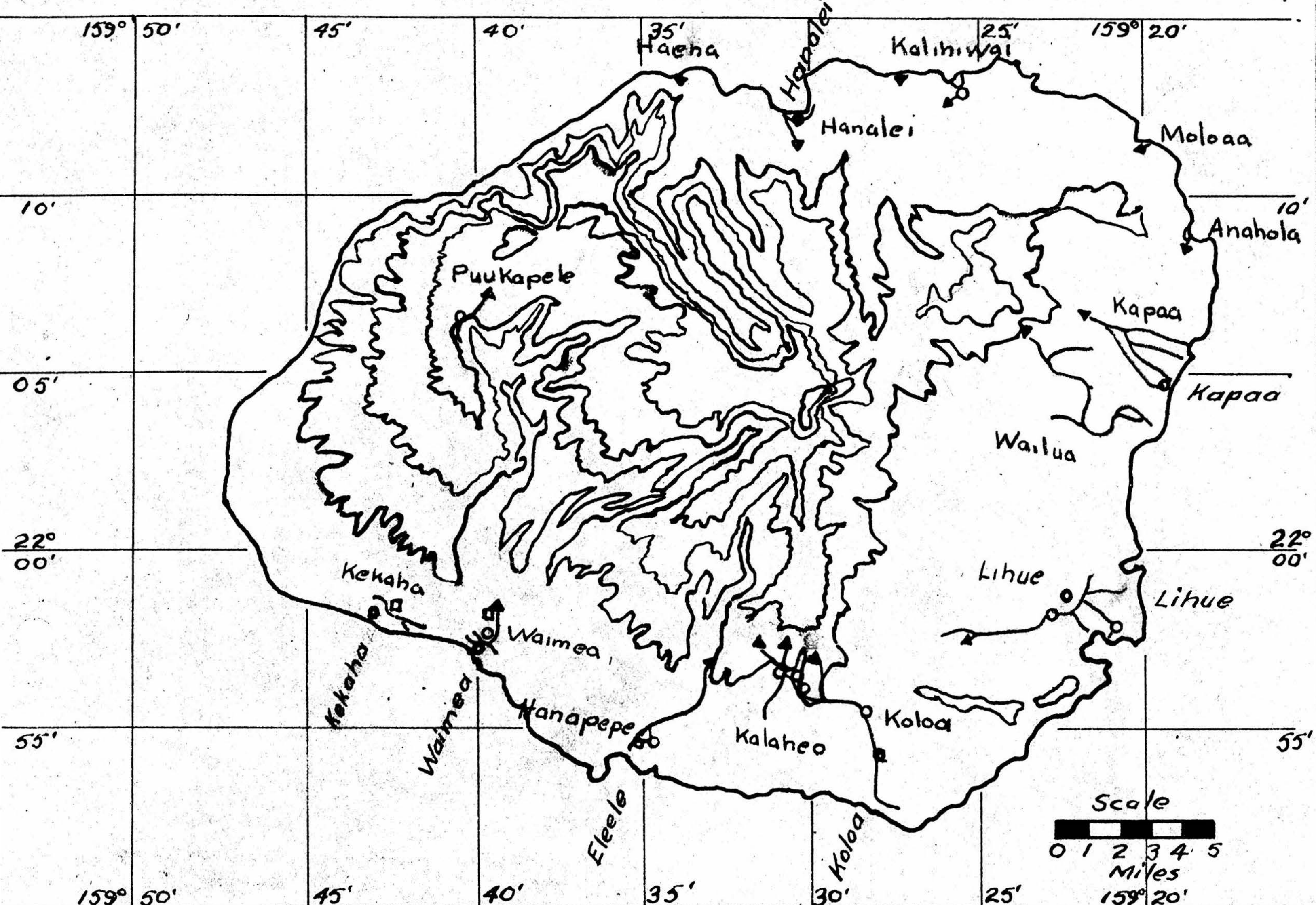
Plantation Water Supply, Island of Kauai (17)

No.	Locality	No Serv.	Source of Supply	25% Excess Capacity	Certified Supply
19	Kilauea	50-100	surface	yes	---
20	Kealia	250-500	well	yes	yes
21	Lihue	over 500	tunnel	yes	yes
22	Puhi	250-500	tunnel	yes	yes
23	Aakukui	100-250	tunnel	yes	yes
24	Koloa*				
25	Wahiawa(1)	over 500	surface	yes	---
26	Wahiawa(2)	250-500	surface	yes	---
27	Eleele	over 500	surface	no	---
28	Pakala	under 50	surface	yes	---
29	Waimea	100-250	tunnel	yes	yes
30	Hukipo	under 50	surface	yes	filtered supply
31	Kekaha*				
32	Kaunalawa	under 50	surface	no	filtered supply
33	Mana	under 50	tunnel	no	---
34	Polihale	under 50	surface & well	yes	yes

* see county water works supply table

Figure 5

Map of Kauai Showing County Water



Topography: 1000' contour interval
Scale 1" = 5 mi.

County Water Mains

▼ Spring, Tunnel
o Tank
— Main

Source: Terr. Planning Board 1939

since that time. As the quota limits the tonnage of sugar produced, technological advances in growing the acreage will decrease rather than increase. It should be noted that the production of sugar per acre in Hawaii is approximately three times as high as in Cuba, Puerto Rico, or continental United States where twenty tons per acre are common, and is shown in Table 8..

Accordingly, the development of future water is primarily a political question. With a revision or end of the quota the development of sugar would be dependent upon the price of sugar which is again influenced by the tariff on Cuban sugar, a political question. Any estimate of future irrigation needs for sugar cane is unwarrented and will be decided by a mixture of political and economical facts. It might be noted that since 1910 the annual wholesale price per pound of refined sugar has ranged from a high of 13.176 cents in 1920 to a low of 2.93 cents in 1932 and 1938.. There has been an equally wide variation in the total values of the crop with a low of 43 million dollars in 1910 to a high of 146 million dollars in 1920. (19)

As pineapples are grown without irrigation water at present the change in acreage of pineapples does not affect the quantity of irrigation water..

Geomorphology

The islands of Kauai and Niihau represent the highest summits of one of the principal volcanic mountains in the Hawaiian

Table 8

Production of Sugar, Hawaii (18)

Year	Cane Prod. 1000 tons	Tons per Acre	Equ. Refined Sugar
1930	8485	62	951
1931	8865	63	988
1932	8567	59	994
1933*			119
1934	7992	60	897
1935	8555	68	922
1936	9170	70	974
1937	8803	70	883
1938	8835	65	880
1939	8610	62	929
1940	8557	63	913
1941	8560	66	885
1942	7918	69	813
1943	8185	72	828

*Change from crop to calender year..

range. The mountain area of the base is not accurately known because of limited soundings but is estimated as having major and minor diameter of 100 miles and 50 miles respectively. (20) The total height of the mountain is between 17,000 and 22,000 feet. The island of Kauai rises 5000 feet above sea level and has a long diameter of thirty three miles and a short diameter of twenty five miles.

Kauai is the most weathered of the windward group of islands. Originally it was of the simple "lava dome" type of structure, similar to the young volcanoes in the Hawaiian group, Mauna Loa, Mauna Kea, Kilauea, and Hualalai. It was a land form of simple outline composed of relatively homogeneous layers of rock dipping seaward at an angle of ten degrees. It was probably about at the present height. At present the principal eruptive area is hidden below the jungle mantle. In the central part of the island the dip of the lava flows diminishes to less than three degrees indicating this as the eruptive center. There may not have been any sink or crater. If there was it is filled at present. Fissures were numerous and are evidenced by abundant dikes throughout the island. The lavas are cut at only one known horizon by a conglomerate which may be seen in the Waimea Canyon at an elevation of 500 feet above sea level. This conglomerate does not exceed 75 to 100 feet in thickness, and was originally thought to indicate a long erosional period. However, in a later study, Stearns (21) points out that the lava overlying the conglomerate is a flow belonging to the Koloa volcanic series; hence it is not evidence of an erosional interval.

The dominant Kauai lavas are olivine basalts. They compose about 85% of the visible land mass and range in color from medium gray to black or greenish black.

Table 9

Analysis of Hawaiian Lavas (22)

	Group 1	Group 2
SiO_2	47.24%	48.69%
Al_2O_3	12.80	14.00
Fe_2O_3	1.79	5.03
FeO	10.17	8.01
MgO	13.42	7.12
CaO	9.16	9.00
Na_2O	1.92	3.55
K_2O	0.52	1.24
H_2O	0.50	----
H_2O-	0.17	----
TiO_2	1.82	2.29
P_2O_5	0.19	0.49
MnO	0.18	0.41
Total	100.24	99.83

Group 1--Average of two field groups:

a. Coarse-grained chrysophyre, Olokele Canyon, Kauai
W. T. Schaller, analyst

b. Fine-grained chrysophyre, Olokele Canyon, Kauai
W. F. Hillebrand, analyst

Group 2--Average of forty three Hawaiian Lavas by Cross, "Lavas of Hawaii and their Relations",U.S.G.S.. Sur. Prof. Paper 88, 1915.

The weathering of Kauai lavas has taken place under a great variety of climatic conditions of rainfall. Primarilly the weathering has been chemical. Mechanical disintergration is only important along the sea coast, stream beds, and on steep slopes where landsliding and creep are found. Only at the highest elevations is frost ever found and even there relatively infrequently. The soils and subsoils are in general residual. On the lowlands of eastern Kauai alluvial deposits have been formed.

The soils are primarily lateritic of varying composition.. In the drier portion of the island the soils are brick red in color while in the wetter portions they vary in color becoming darker red and brown. Yellow, gray, or green subsoils of throughly decomposed lava are general..

Table 10

Composition of Kauai Soil from Koloa, southern Kauai (23)

Volatile Matter	15.60%
Fine Gravel Coarse Sand	1.23
Fine Sand	11,78
Silt	11.65
Fine Silt	24.20
Clay	35.80

Table 11

Soil Analyses, Kauai (24)

	Average of 26 soils	Average of 8 subsoils	Alluvium
Insoluble residues	31.03%	29.98%	44.57%
Al_2O_3	19.16	22.77	18.81
Fe_2O_3	21.50	20.57	16.37
MgO	1.32	.66	3.46
CaO	.60	.33	1.13
Na_2O	.31	.36	.30
K_2O	.38	.31	.17
TiO_2	1.66	1.90	2.62
Mn_3O_4	.38	.42	.27
P_2O_5	.50	.40	.49
SO_3	.32	.32	.29
N	.12	.12	.19
H_2O	99.16	8.14	----
Volatile matter	10.05	14.57	12.56

The original simple dome-like structure of Kauai has been modified by fluvial and marine erosion, by downfaulting, by changes in relative levels of the land and the ocean and by tilting. As a consequence the island can be divided into four major divisions at present:

1. The summit plateau
2. The dissected highland
3. The wave cut platform of eastern Kauai

4. The constructional plain lying west of the Waimea River

1. The summit plateau

The summit plateau or Alakai Swamp is the principal remanent of the constructional surface of the Kauai dome and extends over an area of thirty square miles. Most sides of the plateau are clearly defined by great palis, cliffed walls and canyon mouths. The general slope of the plateau is southwest. The surface of the plateau is traversed by ill-defined drainage lines. Rolling topography is characteristic of the summit. It rains constantly on the plateau and because of the low relief drainage is slow and large areas are swampy. The area is treeless except for the highest areas and dry areas are covered by jungle growth. Because of the high temperature rapid plant tissue decay is present and organic acids are added to the subsurface water which percolates through the porous lava..

2. The dissected highland

The dissected highland of Kauai covers two-thirds the area of the island. Dissection is of varying intensity, being much greater on the windward side of the island because of the great volume and number of streams. Along the leeward coast downcutting has been so much slower that the mouths of many of the gorges still hang some distance above the base of the great cliffs. According to Hinds, (25) the greater drainage on the windward side of Kauai has been aided by two special conditions: (1) abnormal development of drainage due to deflection of a part of the streams by a fault zone along which the Waimea River runs, and (2) downfaulting of a large section of the eastern part of the dome. However, Stearns (26) in a later study points out that while the position of the Waiahulu tributary was determined by a fault, Waimea Canyon from the mouth of this fork to the sea owes its position to displacement westward by lava flows of the Koloa volcanic series..

Canyons are in general narrow with steep walls as a result of the speed at which downcutting has taken place and the average high resistance of the lavas to erosion. Surface lavas are deeply weathered and the streams cut through rapidly. Because of the abundant precipitation, average high temperature, and the extremely porous structure of the lava chemical decay proceeds rapidly. Atmospheric and ground water solutions readily penetrate and attack the rocks, and on the windward side in particular, they have altered the rocks to considerable depths. Mechanical disintergration is at a minimum, except in channels of streams, along the shorelines, and in places where landsliding of large rock masses takes place. The major streams are large and have moderately steep gradients; hence they are rapidly deepening their canyons and eroding them headwards..

3. The wave cut platform

The wave cut platform of eastern Kauai, extends from Hanalei Bay on the north to Waimea River on the south. The platform varies in width from one to eight miles and the gradient is sixty to a hundred feet per mile. In places there are cliffs 100 to 250 feet in height..

Hinds (27) feels that the wave cut platform is an emerged marine abrasion platform rather than the work of streams and cites the following points:

1. The platform slopes from the base of the highland towards the shoreline rather than from a series of divides towards the various river valleys..

2. The ends of the spurs along the inner margins of the platform are frequently sharply truncated, hence they mark the line of former shore cliffs.

3. The prominent ridges paralleling the shore of eastern Kauai have been wave cliffed..

4. The surface of the platform is more even and its gradient more uniform than if the platform were the product of fluviatill erosion.

5. At various localities, minor terraces have been cut into the main structure indicating apparent interruptions in the emergence.

6. Boulder beaches are present at many places along the shoreward margin of the platform.

Hinds reports some volcanic activity on the platform after emergence with the largest of the tuff cones being Kilohano near Lihue. Most of the cones are deeply eroded, some by marine action according to Hinds..

A later study made by Stearns (28) points out, however, that this is not a marine plain but a series of plateaus built by lavas of the Koloa volcanic series. The hills or tuff cones thought by Hinds to indicate post-emergence volcanic activity are erosional remanents of the lower member of the Waimea volcanic series nearly buried by the lavas of the Koloa series as shown by the dip and character of the lavas in them.

4. The constructional plain

The constructional plain is a crescentic lowland (Mana Flats). At one time, before emergence, a reef grew on the platform but is now covered with debris eroded from the basaltic highland. The greatest width of the plain is about two miles; nowhere does it exceed fifty feet in elevation above sea level. A coastal rampart of sand dunes less than thirty feet in height constitutes the only relief. Shallow, salt marshy depressions of considerable size are present at a number of places behind the coastal dunes. Along the base of the highland talus and alluvial aprons are common. There are no valleys cut in the plain; any flood waters are quickly absorbed in the porous soil.

Coastal Topography

The coastal topography of Kauai is relatively simple. The principal indentations are Hanalai Bay, Nawiliwili Harbor, and Hanapepe Bay. Before the creation of the plateau, Kauai was strongly cliffed on all sides. It has been suggested that the cliffs of western Kauai were eroded by winds when prevailing wind direction was different than today. The eastern cliffs are stream eroded. The straightness of the Napali Coast is the most notable feature of the Kauai coast. Stearns (29) points out that this is not a fault scarp as commonly supposed. It was caused by marine erosion battering back, as the island submerged the interstream divides composed of weak lavas in the lower member of the Waimea volcanic series. The sea has been arrested by a massive wave resistant upper member of the series. The ancient fault dips southeastward away from the coast rather than northwestward into the ocean.

The Fringing Reef

At various localities along the coast are patches of narrow practically extinct fringing reef. These are naturally widest and most extensive on the windward side but even here there are long stretches of reef-free coast. At a number of places there are small colonies of reef building organisms which can hardly be designated as reefs.. Along the Napali Coast there are two small reefs at Milolii and Nualolo. An extinct fringing reef probably underlies the surficial deposits of the southwestern crescentic plain (Mana Flats).

The reefs about Kauai and other islands are discontinous and feebly developed. Apparently the reefs developed in late Pleistocene or Recent times in seas none to favorable for the reef builders.. Later they have been gradually killed off as certain elements in their environment became less satisfactory.

Sedimentary Deposits

The chief sedimentary deposits thinly veneer the coastal margins of Kauai and have accumulated to depths of a hundred or more feet in the mouths of valleys crossing the eastern platform. Inland there are local talus cones and aprons, stream gravels and boulders of minor importance. Sediments for the most part are of recent age.

Drainage Basins

According to Martin and Pierce, (30) the drainage basins of Kauai are determined by three great ridges which branch off from Waialeale and Kawaikini, the central and highest points of the island: "One of these ridges extends toward the northeast through peaks back of Kealia and along the crest of the Anahola Mountains to the sea. The other two constitute the main divide or backbone of the island, which, starting at the southeast, follows along the Haupu Ridge east of Koloa across the Koloa-Lihue Gap and then northward along the ridge east of Hanapepe basin to the summit, where it turns slightly to the northeast along the western edge of the Wainiha Basin to the sea. Another important divide leaves the main one at Kilohana, north of the Alakai Swamp, and follows westward along Kaunuohua Ridge, and then southward along the western edge of Waimea Canyon to the sea. These watersheds mark out four distinct drainage areas or basins."

Hinds (31) points out, however, that Martin and Pierce have included some streams from the Alakai Swamp which flow to the northwest coast in the morphologically unrelated western drainage basin. Hinds draws a more natural boundary for the northern province thusly: "The western rim of Wainiha Canyon from Waialeale to Kilohana from the latter point westward along Kaunuahua Ridge and then northwestward to the sea along the divide between Awaawapuhi and Nualolo valleys." Hinds named three of the drainage basins from the principal streams running through them--Northern or Hanalei Basin, Eastern or Wailua Basin, Southern or Hanapepe-Waimea Basin, and the Western Basin for the name of the low arid flats--Mana Flats. These drainage basins are shown in Figure 6.

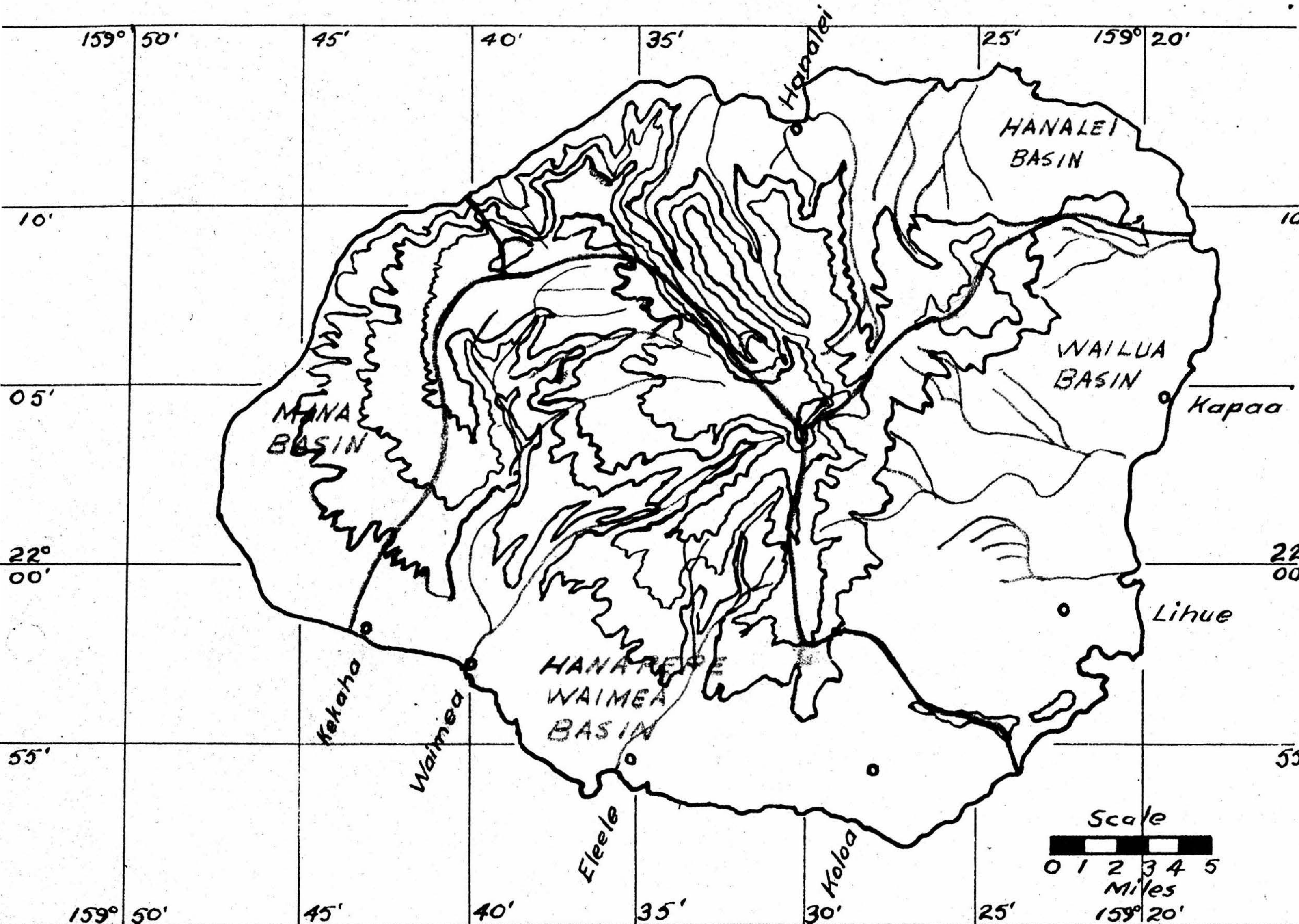
The Hanalei Basin receives on the average the heaviest rainfall of the island, hence its streams are the largest and most numerous. The chief rivers are the Wainiha, the Hanalei, and the Lumahai, while of less importance are the Waioli, the Kalihiwai, the Kilauea, and the Moloaa. The streams crossing the section of the basin west of the Wainiha River are smaller but their short canyons compare in depth with those farther to the east. The source of the drainage flowing through this basin is either in the bogs of the summit plateau or from precipitation which falls over the crests and northern slopes of the Anahola Mountains. As with all of the streams of Kauai and of other parts of Hawaii, underground drainage, which migrates rapidly through the porous and cavernous lavas, is an important or even a principal source of the surface streams.

The main rivers of the Eastern or Wailua Basin are the two forks of the Wailua River, which flow from the summit plateau and the adjacent mountain slopes. There are several minor streams which drain areas to the north and to the south of the Wailua systems.

The largest rivers of the Southern Basin are the Hanapepe, the Olokele, the Mokihana, and the Waimea. Through this area passes most of the run-off from the Alakai watershed. While it

Figure 6

Map of Kauai Showing Drainage Basins



Topography: 1000' contour interval
Scale 1" = 5 mi.

Four Principal Drainage Basins on Kauai

Source: Hinds - Geology of Kauai & Niihau has been thought that the Waimea system was displaced by a fault running along the course of the Waimea River, it is now shown that only the Waiahulu tributary was determined by a fault and the Koaie, the Waiale, the Oomau, and the Mokihana are displaced by lava flows of the Koloa volcanic series.

The western or Mana Basin is nearly cut off from the Alakai watershed by the wandering, southward flowing Waimea River. Because the precipitation over the basin is light, and occurs very largely during the rainy season, most of the streams have water in them only during the heavy rains.

In general, the courses of the streams flowing from the summit plateau are roughly radial.

Surface Flow and Underground Drainage

In Hawaii, the most casual observations show that the amounts of run-off and of water penetrating below the surface vary greatly at different times in the same area and vary permanently over different sections of the same mountain. This is notably so on the higher, better watered domes of the group.

On Kauai, no quantitative measurements of the relation between run-off, evaporation, and accessions to the groundwater supply have been made, but certain general facts are perhaps worthy of brief consideration.

1. On the mountains of Kauai, the windward slopes receive much heavier precipitation than do the leeward. Because of the more abundant run-off and groundwater, the windward rivers are larger, more permanent, and less subject to great fluctuations in volume.

2. The storms vary greatly in intensity; during the rainy season, the fall of water is extremely heavy, so that very high maxima are commonly measured for brief periods of time. The precipitation over the whole island is in the form of rain. It is evident that the accessions to the groundwater supply are much more per unit of water falling during the light rains of the drier months than during the torrential rains.

3. According to existing records, Kauai is the most heavily watered of the Hawaiian Islands; the grestest annual average measured elsewhere in Hawaii is 350 inches on the summit of West Maui. Over the Kauai lowlands, most of the rain falls during the winter months; on the highland slopes, it is much more uniformly distributed throughout the year.

4. The relief of most parts of Kauai is extremely rugged, and the slopes are steep. The eastern platform, the various constructional plains, and the summit plateau have gentle slopes. The constructional plains have the least diverse surfaces and the lowest slopes.

5. Except in the rainy sections of the island, the soils are porous and allow the ready penetration of groundwaters. Even through the more compacted clayey soils of the heavily watered upland, great quantities seep. The most porous surficial materials are the moderately coarse grained calcareous and basaltic sands of the constructional lowlands, and through these even the torrential flow from the highland valleys quickly sinks. Below the soil cover and the zones of deeply weathered

rocks, the fresher lavas are abundantly supplied with openings; vesicles; vesicular, scoriaceous, and brecciated flow tops; joints of all sizes; cavernous spaces between the various layers of many flows and between the flows themselves; and faults. Even though much compacting has taken place from the crushing weight of the overlying lavas, the rocks exposed farthest below the surface have innumberable channels through which waters can penetrate. A few extremely dense flows and many of the sills and narrow dikes are relatively impervious.

6. Except in the rainiest sections, the saturation of the soils and immediately underlying rocks varies with the seasons. During the rainy months, the water table is close to or at the surface, but falls rather rapidly during the drier portion of the year. In the uplands, the more or less continuous fall of rain keeps the soils well saturated. Farther below the surface, certain of the porous zones evidently carry nearly their maximum quantity of water, but most are far from saturated.

7. The lavas dip seaward from the central part of the island at angles generally less than ten degrees. This domelike structure, combined with the high porosity of the rocks, makes for the active migration of the groundwater solutions. Downward penetration and migration along the dip are rapid. The meteoric supply works its way for some distance below sea level, and has sufficient head to force back the ocean waters which otherwise would occupy the openings. Wells drilled far enough from the sea and reaching zones in which the flow of water is rapid re-

main fresh. Migration of groundwater and the abundance of the supply are apparent along most of the mountain slopes; many streams are fed from spring lines and not from the surface flow. Not infrequently these springs are located hundreds of feet below the crests of the interfluves.

8. The vegetation cover in the rainy sections plays an important part in checking the rate of run-off from the steep slopes. Over the lowlands and the leeward sections the plant cover is relatively scanty.

Permanency of Streams

On the windward side of Kauai there are fifty nine permanent streams and two intermittent. There are many tributaries on the large streams. There are only fourteen permanent streams on the leeward side of the island, and sixty intermittent streams. There are few tributaries on the leeward streams.

Climate

The outstanding features of the climate of the island of Kauai are the remarkable differences in rainfall over adjacent areas; the tenaciousness of the trade winds throughout all seasons; and the persistently equable temperature. It is these features of an even warm climate with considerable rainfall that make the Hawaiian Islands so suitable for tropical agriculture. Although the islands are at the northern margin of the tropics, they have a subtropical climate because cool waters from the Bering Sea drift to the region. The temperature of surrounding waters is about 10°F. lower than that of other regions of the same latitude; and this relative coolness is, in part, the reason for poor development of coral reefs.

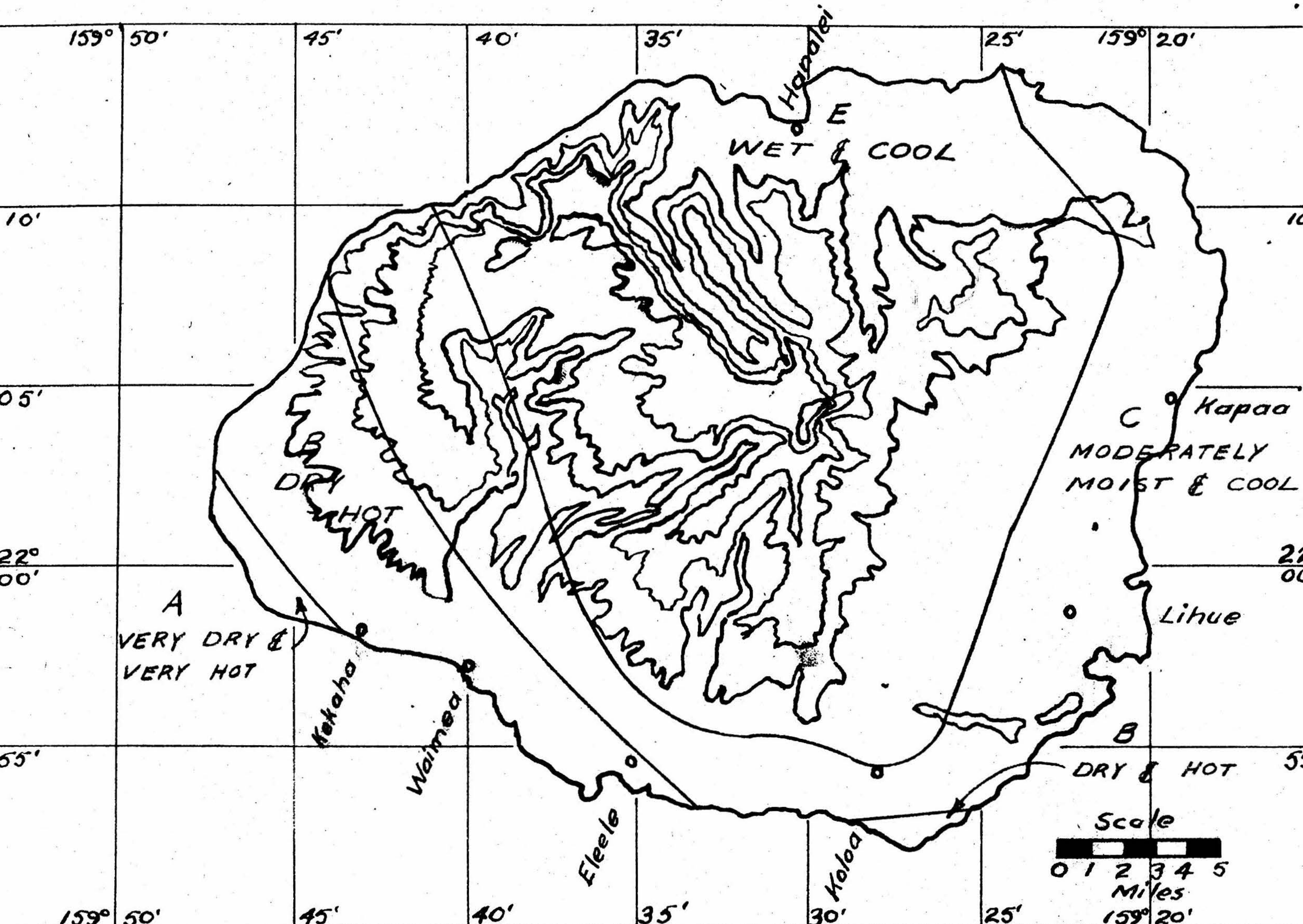
Kauai may be divided roughly into four climatic zones. These are shown in Figure 7. Zone A is characterized by a very low rainfall and high temperature; an effective rainfall corresponding to twenty inches or less annually. This zone occurs chiefly on the leeward side of the island and the chief indicator plants are algaroba and native pili grass. Zone B is characterized by low rainfall and high temperature; an effective rainfall corresponding to twenty to thirty five inches annually. Zone B is chiefly on the leeward side and the indicator plants are lantana, ilima, cactus, and haole-koa. Zone C has moderate rainfall and temperature; an effective rainfall corresponding to thirty five to sixty inches annually. It occurs in the uplands, in the leeward slopes and table lands and in the lower lying areas on some of the windward islands. Characteristic indicator plants are Bermuda and rat-tail grass. Zone E is characterized by high rainfall and moderate temperature; an effective rainfall corresponding to an annual rainfall of sixty inches or more. It is the characteristic climate of the windward slopes of the island and the dome of Mt. Waialeale on Kauai.

Temperature

The territorial average mean temperature is 71.9°F. for the forty year period from 1905 to 1945. At an average station

Figure 7

Map of Kauai Showing Climatic Zones



Topography: 1000' contour interval
Scale 1" = 5 mi.

Climatic Zones on Kauai

Source. Terr. Planning Board 1939

there is 7.5°F. difference between the mean temperature in the warmest and coolest months. (32) The highest temperatures are recorded on the leeward side of the island and the lowest occur at the highest altitude, a range of temperatures from below freezing to 97°F. Table 12 gives the average monthly temperature, mean maximum temperature, mean minimum temperature, and the highest and lowest temperatures for a number of well established stations on Kauai..

Records on Kauai are not extensive enough to provide data as to the variation of temperature with elevation. Data from throughout the islands indicates that there is a temperature decrease of 1°F. for each 300 feet rise in elevation. Frost is almost never known below 4000 feet elevation. Only on the islands of Maui and Hawaii at very high elevations above 9000 to 10,000 feet is snow found..

On the whole the climate is unusually pleasant for the tropics. There is little uncomfortable heat for the latitude.. Nevertheless it seems doubtful that one could find anywhere else, within such short distances, such a wide diversity of climate as in the Hawaiian Islands. Within a few miles of each other there is practically uninterrupted summer in the lowlands while at the highest elevations cnnditions approach continual though moderate winter. So called "thick weather" is practically unknown and is confined to mist and rain weather rather than fog..

Wind

The Hawaiian Islands lie in a belt of northeasterly trade

TEMPERATURE DATA KAUAI

TABLE 12

Station	Elev.	Years of Record	Jan	Feb.	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Annual
			AVERAGE TEMPERATURE BY MONTHS °F												
Eleele	150	28	70.8	71.0	71.4	72.2	74.5	76.0	76.8	77.4	77.4	76.6	74.2	71.9	74.2
Kealia	150	39	71.0	70.9	71.3	73.0	75.0	76.9	78.0	78.7	78.6	77.3	74.8	72.8	74.9
Kilauea	317	40	69.4	69.5	69.6	71.0	72.8	74.5	75.6	76.2	76.0	74.8	72.5	70.8	72.7
Koloa	241	40	69.3	69.6	70.2	71.4	73.4	75.2	76.0	76.6	76.6	75.5	72.9	70.9	73.1
Lihue	207	40	69.2	69.1	69.8	71.1	73.3	75.3	76.4	76.9	76.8	75.1	72.5	70.8	73.0
Makaweli	140	40	70.8	71.1	71.6	72.9	75.0	76.9	78.0	78.6	78.3	77.0	74.5	72.4	74.8
Mana	15	40	69.8	70.3	70.7	72.3	74.4	76.2	77.2	77.9	77.4	76.1	73.5	71.2	73.9
Means			69.3	69.7	70.3	71.1	73.3	75.3	76.2	76.9	76.7	75.4	72.9	71.0	73.2

Station	Elev.	Years of Record	Jan	Feb.	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
			MEAN MAXIMUM TEMPERATURE BY MONTHS °F												
Kealia	150	13	77.4	77.9	77.3	78.8	80.2	81.7	82.7	83.5	83.9	82.9	80.9	78.9	80.5
Kilauea	317	14	75.7	76.5	76.1	77.7	79.4	80.8	81.7	82.4	82.7	81.1	78.9	76.7	79.1
Koloa	241	14	77.0	77.6	77.4	78.2	79.9	81.0	81.9	82.5	83.1	82.3	80.2	77.8	79.9
Lihue	207	14	76.5	76.7	76.8	77.9	79.9	81.7	83.0	83.3	83.5	82.1	79.8	77.7	79.9
Makaweli	140	14	79.2	80.4	80.0	81.2	83.1	84.7	85.9	87.0	86.6	85.6	83.4	81.7	83.2
Mana	15	13	77.0	79.4	79.5	81.3	84.4	85.8	86.7	87.6	86.8	84.9	82.1	78.9	82.9

Station	Elev.	Years of Record	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
			MEAN MINIMUM TEMPERATURE BY MONTHS °F												
Kealia	150	13	60.9	60.8	62.5	64.8	66.9	69.3	70.4	71.0	70.5	69.3	66.5	64.6	66.5
Kilauea	317	14	61.3	61.1	61.9	64.3	65.6	68.0	69.0	69.7	69.1	68.0	66.0	64.1	65.7
Koloa	241	14	61.2	61.1	62.0	64.3	66.3	69.0	70.0	70.6	70.3	68.6	66.5	64.2	66.2
Lihue	207	14	59.9	59.3	61.3	63.5	65.6	68.1	68.9	69.6	69.2	67.2	64.8	62.8	65.0
Makaweli	140	14	62.6	62.6	63.2	64.8	66.5	68.7	69.4	70.2	69.9	68.7	66.9	64.5	66.5
Mana	15	13	60.9	61.0	61.5	62.8	64.6	66.2	67.2	68.0	67.9	66.4	64.3	62.1	64.4

MAXIMUM AND MINIMUM TEMPERATURES °F

Station	Max. Temp °F	Date	Min Temp °F	Date
Kealia	93	Oct. 1918	44	Jun 1918
Kilauea	94	Aug 1929	50	Feb 1918
Koloa	89	July & Sept 1918	46	Mar 1936
Lihue	91	July 1918	46	Jan 1930
Makaweli	94	June 1942	50	Jan 1918
Mana	95	Sept 1926	48	Jan 1929

winds which persist throughout the year. On Kauai the trades hold at most stations. The mean direction of the trade winds is not constant. Weather Bureau records for the decade following 1900 show that the winds veered progressively to the east, but in late years they have shifted slowly back towards the north again. This change in wind direction is important because the consequent shift in precipitation affects the erosive power of streams. The most important modification to the trades are the few days of "Kona" weather. This is a warm wind from the south and is most likely to occur during September. Both trade and Kona winds bring rain to the islands, the heaviest storms being from the south.

Prevailing wind direction by months was published by the Weather Bureau up to 1918. Average directions are given in Table 13.

Table 13

Prevailing Wind Direction (37)

Station	Len. of Rec.	J	F	M	A	M	J	J	A	S	O	N	D	An
Kealia	13	nw	ne	ne	ne	ne	ne	ne	ne	ne	ne	ne	ne	ne
Kilauea	14	se	se	se	e	se	se	se	se	se	se	se	se	se
Koloa	14	ne	ne	ne	ne	ne	ne	ne	ne	ne	ne	ne	ne	ne
Lihue	14	ne	ne	ne	ne	ne	ne	ne	e	ne	ne	ne	ne	ne
Makaweli	14	e	e	e	ne	ne	e	e	e	e	ne	e	e	e
Mana	13	n	n	nw	n	n	n	n	n	nw	nw	nw	nw	n

The southeast wind at Kilauea is due to mountain structures which deflect the wind. Figure 8 shows the prevailing annual wind directions plotted on a map of the island.

Wind velocity figures are not available for Kauai. There is a very quiet zone sheltered by the mountains from the trade winds. This zone is centered roughly at Kekaha. The average wind velocity as reported at Honolulu for the ten year period from 1934 to 1944 was 9.2 miles per hour. (38) This average is probably correct for corresponding topographical positions on Kauai, for example the wind velocity at Eleele or Koloa. In exposed positions on the windward side of the island the average velocity might be fifty percent greater while at Kekaha it is probably only fifty percent of the average velocity.

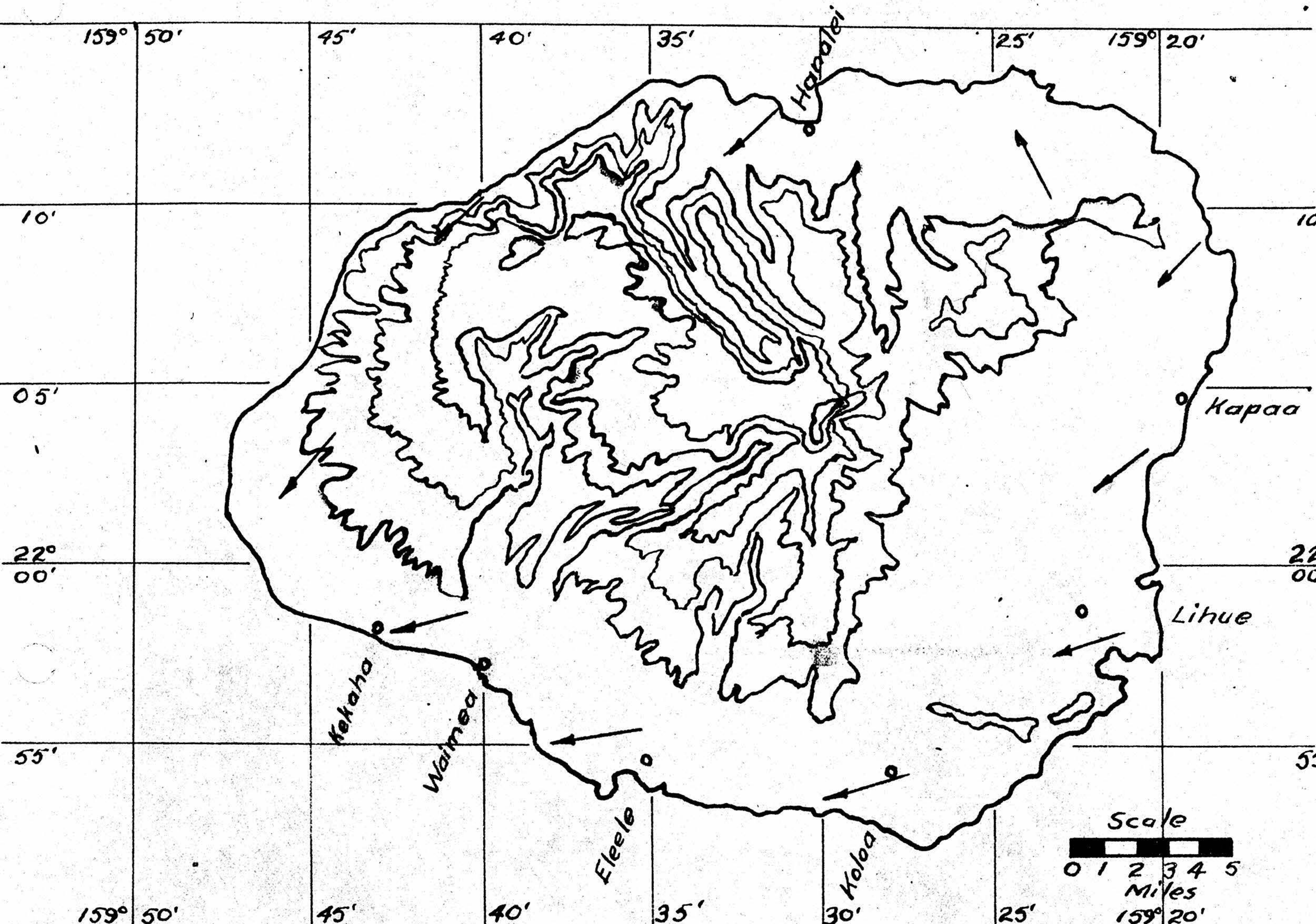
Hurricanes, tornadoes, and typhoons are extremely infrequent in Hawaii. The maximum wind velocity has never reached over fifty miles per hour on Oahu. (39) The only recorded tornado was on January 30, 1937. This tornado accompanied by heavy rains struck Kihei, Maui and swept inland damaging buildings and trees along its path for about one half mile. Fallen trees indicated a counter clockwise rotation of the wind.

Humidity

Humidity records have not been taken on Kauai. Table 14 gives the relative humidity average for Honolulu which may be taken as typical for Hawaii. In general with the "Kona" storms the relative humidity may increase to as high as 95% which

Figure 8

Map of Kauai Showing Prevailing Winds



Topography: 1000' contour interval
Scale 1" = 5 mi.

Prevailing Wind Directions Kauai

Source: Weather Bureau Climatological Data causes the uncomfortable feeling with the storms.

Table 14

Mean Relative Humidity, Percent, Honolulu (40)

Time	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Ann
8 AM	70	70	69	66	66	65	65	66	66	67	69	70	68
8 PM	73	73	71	71	71	71	70	70	70	71	72	73	71

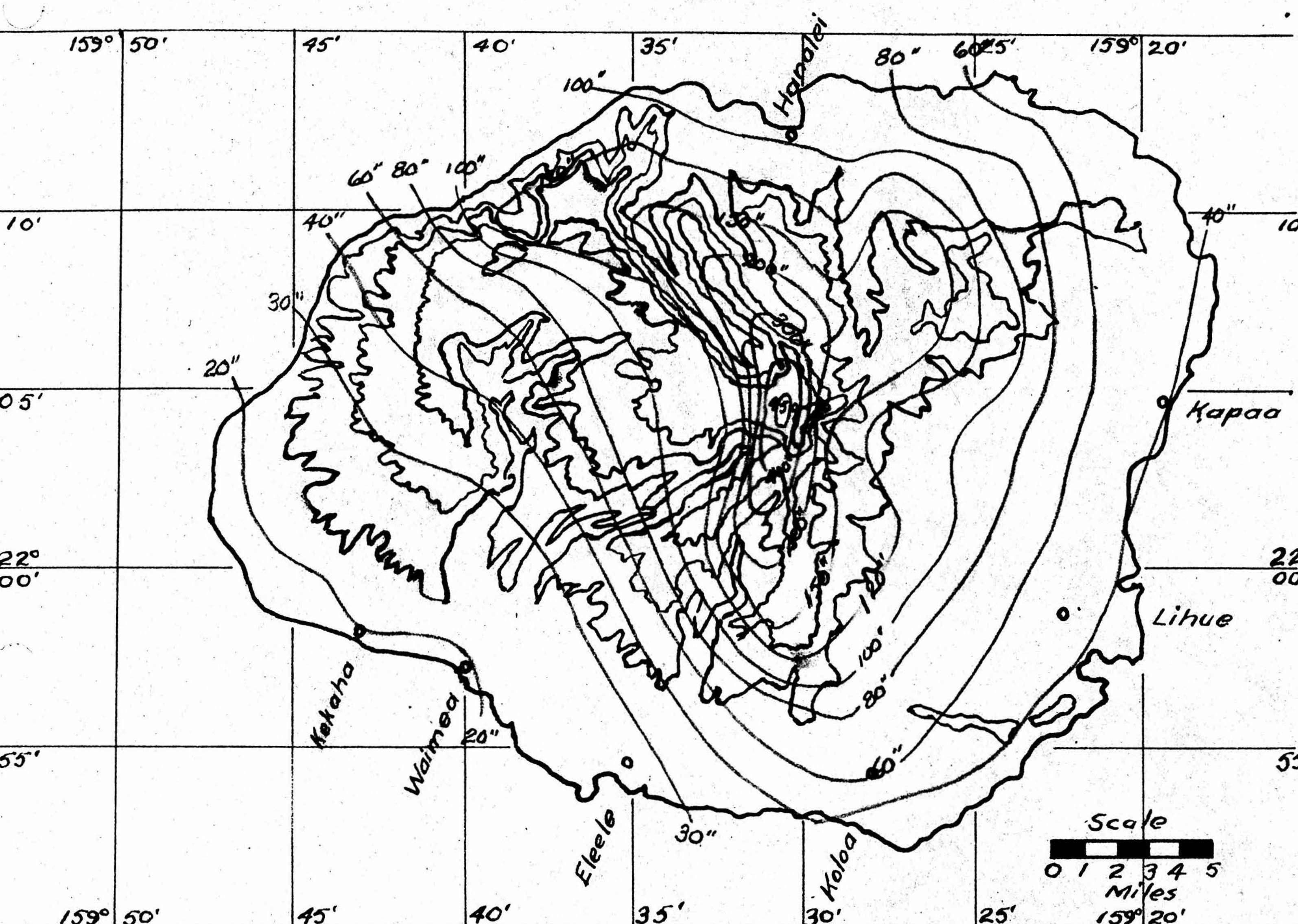
Rainfall

The rainfall on Kauai is extremely varied. From an average annual rainfall of over 450 inches on Waialeale the rainfall varies to less than twenty inches on the extreme southwestern edge of the island, a distance of sixteen miles. The rainfall map is shown in Figure 9. It shows an average rainfall of forty to one hundred inches on the windward lowlands while an average of twenty to forty inches occurs on the leeward lowlands. The tremendous rainfall on Waialeale (5080') has only been checked by incomplete records. Because of the inaccessibility of the station for many years the rain gage was not read and on occasions it was found overflowing. Table 15 gives the concentration of rainfall on the island of Kauai.

Winds, bringing rains to the islands, blow across miles of ocean before reaching the islands and consequently arrive laden with moisture. As they rise over the mountains, the winds are cooled and drop their moisture. The northeastern sides of the islands are usually wettest because the prevailing wind is from that direction. The maximum precipitation occurs between alti-

Figure 9

Map of Kauai Showing Annual Rainfall



Topography: 1000' contour interval
Scale 1" = 5 mi.

Average Annual Rainfall - Kauai

Note. Isohyetal lines based on records from 73 stations covering available data for years 1883 - 1935, totaling 1,693 station years.

Source: Terr. Planning Board 1939

Table 15

Concentration of Rainfall, Kauai (41)

Rainfall	Average	Area (sq. mi.)
over 450"	455"	0.4
400-450	425	2.5
300-400	350	7.1
200-300	250	15.0
150-200	175	38.2
120-150	135	53.9
100-120	110	72.1
80-100	90	59.3
60-80	70	69.0
40-60	50	98.6
30-40	35	55.8
20-30	25	73.3
under 20	17.5	9.8

tudes of 2000 and 6000 feet depending upon the form and height of the island. Above 6000 feet the precipitation decreases, making high peaks semiarid. As the winds descend the lee slopes, they become warmer, drying winds, causing arid and semiarid climates on the leeward sides of the islands. However, on the island of Hawaii, where the mountains are sufficiently high to pierce the layer of trade winds, eddies result in prevailing southwest winds on the lee side so that the climate in the leeward districts is fairly wet..

There is a large variation in precipitation from year to year. On the leeward slopes a "kona" storm may leave the average annual rainfall in one storm. Table 16 gives rainfall data for a number of selected stations. However, since "kona" storms bring a great deal of water in a short time, and resultant runoff is very great they do not contribute proportionally to underground supplies.

The effect of elevation to rainfall is pronounced. It is shown in Table 17 for the windward and leeward slopes of the island. The mountains rise abruptly causing rapidly rising currents of air. The air cools as it rises and forms a constant cloud cap over the top of the island at an elevation above 2000 to 2500 feet. With the cloud cap there is more or less regular precipitation of the condensed moisture. On the top of Waialeale there is little variation in topography causing the Alakai Swamp. When the temperature of the lowlands rises to above 85°F. the clouds generally rise 1000 to 2000 feet above their normal elevation and may clear the mountains. When the wind

Monthly & Annual Average Precipitation Table 16

Kauai (inches)

	Station	(ft) Elev. above sea level	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug	Sept.	Oct	Nov	Dec.	Annual
1	Anahola	40	4.95	6.20	7.29	3.71	3.44	1.87	2.60	3.04	3.01	6.30	4.35	3.93	50.69
2	East Lawai	450	7.62	4.87	6.86	4.68	4.24	4.11	5.17	5.58	5.14	5.33	6.02	6.77	66.39
3	Eleele	150	4.38	3.11	3.96	1.74	1.35	1.05	1.29	1.29	1.91	2.12	2.76	3.69	28.65
4	Grove Farm	200	6.03	4.66	5.82	3.44	3.27	2.15	2.88	2.85	3.36	4.11	5.21	5.58	49.36
5	Hanalei Tunnel	1218	15.71	15.65	14.02	13.71	11.96	9.53	15.02	15.10	14.86	12.53	15.26	14.56	167.93
6	Hanamaulu	175	7.51	4.79	6.72	3.88	3.37	2.51	3.29	2.91	3.62	4.59	5.86	6.53	55.69
7	Homestead	700	6.91	3.96	4.97	3.42	3.36	3.11	4.04	3.62	4.27	4.21	5.16	5.90	53.02
8	Intake Wainiha	700	19.07	13.95	20.37	18.75	13.08	9.60	13.13	13.00	10.47	11.12	17.07	19.96	179.97
9	Kalihiwai Res.	400	7.78	8.54	9.81	9.56	10.52	6.64	8.92	9.50	7.39	8.45	9.40	8.84	107.19
10	Kealia	11	5.02	3.70	5.34	2.74	2.32	1.77	2.53	2.00	2.83	3.35	4.23	4.98	40.81
11	Kekaha	9	3.40	2.85	3.13	1.01	0.74	0.55	0.53	0.94	1.17	1.42	2.14	3.10	20.98
12	Kilauea	317	6.61	5.46	8.40	5.44	5.08	3.64	4.75	4.64	4.89	5.34	6.99	6.97	68.21
13	Kilohana	4023	—	—	—	—	—	—	—	—	—	—	—	—	140.00
14	Koloa	241	6.96	5.06	6.77	4.67	4.57	3.85	4.82	4.87	4.62	5.14	6.03	6.44	63.80
15	Koloa mauka	640	10.76	6.91	10.19	7.47	7.68	6.42	7.19	8.42	8.39	8.41	9.99	10.03	101.96
16	Kukuiula	65	5.19	3.31	4.55	2.41	2.01	1.67	2.07	2.24	2.62	2.80	3.69	4.81	37.37
17	Lihue	207	7.32	4.06	5.95	3.62	3.55	2.44	3.30	3.19	4.16	4.80	4.93	6.02	53.34
18	Makaweli	140	3.54	3.07	3.19	1.10	0.90	0.71	0.68	0.90	1.28	1.61	2.47	3.27	22.72
19	Mana	15	4.70	1.93	3.41	1.01	0.95	0.77	0.68	0.90	1.03	1.63	1.90	3.34	21.73
20	Moloaa	330	5.02	5.68	6.06	4.09	2.72	1.65	3.13	2.68	2.37	4.39	5.42	5.17	48.48
21	Molokoa	200	6.44	4.81	6.59	4.08	3.83	2.86	3.49	3.87	4.22	5.02	5.58	6.18	57.15
22	Mt. Waialeale	5075	—	—	—	—	—	—	—	—	—	—	—	—	460.00
23	N. Wailua Ditch	1110	16.02	16.96	14.42	15.24	13.30	10.52	17.22	17.37	17.49	13.92	15.48	12.48	182.92
24	N. Wailua River	650	10.34	12.69	9.64	8.46	9.71	7.00	11.90	11.77	9.20	10.20	10.65	10.58	122.14
25	P.H. Wainiha	101	12.13	8.15	13.00	10.79	9.01	6.74	9.61	9.77	7.25	7.21	10.33	13.37	117.44
26	Wahiawa	225	4.72	2.78	3.86	2.13	1.63	1.41	1.85	1.81	2.09	2.53	2.97	4.06	31.84
27	Wahiawa Mt.	2100	14.62	12.07	14.82	11.98	12.19	11.44	13.99	14.78	12.48	12.69	13.48	15.21	159.75
28	Waiawa	38	2.90	2.57	2.83	1.01	0.73	0.61	0.58	0.64	1.21	1.47	2.05	2.95	19.55
29	Waimea	10	3.20	2.17	2.30	1.09	0.65	0.57	0.64	0.72	1.10	1.83	1.64	3.33	19.24
30	West Lawai	240	5.64	3.65	5.12	2.84	2.33	2.07	2.85	2.85	3.28	3.43	4.06	4.88	43.00

Source: U.S. Dept. Commerce Climatological Data Hawaii Section 1944

Table 17

Rainfall vs Elevation, Kauai (42)

Leeward Station	Elev.	Average	Windward Station	Elev.	Average
36	5 '	42.51	12	10'	98.50
27	9	21.54	25	11	40.29
72	20	18.56	2	20	49.90
41	30	21.75	64	80	48.43
71	30	19.40	10	253	49.58
40	140	22.12	23	307	57.78
8	150	28.59	28	320	68.03
5	200	22.69	45	330	46.59
66	210	31.28	47	350	70.31
73	240	42.47	58	400	88.51
3	250	27.09	21	400	100.44
4	370	21.18	60	415	87.49
61	435	26.76	13	625	169.45
15	530	118.61	24	635	132.87
17	700	51.24	20	650	197.40
6	850	24.57	49	650	94.61
42	900	67.56	65	1900	190,36
57	945	27.63	48	5075	451.1
51	1310	104.66			
16	2080	216.00			
67	2100	158.78			
52	2100	143.25			
26	4450	117.75			
48	5075	451.1			

slackens the clouds rise and disappear for a few hours. The cloud cap may be gone for a period of a few days with the Kona storms.

The maximum rainfall for twenty four hours recorded on Kauai was 24.40 inches at Wainiha, January 16, 1921. (43) However, higher rates are undoubtably present that have not been measured. On the other islands a maximum of twenty eight to thirty two inches for a twenty four hour period has been measured and this maximum could be expected on Kauai. Maximum hourly rates of rainfall for Kauai are not published and probably have not been taken.

Transpiration and Evaporation

In any study of water resources the recharge of the ground water is dependent on transpiration and evaporation. As no records are available for Kauai an estimate must be made by comparison with records for Oahu where a number of stations have been set up.. The results of these studies have been summarized by Stearns (44) as follows:

"It was evident at the beginning of the investigation that a thorough study of the disposal of the rainfall, especially in relation to ground water recharge, involved a study of transpiration and evaporation. No records of transpiration existed except for sugar cane, and that study had just been started.. Some local engineers believed that transpiration is greater in areas where the annual rainfall is about 200 inches and dense jungle covers the surface than in areas where the rainfall is about 100 inches and the jungle is replaced by grasses and shrubs..

The United States Weather Bureau has recorded evaporation from a free water surface at a point where the mean annual rainfall is about 100 inches, but no records of evaporation existed for the areas of heavier rainfall. It was also found that during heavy downpours these records were not reliable, because of spatter or overflow. The Weather Bureau practice is to discard the records of the day of rain, the day before, and the day after and to substitute for these records the mean daily evaporation for the remainder of the month. In a region of heavy rainfall the record for weeks at a time may be lost because of spatter. Further, the method of subsituting a mean that includes the evaporation on sunny days for the evaporation on rainy days leads to a cumulative error that makes all the results large. Consequently two stations were established at which the evaporation is measured volumetrically, as explained below, instead of daily with a hook gage, as is done by the Weather Bureau.

The lower Luakaha station was installed in November, 1930 by Mr. Vaksvik at an altitude of 890 feet on the west side of Nuuanu Stream, adjacent to the Lower Luakaha automatic rain gage, which is maintained by the Honolulu Board of Water Supply. The rain gage is on the roof of a small shed nearly level with the evaporation and transpiration pans. Both of these pans are on the leeward side of a bank, and some what sheltered from the high winds that blow through Nuuanu Gap. This site was chosen because it appeared to represent average weather conditions on the southwest side of the Koolau Range at this altitude and because a long record of rainfall was available at this place.

The evaporation pan is of the standard Weather Bureau Class A type and is set on 4 by 4 inch timbers on the ground. An overflow pipe with its bottom three inches below the rim connects with a storage tank equipped with an automatic water-stage recorder. Until April 29, 1932 the bottom of the overflow pipe was two inches below the rim, but because occasionally water was lost from the pan by spatter the pipe was lowered one inch. Rain falling in the pan not lost by evaporation overflows into a storage tank, where it is measured volumetrically by an automatic water-stage recorder. The difference between the overflow and the rainfall is the evaporation. During one or two dry spells the water surface has fallen about an inch below the overflow pipe. Thus, the water surface is consistently about one inch lower than in the evaporation pans of the United States Weather Bureau stations. A three cup anemometer at the same level records the wind movement. The station is visited weekly.

The transpiration pan is a circular galvanized iron tank four feet in diameter and five feet deep, painted with asphalt to prevent corrosion and planted with panicum grass. In the bottom of the pan are the contents of one bag of No. 2 and three bags of No. 3 fine crushed rock, and three bags of sand to a depth of one foot. Above this material is three feet of the residual clayey loam soil of the Nuuanu volcanics, dug from the hole in which the pan is set. A perforated 1 3/4 inch brass pipe eighteen inches long in the bottom of the pan is connected to a storage tank where the surplus water is measured volumetrically by an automatic water-stage recorder. A tunnel leads from the storage tank shelter to the transpiration pan so that the pan can be inspected for leaks.

Although the pan projects twelve inches above the surface, this part is hidden from the sun by a dense mat of grass. The grass in and outside the pan intertwines and completely conceals the pan from view. On the adjacent hillside are scattered guava bushes with a dense undergrowth of panicum grass. The vegetation is so similar inside and outside the station that the position of the pan is not evident. The transpiration during the first few months when the grass was making its maximum growth was a little higher than normal. The loss from the transpiration pan, comprising both evaporation and transpiration, is known as "consumptive use", to distinguish it from losses by either transpiration or evaporation. The water collected in the storage tank is equivalent to the sum of run-off and deep percolation. The results obtained at this station are given in Table 18.

The Kaukonahua station was installed in July 1931 by Mr. Vaksvik at an altitude of 1,250 feet on the south bank of the North Fork of Kaukonahua Stream near the Wahiawa intake rain gage, where almost the heaviest rainfall on Oahu is recorded. It consists of a rain gage, evaporation pan, panicum pan, and

Table 18

Evaporation and transpiration, in inches, at Lower Luakaha (Nuuanu Valley) station   Altitude 890 feet

Month	Rain inches	Evaporation from free water surface	Consumptive use
Jan. 1931	6.67	1.942	3.152a
Feb. "	7.76	3.690	7.760a
Mar. "	4.12	2.616	2.290a
Apr. "	7.23	3.290	5.955a
May "	7.30	4.202	5.220a
June "	7.06	5.412	5.418
July "	11.89	6.505	6.037
Aug. "	26.09	7.069	8.169
Sept. "	25.02	5.906	2.230
Oct. "	15.75	2.797	.792
Nov. "	17.35	2.718	1.091
Dec. "	8.47	1.451	1.925
	144.71	47.598b	50.039
Jan. 1932	16.54	1.930	
Feb. "	41.58	1.800	
Mar. "	18.51	1.835	
Apr. "	23.80	3.100c	
May "	10.57	3.350	
June "	8.24	3.296	
July "	14.29	5.996	
Aug. "	11.94	3.810	
Sept. "	8.65	3.808	
Oct. "	6.35	2.672	
Nov. "	6.44	.989	
Dec. "	13.32	1.584	
	180.23	34.170	
Jan. 1933	10.03	1.377	1.65 d
Feb. "	25.03	2.003	2.40 d
Mar. "	14.23	3.890	4.67 d e
Apr. "	4.91	3.164	3.264
May "	4.42	2.744	3.810
June "	8.20	3.860	5.453
July "	7.00	4.749	5.203
Aug. "	4.56	3.868	4.049
Sept. "	5.31	3.284	4.451
Oct. "	2.04	1.802	2.019
Nov. "	2.80	1.058	2.800
Dec. "	8.37	1.500	5.012f
	96.90	33.299	44.781

a. Abnormally high transpiration due to plants being transplanted
b. Evaporation too high, owing to a slight amount of spatter during heavy rains.
c. Some spatter prior to this date during heavy rains, so outlet was lowered one inch.
d. Estimated on basis 1.2 times evaporation
e. Inflow over top of grass tank stopped
f. Rainfall so low that no water passed through tank from Oct. 6 to Dec. 29, hence October and November losses appear in this figure..

fern pan, all of which are connected to storage tanks equipped with automatic water-stage recorders. The tanks and pans were transported on a small boat to the station by the Wahiawa Water Company through two miles of tunnel.

As the mean annual rainfall is about 250 inches at this station it is about 100 inches greater than at the Lower Laukaha station, and therefore this experiment gives a comparison between the consumptive use of panicum at places with very different rainfall. Panicum grass does not occur in the area and had to be brought in from lower down in the valley. It grew slowly after transplanting, because the climate is not as suitable as at Lower Luakaha, yet in 1933 it had become very dense..

Another pan, similar in shape to the panicum pan, was installed to obtain the loss from ferns, which are common in this area. The annual loss by both pans was so nearly the same that transpiration is apparently quite uniform at this place.

The results given in the Table 19 show that the loss by evaporation at this station is only about a third and the consumptive use only about half as great as at the Lower Luakaha station. This decrease in consumptive use with high rainfall appears to be due chiefly to the smaller number of hours of sunshine, with difference in mean temperature and wind as minor causes. The difference in mean temperature between the two stations is probably less than 5°F. Recent unpublished studies by the Hawaiian Sugar Planters Experiment Station in Honolulu show a quantitatively measurable decrease in the rate

Table 19

Rainfall, evaporation, and consumptive use, in inches, at the Kaukonahua station, altitude 1,250 feet

Month	Rainfall	Evaporation	Consumptive Use	
			Fern Pan	Pancium Pan
Sept. 1931	39.195	1.24	2.18	2.29
Oct. "	18.255	1.63		2.28
			3.13a	
Nov. "	24.970	.71		.98
Dec. "	10.605	.47		1.56
			2.00a	
Jan. 1932	31.085	.51		2.48
Feb. "	69.290	.50b	.90b	
				2.60a
Mar. "	13.135	1.59	1.38	
Apr. "	30.590	.93	1.95	1.67
May "	22.970	1.24	2.15	1.31
June "	19.580	2.14	3.09	2.07
July "	21.975	2.60	4.21	2.63
Aug. "	14.570	1.89	2.57	2.41
Year ending Aug. 1932	316.22	15.45	23.56	22.28
Sept. 1932	11.185	2.04	1.34	1.66
Oct. "	12.184	1.18	2.07	2.54
Nov. "	17.105	1.20	2.20	1.48
Dec. "	25.725	.49	1.60	.47
Totals for 1932	289.39	16.31	24.46	21.32
Jan. 1933	29.95 c			
Feb. "	26.00 c	1.70b	3.00b	2.50b
Mar. "	20.40 c			
Apr. "	11.030	.647d	2.344d	2.130d
May "	10.658	2.085	3.600	3.876
June "	19.850	.850	3.702	2.556
July "	14.400	1.460	2.874	3.644
Aug. "	9.980	2.680	3.496	3.662
Year ending Aug. 1933	280.47	14.33	26.23	24.52
Sept. 1933	12.560	1.714	2.444	3.236
Oct. "	4.560	1.688	2.216	2.960
Nov. "	4.495	.873	.359	1.651
Dec. "	9.375	.927	.524	1.389
Totals for 1933	173.26	14.62	24.56	27.60

a. No stopping point in record at end of month
b. Partly estimated
c. Rainfall at adjacent Wahiawa Water Company's rain gage.
d. Perhaps slightly low owing to use of Wahiawa Water C. record

of transpiration from sugar cane even when the sun is obscured by a cloud for only a few minutes.

Owing to the slow rate of percolation through the clayey soil the rainfall of one month does not always reach the storage tanks by the end of the month. Slight inconsistencies in the monthly rate of loss in the two transpiration pans are caused in this manner. Losses during February 1932 had to be partly estimated, because all storage tanks overflowed when more than thirty three inches of rain fell in one week.

Evaporation records at two United States Weather Bureau Stations are given in Table 20. Upper Hoaeae is a few miles southwest of Kaukonahua station, and Maunawili is a few miles northeast of the Luakaha station. The similarity of the rate of evaporation at the Maunawili and Luakaha stations, in spite of a difference of about fifty percent more rainfall at Luakaha, is due in part to the method of computation used by the Weather Bureau for the Maunawili record and in part to the fact that Maunawili is more exposed to the wind.

Surface Run-off

The streams of Kauai tend to be flashy in behavior caused by a concentration of the rapid run-off during rains from their small steep watersheds. As all the larger rivers reach back close to Mt. Waialeale they receive much of their flow from the excessive rainfall in this region. However, the run-off is rapid after each rain and accordingly the stream flow varies more from day to day than from month to month. Before utilizing stream flow for irrigation it is necessary to study the

Table 20
Evaporation at Upper Hoaeae
Altitude, 705 feet

Year	Rainfall inches	Evaporation Inches	Evaporation Percent of Rainfall
1921	34.34	69.26	202
1922	25.16	61.80	246
1923	49.46	59.47	120
1924	-----	60.44	---
1925	24.79	59.62	240
1926	22.06	-----	---
1927	67.39	57.67	86
1928	24.13	57.29	237
1929	44.78	58.10	130
1930	37.14	60.11	162
1931	25.32	63.20	250

Evaporation at Maunawili Ranch
Altitude, 250 feet

Year	Rainfall inches	Evaporation Inches	Evaporation Percent of Rainfall
1921	98.67	41.71	42
1922	66.34	43.60	66
1923	117.93	50.27	43
1924	73.57	48.13	65
1925	73.76	43.70	59
1926	62.36	44.26	71
1927	140.63	43.62	31
1928	62.41	46.34	74
1929	75.36	44.91	60
1930	-----	-----	--
1931	-----	-----	--

stream flow to find the distribution of discharge by day, month, and year. Development of storage of streamflow is limited because of the few good dam-sities. In general the high porosity of the lava formations makes a dam of little value for storage.

Streamflow

Daily discharge of a large number of streams is measured and reported in the annual Water Supply Papers of the Geological Survey. A summary of these records of streamflow as well as other unpublished data collected by other organizations has been prepared for the years up to 1938 by the Territorial Planning Board for the streams in the Hawaiian Islands. (45) A total of 123 gaging stations on the island of Kauai are listed. Ninty eight of the stations were established by the United States Geological Survey cooperating with the Territorial government. A few of these stations date back to 1909. However, at the present only twenty four of the United States Geological Survey stations are active, twelve of them are stream gaging stations and the other twelve are ditch gaging stations.

Unfortunately very few records are available for the diversions of the various streams so that the complete run-off value can only be estimated for the island..

Size of Streams

As was pointed out earlier there are seventy three permanent streams and sixty two intermittent streams on Kauai which reach the ocean. Table 21 lists the more important streams and ditches for which records are being taken giving their average discharge, maximum and minimum discharge, as well as the discharge that is exeeeded ninty and eighty percent of the time.. From this table it is possible to find values of the usable water supply for these streams using the discharge that is exceeded eighty or ninty percent of the time depending upon the amount of storage available and the length of time it is possible to obtain water from other sources or to lower the irrigation demand.

Figures 10, 11, 12, and 13 give duration discharge records for two windward streams, Hanalei and the South Fork of the Wailua; and two leeward streams, the Waimea and the Hanapepe. (47)

The most apparent data on stream flow shows that the streams vary by a large factor during the course of the year dependent on the rainfall and on the conditions of the watershed as to saturation of the surface..

From Table 21 it is also seen that the instantaneous flood stage is much higher than that of the average twenty four hour flood stage. This is due to the small area of the watershed and steep slopes. Run-off is consequently rapid after heavy rains.

Quantity of Water

The distribution of streamflow with the years is best shown by means of mass diagrams. Residual mass diagrams are presented

KAUAI

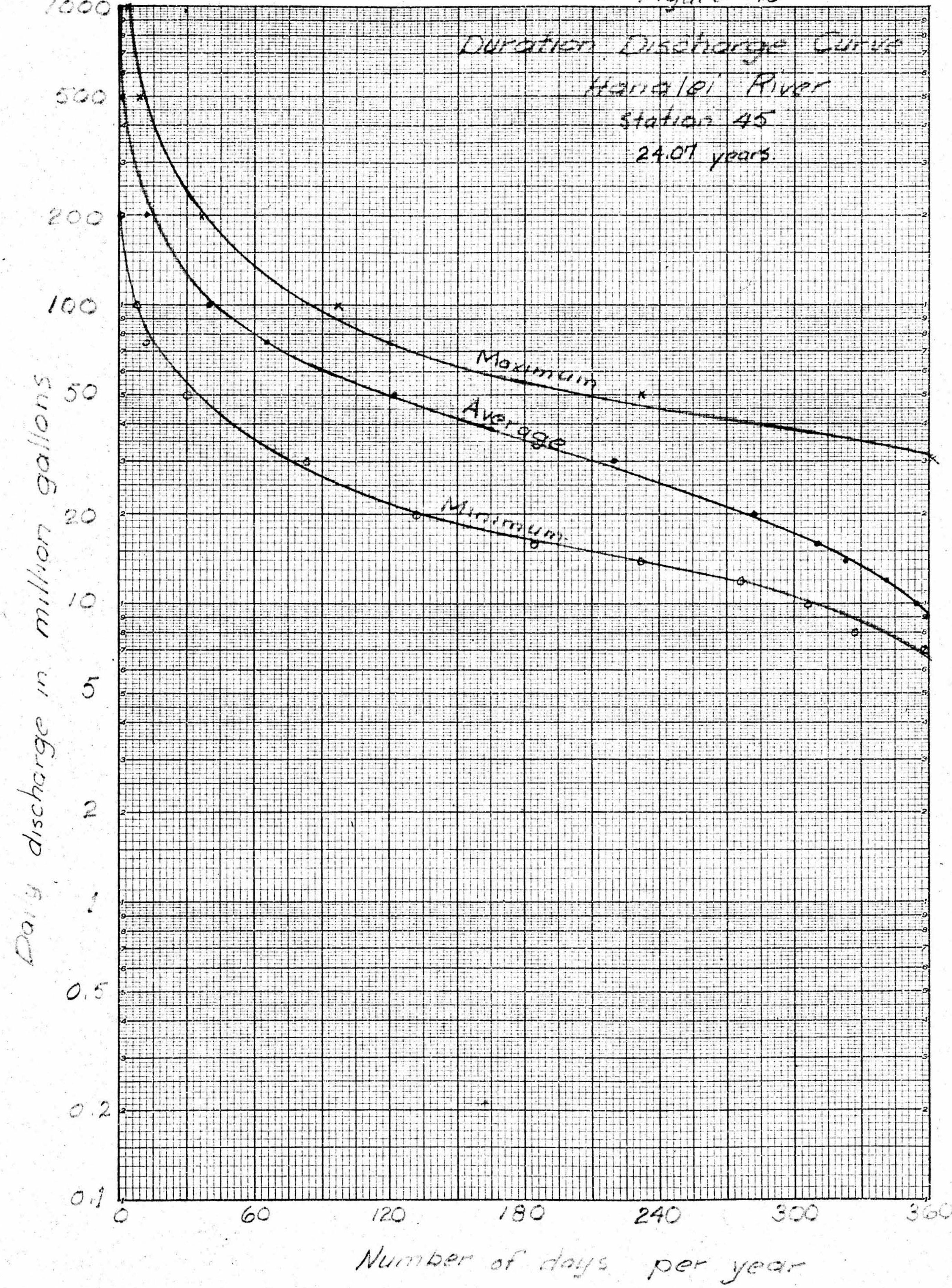
STREAM DISCHARGE TOTAL & PER SQUARE MILE

USGS No	Stream	Lat °N	Long °W	Number Years Record	Elev. of station ft	Area Watershed sq. mi.	Ave. Daily Discharge MGD	Max Instan. Discharge MGD	Max Daily Discharge MGD	Min Daily Discharge MGD	Discharge Exceeded 90% Days MGD	Discharge Exceeded 80% Days MGD	Ave. Daily Discharge MGD/sq mi	Max Instan. Discharge MGD/sq mi	Max Daily Discharge MGD/sq mi	Remarks.
87	Waimea	22°02'40"	159°38'35"	15.93	490	45.0	46.0	10,700	2810	0.0	.14	.24	1.88	239.	64.0	(1)
8	Kawaikoi	22°08'00"	159°37'15"	25.28	3420	4.1	22.0	4670	899	1.0	3.0	4.2	5.36	1140.	219.0	
80	Mohihi	22°07'05"	159°36'15"	8.08	3500	1.6	5.89	520	246	0.2	0.5	0.8	3.68	325.	154.0	
75	Waiahulu	22°04'45"	159°39'15"	14.45	890	20.0	32.8	2550	715	5.2	8.3	9.2	1.64	128.	35.8	
90	Kokee Ditch	22°06'25"	159°40'45"	11.79	3310	—	18.8	76	60	0.0	5.2	7.0	—	—	—	
26	Kekaha Ditch	22°02'35"	159°38'30"	28.13	520	—	38.5	71	67	0.0	23.0	27.5	—	—	—	
29	Hanapepe	21°57'20"	159°33'15"	21.46	150	18.8	57.6	5550	2350	7.5	11.5	14.0	4.40	298.	127.0	(2)
31	Hanapepe Ditch	21°57'10"	159°33'00"	22.73	490	—	25.2	39	36	0.0	16.0	20.5	—	—	—	
22	So. Fork Wailua	22°02'10"	159°22'55"	25.80	230	22.4	86.0	29,000	8900	1.2	4.0	7.0	4.91	1310.	405.0	(3)
16	Hanamaulu Ditch	22°01'50"	159°25'50"	21.05	500	—	24.1	380	166	0.0	3.0	8.0	—	—	—	
70	No. Fork Wailua	22°03'50"	159°26'20"	21.92	650	6.6	53.1	3720	1030	1.6	18.5	23.5	13.90	585.	173.0	(4)
98	Hanalei Tunnel	22°05'10"	159°28'15"	11.50	1210	—	25.6	78	77	0.0	17.2	19.1	—	—	—	
99	No. Wailua Ditch	22°03'40"	159°27'55"	11.46	1105	—	13.1	59	38	0.0	9.2	10.3	—	—	—	
24	Kanaha Ditch	22°03'50"	159°25'30"	27.43	540	—	10.3	45	27	0.0	1.0	4.5	—	—	—	
60	East Branch No Fork Wailua	22°04'10"	159°25'05"	24.02	500	6.2	31.6	3340	1430	4.4	12.1	14.6	5.10	539.	231.0	(5)
14	Kapahi Ditch	22°06'00"	159°22'30"	27.08	360	—	8.35	233	89	0.0	0.9	2.6	—	—	—	
12	Anahola	22°08'55"	159°21'20"	25.01	770	5.5	14.0	3580	577	1.4	3.2	4.2	3.17	675.	112.0	(6)
72	Anahola Ditch	22°08'00"	159°22'30"	21.42	830	—	3.43	130	40	0.0	0.02	0.50	—	—	—	
45	Hanalei	22°07'10"	159°28'05"	24.07	625	7.4	56.2	11,100	2870	5.8	14.0	18.5	7.60	1500	388.0	
91	Hanakapiai	22°11'20"	159°35'50"	6.52	450	2.6	12.6	2680	205	2.5	3.4	4.1	4.48	1030	79.0	
96	Hanakoa	22°11'00"	159°37'35"	6.53	470	1.1	4.06	569	90	0.17	0.45	0.55	3.70	516	82.0	
95	Kalalau	22°09'50"	159°38'15"	6.65	960	1.6	4.70	168	80	1.9	2.5	2.7	2.94	105	50.0	

(1) Waimea includes Kekaha Ditch in Discharge per square mile.
(2) Hanapepe " Hanapepe Ditch " " " " "
(3) So. Fork Wailua " Hanamaulu Ditch " " " " "
(4) No. Fork Wailua " No. Wailua Ditch & Tunnel in " " " "
(5) Ea. Br. No. Fork Wailua " Kapahi Ditch " " " " "
(6) Anahola " Anahola Ditch " " " " "

Based on Data included in Terr. Planning Board 1939

Figure 10



Duration Discharge Curve
Hanalei River
Station 45
24.07 years
Maximum
Average
Minimum
Daily discharge in million gallons
1000
500
200
100
50
20
10
5
2
1
0.5
0.2
0.1
0
60
120
180
240
300
360
Number of days per year

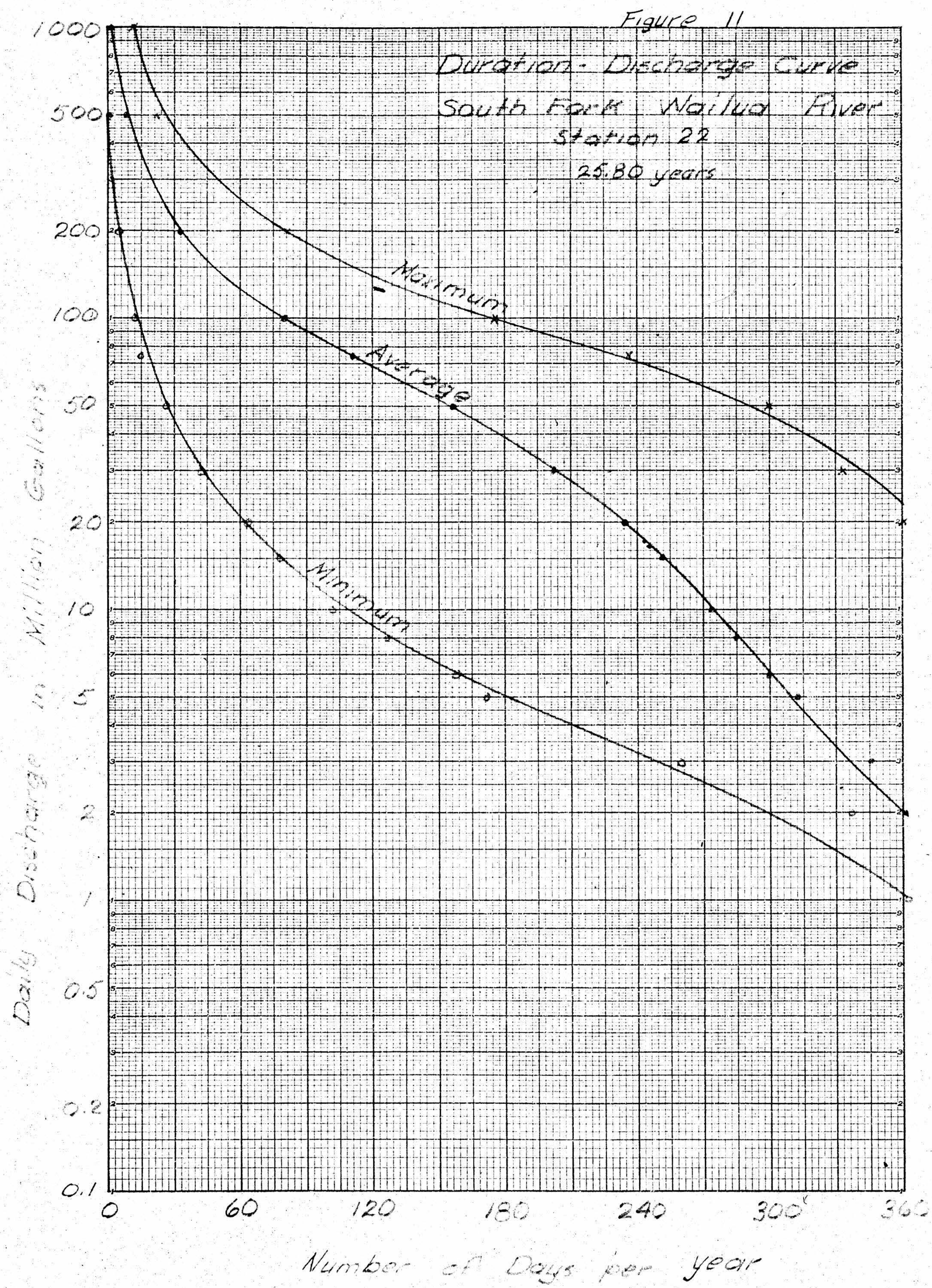


Figure 11
Duration - Discharge Curve
South Fork Wailua River
Station 22
25.80 years
Maximum
Average
Minimum
Daily Discharge in Million Gallons
1000
500
200
100
50
20
10
5
2
1
0.5
0.2
0.1
0
60
120
180
240
300
360
Number of Days per year

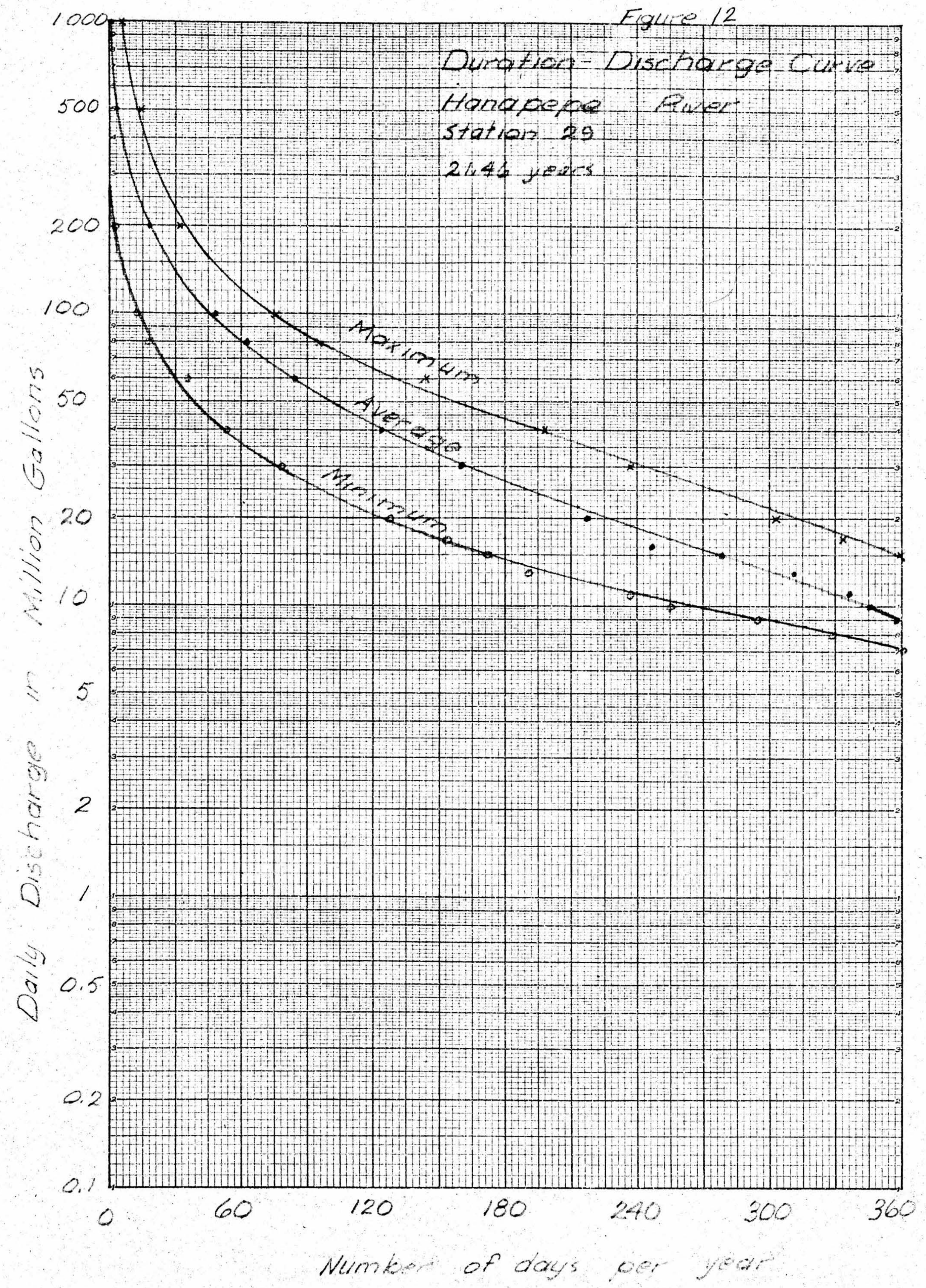


Figure 12
Duration-Discharge Curve
Hanapepe River
Station 29
21.46 years
Maximum
Average
Minimum
Daily Discharge in Million Gallons
1000
500
200
100
50
20
10
5
2
1
0.5
0.2
0.1
0
60
120
180
240
300
360
Number of days per year

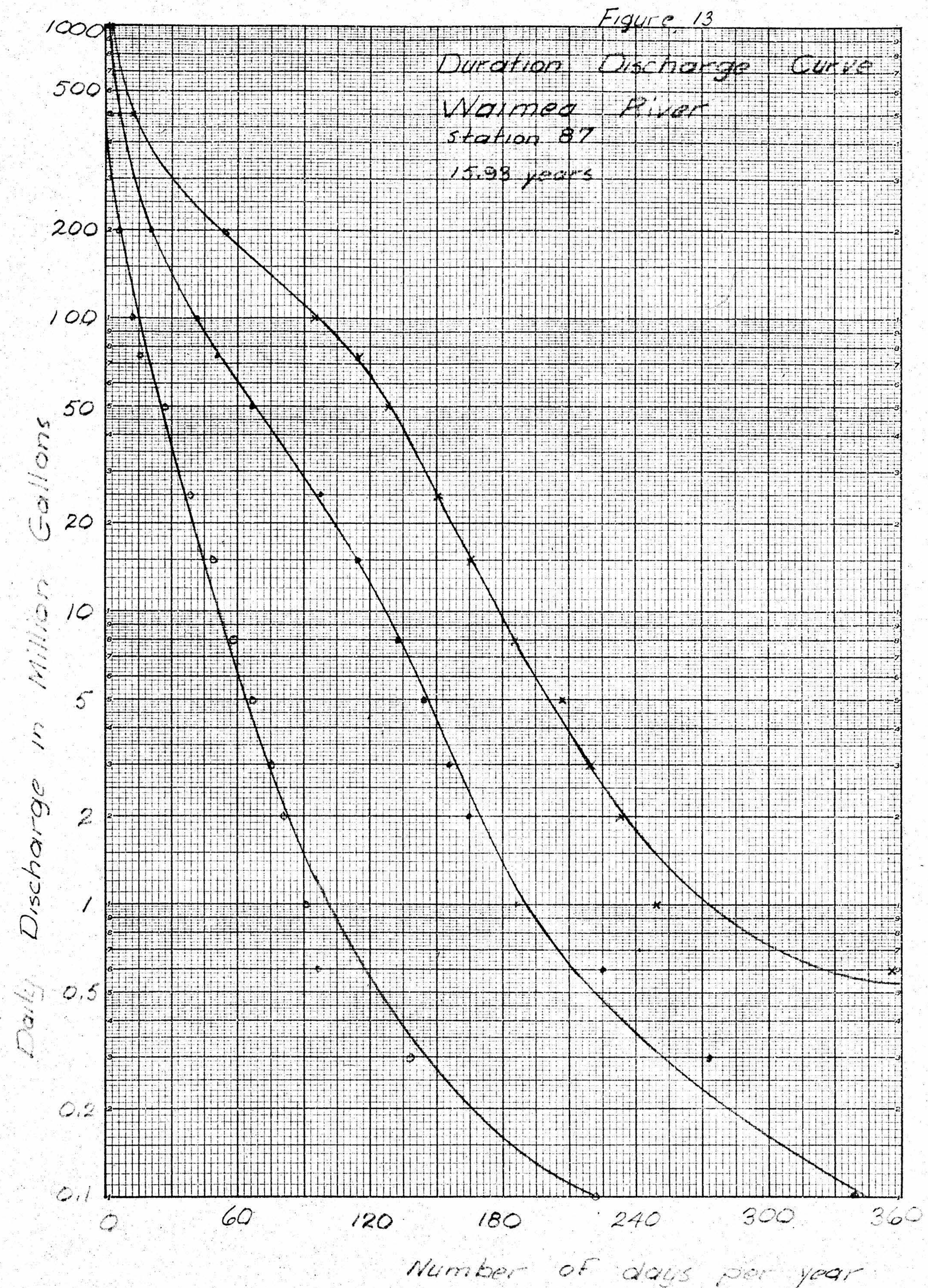
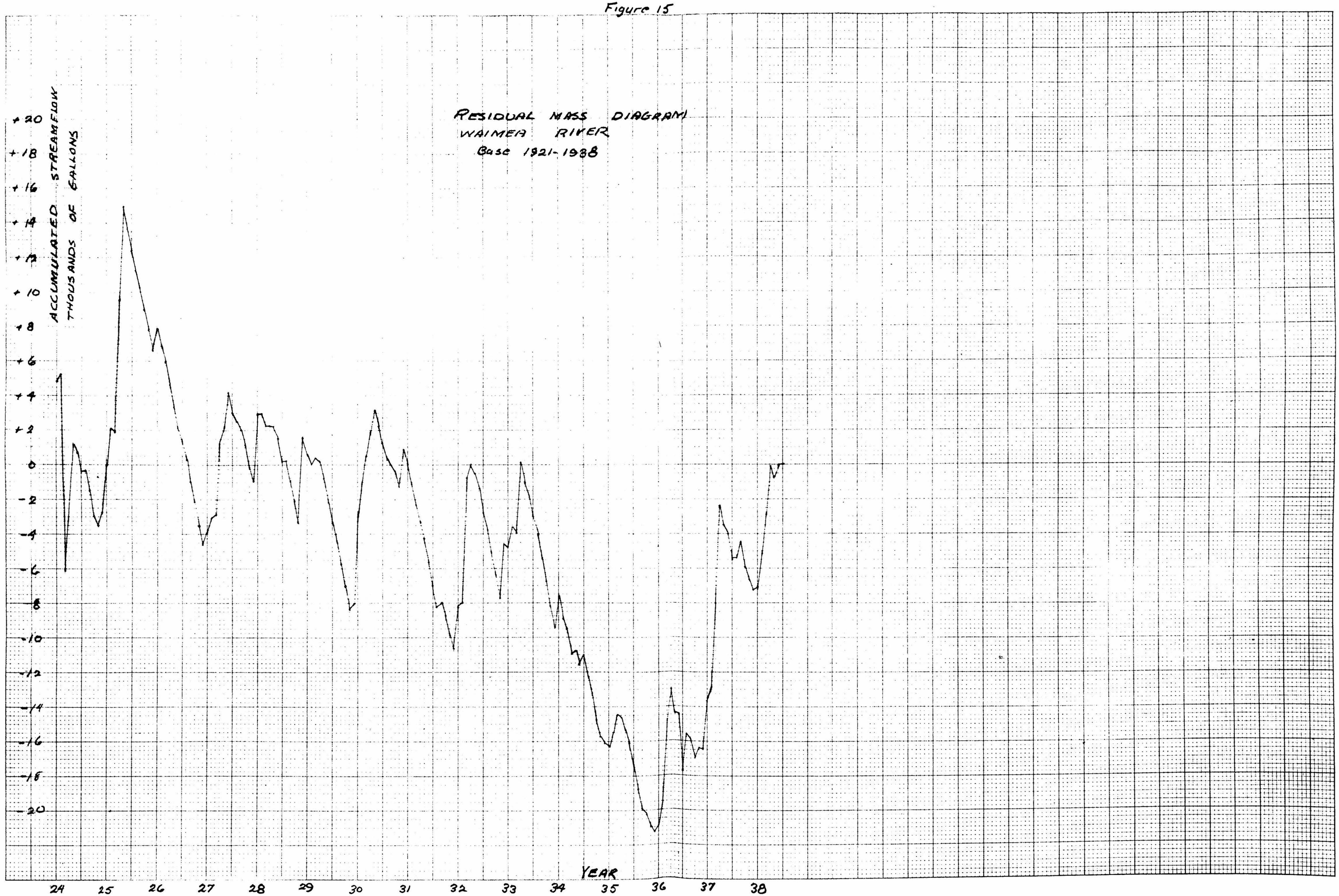


Figure 13
Duration Discharge Curve
Waimea River
station 87
15.98 years
Daily Discharge in Million Gallons
1000
500
200
100
50
20
10
5
2
1
0.5
0.2
0.1
0
60
120
180
240
300
360
Number of days per year

Figure 14

RESIDUAL MASS DIAGRAM
SOUTH FORK WAILUA RIVER
Base 1911-1938
THOUSANDS OF GALLONS - ACCUMULATED STREAMFLOW
110
100
90
80
70
60
50
40
30
20
10
0
-10
YEAR
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38

Figure 15



RESIDUAL MASS DIAGRAM
WAIMEA RIVER
Base 1921-1938
ACCUMULATED STREAMFLOW
THOUSANDS OF GALLONS
+20
+18
+16
+14
+12
+10
+8
+6
+4
+2
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
YEAR
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38

in Figures 14 and 15 for two of the same typical streams for the windward and leeward sides of the island. These diagrams show typical wet and dry cycle years. The diagrams are typical for small watershed with precipitation in the form of rain with rapid run-off.

The seasonal variation of streamflow is not consistent. Variations in the time of rainfall as shown in Table 21 cause changes in the peak months of flow. Figures 16 and 17 give monthly variation in streamflow for a windward stream, Hanalei, and a leeward stream, Hanapepe. In each figure two individual years, 1936 and 1937 are plotted along with the five year average from 1933 to 1938. The two streams show maximum flow in the same months each year revealing the effect of rainy months on the top of the summit plateau which contributes much of the streamflow for all the larger streams.

Run-off and Rainfall

As has been stated before the effect of rainfall on run-off is more closely related on Kauai then in most locations. This is shown by Tables 22 and 23 for the Hanalei and Hanapepe Rivers. In order to make an estimate of the percentage of rainfall that runs off as streamflow, rainfall and streamflow data are analysed in a later section. Before utilizing these figures for an estimate as percentage of run-off for the whole island a number of factors must be considered. First, the data covers only the watershed area in the mountains where transpiration is lessened (see Tables 18, 19, and 20) and rainfall is high. The percent-

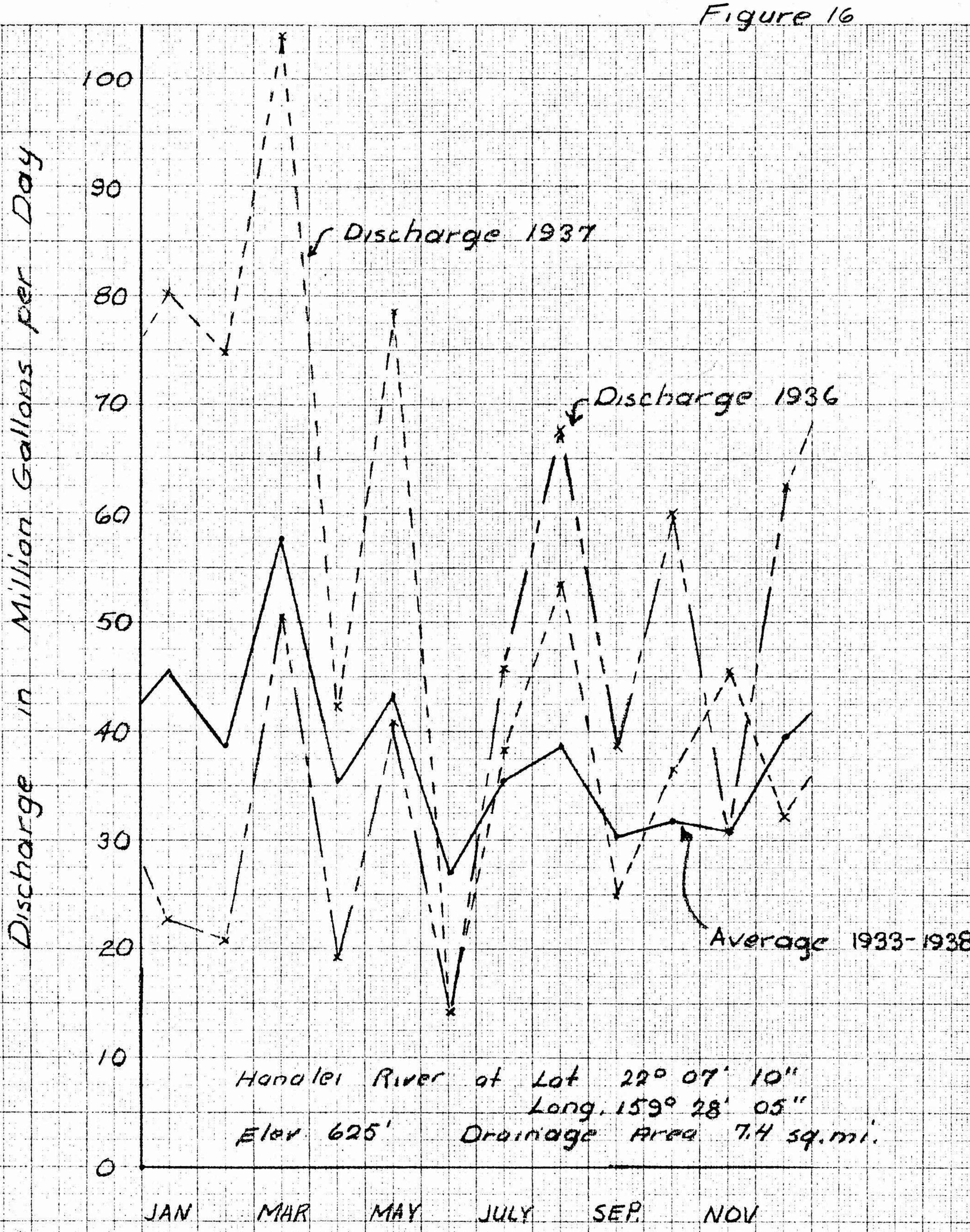
Table 22
Run-off and Rainfall-Hanalei River

Date	Streamflow Av. MGD	Rainfall Kilauea	Date	Streamflow Av. MGD	Rainfall Kilauea
Jan. 1933	78.8	13.12	Jan. 1936	22.6	4.98
Feb. "	45.9	2.79	Feb. "	20.7	4.43
Mar. "	84.0	10.16	Mar. "	50.6	9.43
Apr. "	30.0	2.83	Apr. "	19.2	5.99
May "	41.8	7.25	May "	40.9	4.28
June "	37.3	3.27	June "	14.0	2.65
July "	31.0	3.96	July "	45.8	6.42
Aug. "	21.0	2.03	Aug. "	67.6	8.95
Sept. "	16.4	2.37	Sept. "	38.8	3.73
Oct. "	11.4	1.85	Oct. "	59.9	8.97
Nov. "	14.1	3.12	Nov. "	30.6	3.30
Dec. "	36.2	8.87	Dec. "	62.4	10.30
Jan. 1934	28.8	2.68	Jan. 1937	80.3	8.38
Feb. "	9.9	2.34	Feb. "	74.9	5.85
Mar. "	7.8	1.77	Mar. "	104.	11.27
Apr. "	49.8	4.49	Apr. "	42.4	12.28
May "	33.5	2.73	May "	78.6	6.90
June "	51.9	6.07	June "	14.1	2.07
July "	43.0	5.57	July "	38.2	5.93
Aug. "	15.5	2.40	Aug. "	53.6	5.73
Sept. "	38.0	8.16	Sept. "	24.9	5.85
Oct. "	32.7	6.53	Oct. "	36.6	5.52
Nov. "	35.2	6.40	Nov. "	45.6	5.39
Dec. "	32.7	5.79	Dec. "	32.2	3.24
Jan. 1935	26.7	3.96	Five Year Average		
Feb. "	41.9	4.81	Jan.	45.4	6.62
Mar. "	41.3	5.09	Feb.	38.7	4.04
Apr. "	35.7	2.10	Mar.	57.7	7.54
May "	22.3	1.90	Apr.	35.4	5.54
June "	17.5	4.15	May	43.4	4.61
July "	19.7	4.75	June	27.0	3.64
Aug. "	34.9	2.65	July	35.5	5.33
Sept. "	33.6	5.15	Aug.	38.5	4.35
Oct. "	19.1	4.46	Sept.	30.3	5.05
Nov. "	28.9	4.56	Oct.	31.9	5.47
Dec. "	34.3	11.51	Nov.	30.9	4.55
			Dec.	39.6	7.90

Table 23
Run-off and Rainfall-Hanapepe River

Date	Streamflow Av. MGD	Rainfall Olokele	Date	Steamflow Av. MGD	Rainfall Olokeke
Jan. 1933	151	24.53	Jan. 1936	75	15.60
Feb. "	67	12.50	Feb. "	41	13.50
Mar. "	84	13.44	Mar. "	47	7.30
Apr. "	31	4.36	Apr. "	14	1.90
May "	48	14.10	May "	48	6.08
June "	64	7.59	June "	26	5.17
July "	40	5.34	July "	111	12.34
Aug. "	27	2.92	Aug. "	108	11.63
Sept. "	27	4.64	Sept. "	58	6.29
Oct. "	21	1.32	Oct. "	53	9.31
Nov. "	16	3.19	Nov. "	38	6.90
Dec. "	28	15.04	Dec. "	123	16.98
Jan. 1934	37	6.26	Jan. 1937	189	21.84
Feb. "	34	7.43	Feb. "	136	16.09
Mar. "	17	2.61	Mar. "	167	19.63
Apr. "	30	3.59	Apr. "	58	5,85
May "	28	1.70	May "	70	4.95
June "	85	14.96	June "	22	2.57
July "	46	9.78	July "	79	11.39
Aug. "	19	1.59	Aug. "	123	12.75
Sept. "	52	11.69	Sept. "	29	2.97
Oct. "	36	8.30	Oct. "	57	8.12
Nov. "	47	7.40	Nov. "	73	9.83
Dec. "	60	10.50	Dec. "	53	11.28
			Five Year Average		
Jan. 1935	58	9.82	Jan.	102	15.61
Feb. "	72	10.00	Feb.	70	11.90
Mar. "	42	7.96	Mar.	71	10.19
Apr. "	36	4.17	Apr.	34	3.97
May "	17	1.06	May	42	5.58
June "	27	3.14	June	45	6.69
July "	43	6.15	July	64	9.00
Aug. "	53	9.26	Aug.	66	7.63
Sept. "	112	15.00	Sept.	56	8.12
Oct. "	21	2.10	Oct.	38	5.83
Nov. "	44	5.75	Nov.	44	6.61
Dec. "	40	6.90	Dec.	61	12.14

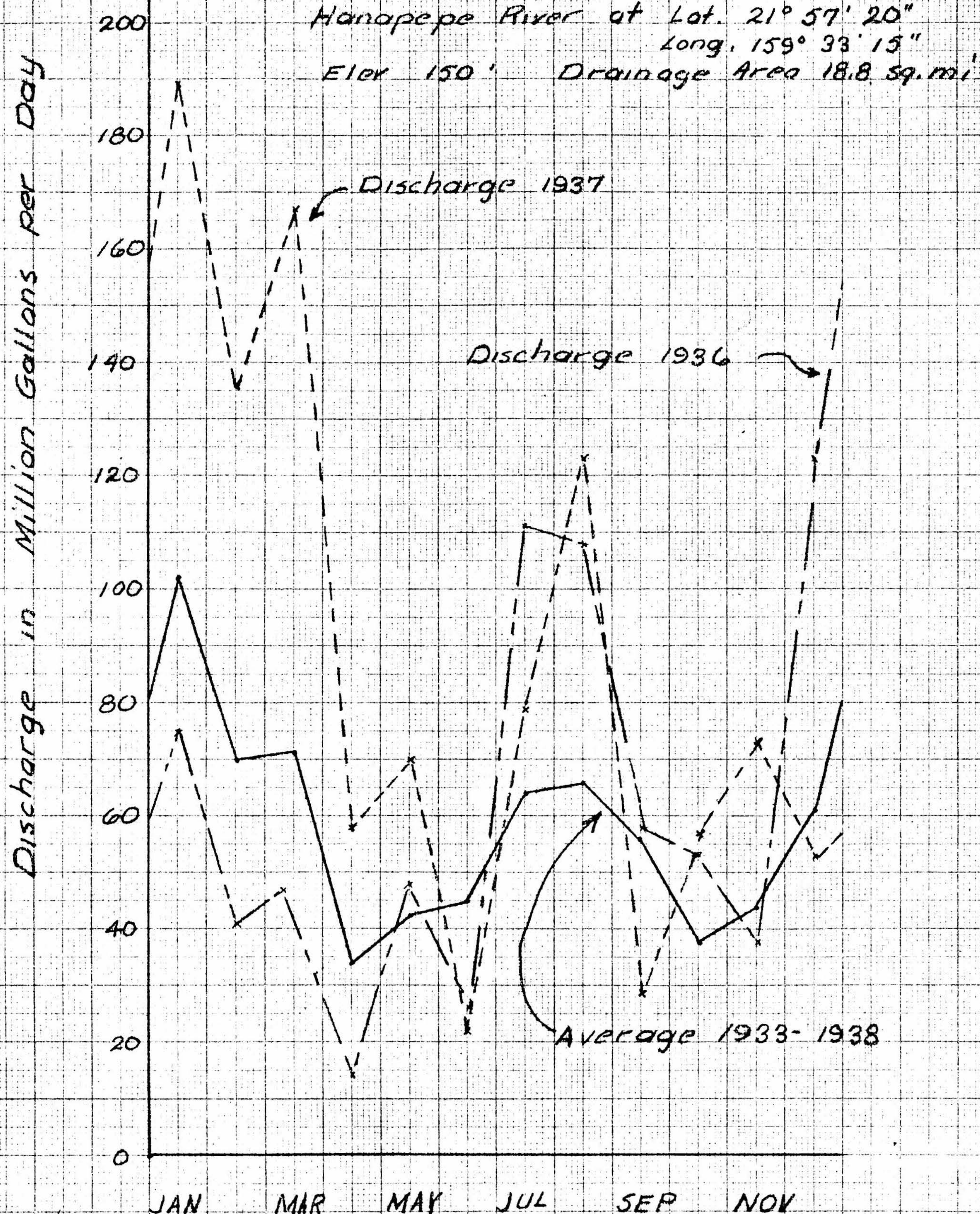
Figure 16



Average Daily Discharge by Months

Hanalei River, Kauai

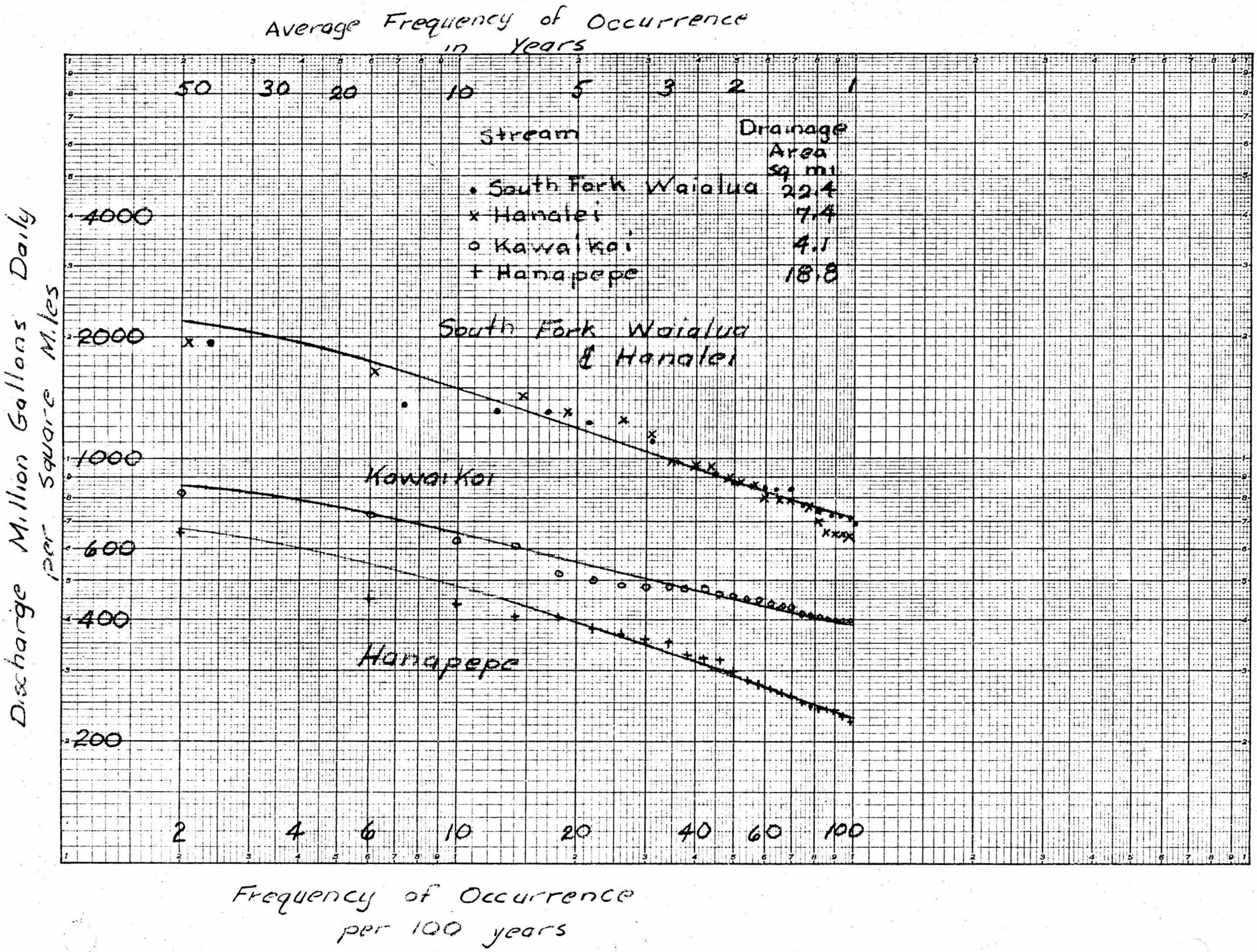
Figure 17



Average Daily Discharge by Months

Hanapepe River, Kauai

Figure



Average Frequency of Occurrence in Years
50 30 20 10 5 3 2 1
Stream
Drainage Area sq mi
• South Fork Waialua 22.4
x Hanalei 7.4
o Kawaikai 4.1
+ Hanapepe 18.8
South Fork Waialua & Hanalei
Kawaikoi
Hanapepe
Discharge Million Gallons Daily per Square Miles
4000
2000
1000
600
400
200
2 4 6 10 20 40 60 100
Frequency of Occurrence per 100 years

age run-off is correspondingly higher on the lower leeward areas where the rainfall is lower and no runoff at all may take place, as for example, on most of the Mana drainage basin. Second, the table accounts for the larger, more permanent streams only, where data is more available. These streams reach back into the mountains where their watersheds are steep and the percentage run-off is accordingly higher than on the lowlands. Accordingly, as an estimate of the average percentage of rainfall that leaves the island as run-off twenty to thirty percent might be used. This figure checks roughly with studies made by Stearns and MacDonald, and Stearns and Vaksvik on Maui and Oahu respectively which is summarized as follows:

"The average daily rainfall on East Maui is 2,360 million gallons, of which only 3.4 percent reappears in the low-water stream flow. The average rainfall on West Maui is 580 million gallons, of which 13.1 percent reappears in the low-water stream flow. The increased percentage is due entirely to differences in geologic structure and stages of erosion of the two volcanoes. The high permeability of the youthful Hana lavas and the lack of deep canyons cutting the dike complexes of East Maui are the chief causes of the great difference in low flow. It is estimated that the volume of high-level ground water in East Maui lost because of these unfavorable geologic conditions averages at least 200 million gallons per day." (50)

"Kunesh estimates that the surface run-off from all streams from Moanalua to Palolo in a year of average rainfall equals

42 million gallons daily. As the daily rainfall for the area tributary to these streams during an average year, as computed by Voorhees, is 194 million gallons, the run-off is about twenty two percent of the rainfall." (51)

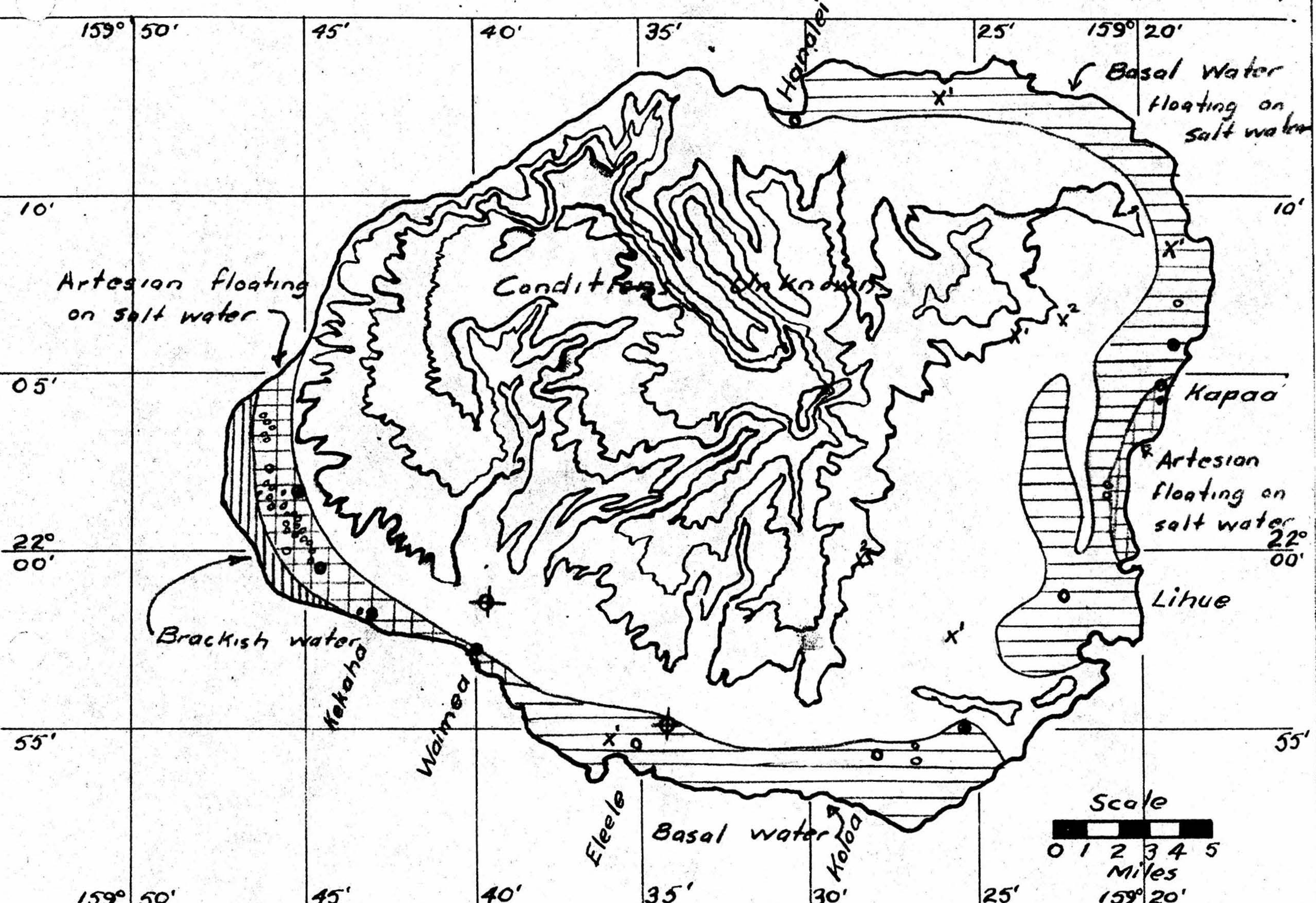
The Maui estimates are for low flow conditions when run-off would naturally be below the average. The topography on Oahu is similar to that on Kauai but the rainfall is lower so that the average percentage run-off for Kauai should be somewhat higher.

Ground Water

The ground water resources of the territory of Hawaii are being systematically investigated by the Division of Hydrography in cooperation with the Geological Survey. At the present time the survey has yet to be made on Kauai so that only very limited data is available as to the actual ground water resources. Accordingly, only general principles can be developed. From plantation and other records it is known that on Kauai, along parts of the coast, a sedimentary caprock confines the basal water in the lava rock under pressure, and wells drilled through the caprock encounter artesian water. A narrow artesian belt lies between Waimea and the Barking Sands, as shown on the map of Kauai, Figure 19. An even narrower belt lies between Hanamaulu and Kealia on the eastern side of the island. This area is poorly defined because so few wells exist. Likewise, little is known regarding the boundaries of the area of basal water shown. Most of Kauai has heavy rainfall and it is

Figure 19

Map of Kauai Showing Ground Water



Topography: 1000' contour interval

Scale 1" = 5 mi.

Legend

- Maui Type Well
- Pumping Station & Battery of Wells
- Drilled well
- X^2 Tunnels recovering Perched water (no. indicates number of tunnels in area)

Drilled Wells on Kauai
69 in use
10 not in use
79 total

GROUND WATER & STATIONS PUMPING GROUND WATER

Source Terr. Planning Board 1939

by Stearns on the basis of Short field trips, that when studied in detail many geologic structures containing valuable supplies of water will be found.

Basal Water

The occurence of ground water in the islands is in two classes: (1) basal ground water, (2) high level or perched ground water.

Basal ground water, as distinguished from high level ground water, is the great body of water that lies below the main water table or upper surface of the zone of saturation of the islands. It is unconfined ground water occuring in the lavas under all the islands except in the rift zones and in the permeable sediments near the coast. Thus, the term is not used to include water in the dike complexes. The basal water table lies near sea level and has only a slight gradient. Geologic studies, especially in connection with the occurance of high level ground water, indicate that the basal water table does not extend under the entire range but surrounds the dike complexes, which contain confined water in many places several hundred feet above sea level. The altitude of the basal water table next to the dike complex is not known, but because of its general flat gradient it is believed to be only a few feet higher there than along the shore.

The Ghyben-Herzberg theory gives the principle of the behavior of fresh water in contact with salt water and is stated by Brown (52) as follows:

"Wherever a coast is formed of pervious rocks containing ground water that receives continual additions from rainfall, this ground water must move downward and laterally toward the shore and mingle ultimately with the salt water of the sea. Such movements have long been a matter of common knowledge. Even on small porous, sandy islands fresh water can generally be found at an altitude slightly above mean sea level. It might be supposed that in such places the salt water surrounding the island would penetrate the sand to mean sea level and immediately absorb all the fresh water that mightpercolate downward to its surface. For several physical reasons this does not happen. Such islands are found, in reality, to contain a dome-shaped lens of fresh water floating upon a concave surface of salt water. The fresh water is enabled to float upon the salt water because it has a considerably smaller density. This principle was apparently first applied to the hydrology of seacoasts by Badon Ghyben, a Dutch captain of engineers, as the result of investigations made in Holland in 1887, but gained little notice from hydrologists at that time. It was also published about 1900 by Herzberg of Berlin, who apparently had no knowledge of the work of Badon Ghyben. Herzberg found in drilling wells on the island of Norderney, one of the East Friesian islands off the coast of Germany, that the dpeth to salt water was roughly a function of the height of the water table above the mean sea level and of the density of the water of the North Sea. The following figure gives the application of his theory:

Let H equal total thickness of fresh water

h equal depth of fresh water below sea level

t equal height of fresh water above mean sea level

Then H equals h plus t

But the column of fresh water H must be balanced by a column of salt water h in order to maintain equilibrium. Therefore, if g is the specific gravity of sea water and the specific gravity of fresh water is assumed to be 1, H equals h plus t equals hg whence

$$h = \frac{t}{g - 1}$$

In any case g minus 1 will be the difference in specific gravity between the fresh water and the salt water. Herzberg gives the specific gravity of the North Sea as 1.027, whence h equals 37t."

The average specific gravity of the ocean adjacent to Kauai is unknown, but off Oahu it is 1.0262 at 22°C., using the specific gravity of fresh water at 22°C. as 1. Using this specific gravity h equals 38.5t. Other factors such as the change in density of the ocean with depth make this value approximate only, hence h equals 40t is in common use. If fresh water stands two feet above sea level in a well, the depth of fresh water below sea level will be theoretically about eight feet. Because of diffusion and mixing, the actual depth of unadulterated fresh water is less than the theoretical depth. (53)

In a small island or narrow peninsula composed entirely of permeable aquifer and surrounded by sea water, this balance between fresh water and sea water occurs. In such an island the resistance of the aquifer to the flow of water causes the fresh water from rainfall to build up a head above sea level sufficient to cause it to flow out into the ocean at the shores of the island. It also prevents the mixing of the salt and fresh water in the aquifer below sea level by wave action. As the aquifer is permeable in all directions, the fresh water head will cause a downward flow of fresh water until it fills the aquifer to a depth at which the head is balanced by the head of salt water.

In nature a body of land composed entirely of permeable material to any great depth is rare. The occurence of beds or layers of impermeable material does not change the basic principles just discussed but it does modify their application. If the island were underlain by clay or bedrock that reached a level above the bottom of the fresh water along the coast the position of the contact would be determined by the head of fresh water, but in the center of the island the fresh water would extend all the way down to the impermeable layer and would not be in direct contact with salt water. These conditions are even more marked on coasts of larger bodies of water, where water bearing aquifers may lie under and between as well as above layers of impermeable material.

Occurance

The cavities and crevices within and between lava flows form a great underground reservoir. How these reservoirs were formed may be described thusly:

"Salt water probably filled the interstices in the rocks concurrently with the building of the volcano above sea level. Rainwater percolating downward through the porous lava floated upon the salt water because of its lower specific gravity. When the island was small this rain water percolated laterally and quickly discharged into the sea, but as the island grew larger the friction increased in proportion to the distance the water had to move to reach the sea. Moreeover, because the salt water in the interstices of the island is not a rigid body, but is in hydrostatic equilibrium with the adjacent ocean level, the fresh water disturbed the equilibrium and cause the surface of the salt water to sag until the body of combined fresh and salt water in the rocks was in equilibrium with the sea."(54)

These cavities and crevices, in order of their potential yield, are (1) interstitial spaces in clinker, (2) cavities between beds, (3) shrinkage cracks, (4) lava tubes, (5) gas vesicles, (6) cracks produced by mechanical forces after the flows have come to rest, and (7) tree mold holes.

Fluctuations

The basal ground water level fluctuates in response to changes in rainfall, tides, and draft and under irrigated areas to changes in the amount of surface water applied to the land. Annual fluctuation ranges from an inch to two feet but fluctuations of more than a half foot are unusual and indicate tremendous changes in the volumne of ground storage. The annual peak usually occurs in the early spring and the annual low in the late fall. The annual fluctuations results chiefly from cessation of pumpage, which is generally concurrent with increased rainfall. The immediate recovery in irrigated areas at the beginning of a wet spell is caused chiefly by cessation of pumpage. A rise due to recharge from rainfall takes several days or weeks.

The basal zone of saturation is recharged by direct percolation from rainfall, seepage from streams and ditches and return flow from irrigated fields. About 25% of Kauai is composed of such permeable lavas and cinders that no water run-off occurs, no matter how much rain falls. The average annual recharge is roughly estimated to be 300,000 million gallons or 1,000,000 acre feet from rainfall on Kauai. Fluctuations due to recharge from rainfall and irrigation seepage are obscured by pumping and tidal fluctuations.

Tidal fluctuations in water levels in wells varies with the permeability of the rock and the distance from the sea. The water table in the very permeable rocks usually fluctuates with the tides, whereas that in the finer grain sediments does not. Figure 20 shows the effect of the tide in a well on Oahu. On Maui, the tide has been found to cause fluctuations of about

Figure 20

Fluctuation of Water Level
on Kauai

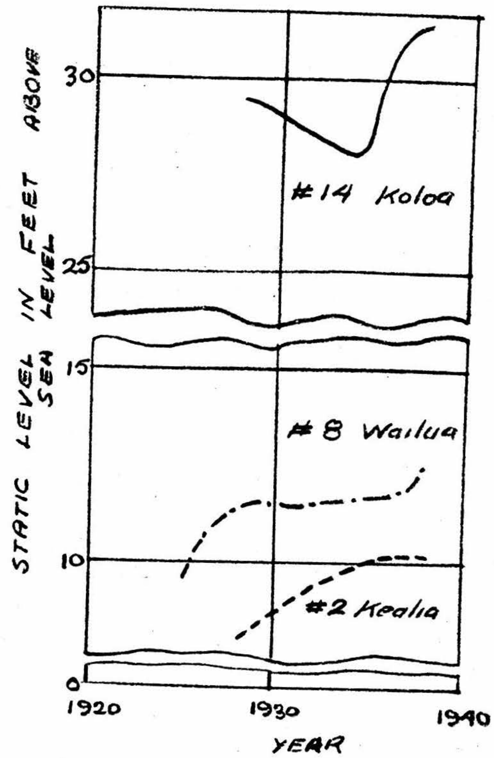
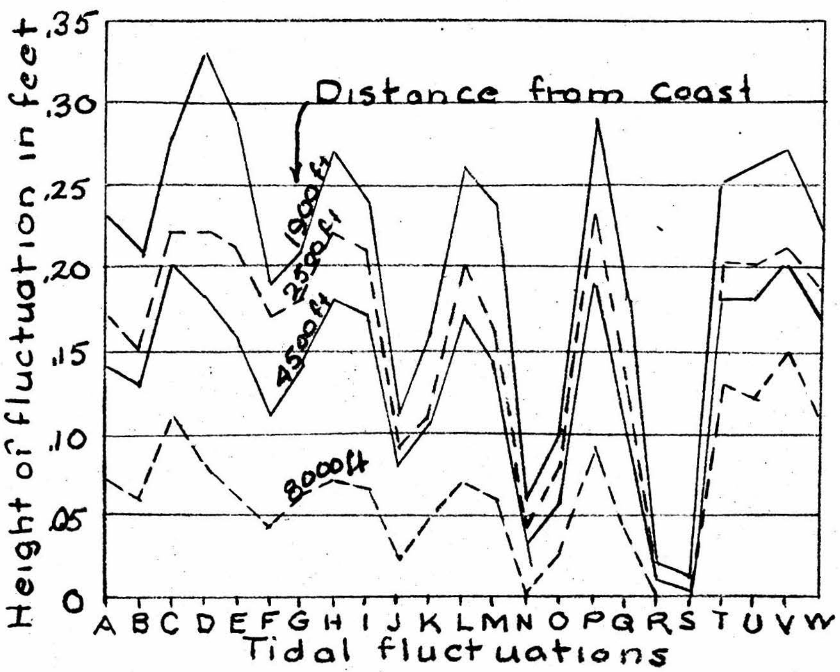


Figure 21

Tidal Fluctuations
on Maui



A to W represent sucessive crests
and troughs of tidal fluctuations

one foot only in wells in loose sand 100 yards from the beaches. Also on Maui, automatic recorders were maintained during non-pumping periods in 1934 on the Maui Agriculture Company wells. Tidal fluctuations were found to travel inland at the rate of 1000 feet per 15 to 20 minutes depending upon the magnitude and frequency of the tides. Tidal fluctuations are barely perciptable 15,000 feet from the coast. It was found that large fluctuations die out more slowly inland than small ones; also that large low tides pass inland as readily as large high tides. These findings are represented graphically in Figure 21.

The amount of the fluctuation of the water level in a well due to pumping varies with the quantity of water being pumped. When pumping begins the water level drops precipitously for a short time, and afterward declines slowly as the cone of draw-down slowly deepens and approaches equilibrium. In some areas where there is slight draft, the cone of draw-down soon reaches virtual equilibrium and thereafter little or no further decline due to pumping occurs. When the pump is shut down the water level rises rapidly for a few minutes and then very slowly for several hours. The cumulative effect of pumping in the basins during times when the draft is in excess of the recharge is to cause the average daily static level to decline. Sometimes, however, nearly all the fluctuation is caused by pumpage.

Measurement of these fluctuations afford an important index to the character of aquifer encountered.

Artesian Water

Very little is known about the artesian water on any of the islands where it is found except for Honolulu. On Kauai, along parts of the coast, a sedimentary caprock confines the basal water in the lava rock under pressure. A narrow artesian belt lies between Waimea and the Barking Sands, and an even narrower belt lies between Hanamaulu and Kealia. This area is poorly defined because so few wells exist.

On Oahu, the effective confining beds in the caprock of the artesian basins consists of lateritic soil (soil formed in humid tropical latitudes and notably high in red iron oxide), tuff deposits from post Koolau eruptions, and the shales, sandstones, and conglomerates laid down beneath the sea by the streams draining Oahu. Except for the tuff and soil these deposits represent the material eroded from the Koolau and Waianae Ranges and deposited in fans and as marine sediments during former high stands of the sea. Where the coastal plain sediments are thick the permeability of the lower fine grained beds in the caprock has probably been appreciably reduced through compression by the weight of the overlying rocks. The reefs and post Koolau basalt flows included in the caprock are too permeable to act as retaining beds. It is not essential for these deposits to make a continuous cover above sea level in order to obtain artesian water. In many places drillers have found a "mudrock" to be the aquifer but closer examination has revealed this to be decomposed Koolau basalt and there is considerable amounts of it to be found below the coastal sediments. Evidence is accumulating to indicate that the Koolau lavas beneath the coastal plain sediments were deeply weathered before submergence and that the soil thus formed is one of the most effective parts of the caprock.

The deepest wells on Oahu have penetrated only water-bearing flow lavas beneath the caprock. Nowhere in the thick sections of Koolau basalt exposed in the canyons adjacent to the artesian areas are there any beds adequate to form a lower confining bed and it is these basalts that dip beneath the caprock and form the aquifer. Furthermore, deep wells have passed through the zone of fresh artesian water into salt water; hence there can be no doubt that a lower confining bed is absent from the artesian basins.

As artesian water can pass freely into the sea around the lower end of the caprock, it is also true that when artesian water is withdrawn in excess of the recharge the direction of movement of water is reversed and sea water can enter the aquifer. Thus artesian water is essentially in hydrostatic equilibrium with the sea water.

The head of the artesian wells of Oahu fluctuates in response to changes in the amount of rainfall on the intake area, changes in draft, changes in barometric pressure, tides and earthquakes.

Annual fluctuations of artesian head occur in the various isopiestic areas and range from about one to five feet, depending upon the amount of draft and rainfall. As the rate of pumping decreases with increased rainfall, the rise in static head during wet weather is a function of both factors and not readily susceptible of separation. It is clear, however, that the immediate recovery at the beginning of a wet spell is caused principally by decreased pumpage rather than solely by recharge because it takes place immediately whereas if it were due to rainfall a lag would occur. The annual peak usually occurs in the spring and the annual low in the fall.

If the caprock of an artesian aquifer is impervious and does not yield to changes in barometric pressure, the water in the well should be depressed and forced into the aquifer during times of high pressure, and it should rise during periods of low pressure. The specific gravity of mercury is 13.59, hence for each rise of 0.1 in a mercury barometer the water in the well should decline 0.113 feet. Observations in wells on Oahu show that the wells show distinct but somewhat dampened fluctuations resulting from barometric changes in pressure..

The tidal range of the ocean about Oahu averages about two feet. This change in pressure on the caprock apparently affects the water level in the artesian wells.

Fluctuations of the water level in artesian wells as a result of the compression of the aquifer by earthquakes were noted in California. In examining the automatic records of wells in the Honolulu area numerous fluctuations produced by earthquakes were found amounting to a change of one foot in the water level. Earthquakes in the Americas, exclusive of Alaska, affected the wells less often than those in Alaska, the South Seas, and Asia, possibly because they were less severe.

Quality

In the Hawaiian Islands the salinity of water is generally expressed as sodium chloride ($NaCl$) in grains per gallon, all chloride being computed as sodium chloride. Strictly, this is not correct, as salt in natural waters includes, in addition to sodium chloride, potassium chloride (KCl) and sometimes magnesium chloride ($MgCl_2$) and calcium chloride ($CaCl_2$) in measurable quantities. As numerous chemical analyses have shown that sodium chloride is by far the predominant one of these salts, however, the assumption that all the chlorides in water are sodium chloride is very nearly correct. The making of a complete chemical analyses of a sample of water is a tediuos and complicated operation, so that usually only the chloride content is determined. This is done by titration and in a well equipped laboratory can be accomplished in a few minutes, the results being expressed in parts of chloride per million parts of water, or just parts per million. If it is assumed that all the salt in the water is sodium chloride the quantity per quantity per gallon is computed by dividing the amount of chlorides as expressed in parts per million by 10.39. Fresh water floats on sea water and is separated from it by a transitionary zone of mixture. The salt content in all wells drilled into the basal zone of saturation in all islands also increases with depth. Permeability of rocks, distance from coast, height of tides, rates of discharge and recharge, and other factors influence the rate the salt increases with depth and the thickness of the zone of mixture.

For example, Oahu is fortunate in having a large supply of generally good ground water. The sugar plantations, which use by far the largest amount of the artesian water on this island, have developed supplies that, although locally somewhat brackish, are entirely satisfactory for irrigation. Very little of the developed ground water contains more than 1000 parts per million of chlorides, and most of it contains less than 300 parts per million. The treasury standard sets 250 parts per million of chloride as desirable for drinking purposes. Although excessive chloride content of water has a bad effect on sugar cane the amount that it will tolerate varies with the type of soil, the terrain, the quantity of water applied to the fields. Several plantation officials have mentioned figures ranging from 700 to 900 parts per million of chlorides as the maximum permissible without impairing the yield of sugar. On one plantation it was found that best results were obtained when the water discharged from a group of wells containing as high as 850 parts per million of chloride was mixed with high-level spring and tunnel water very low in chlorides. On another plantation brackish water from springfed sea level ponds is used for the reason that for certain fields it is the only water available.

All natural waters on Oahu have been found to contain salt. As no point on the island is more than twelve miles from the ocean all of it is reached by fine ocean spray or minute particles of salt that remain suspended in the air when the spray evaporates. This material is blown over the land, and some of it is brought down by the rains. Table 24 gives the chloride determinations of rain water at different points on the island. All the points at which samples of rain water were taken are at low altitudes on the leeward side of the island 0.4 to 1.6 miles from the coast.

Table 24

Chloride Determinations of Rain Water on Oahu (parts per million) (55)

Date 1920	Location	Chloride	Remarks
Apr. 18	U. of Hawaii Campus Honolulu	9	No information given
Apr. 28	U.S.C.&G. Survey magnetic obervatory near Sisal	10	Single shower of 0.25 inches
May 23	ditto	10	Single shower
May 22	Manoa Valley, Hono.	6.5	Single shower of 0.37 inches
Jun. 22	Manoa Valley, Hono.	6	Single shower of 0.33 inches
Jun. 22	Manoa Valley, Hono.	6	Single shower of 0.34 inches
Apr. 2	Roof of Alexander Young Hotel, Honolulu	11.5	Composite samples of several rains
Jul. 13	ditto	11	Single shower
Jul. 17	ditto	29	No infommation given
Aug. 3	ditto	42	No information given
Aug. 14	ditto	6	No information given

As some of the rain water is lost through evaporation and transpiration before percolating into the rocks, a concentrating effect takes place so that the water from high level springs and tunnels will contain somewhat larger quantities of chloride.

the lowest amount found in the natural waters on Oahu was 18 parts per million in a sample taken from the Waiahole collecting ditch, on the windward side of the Koolau Range, at an altitude of 750 feet. Numerous other samples from different sources contained less than 30 parts per million of chlorides. The chlorides found in samples from artesian wells range from 27 to 14,560 parts per million, It is obvious that these large quantities of salt must be due to the intrusion of sea water rather than spray.

Of far greater significance is the contamination that results from direct contact with sea water. The drilling of artesian wells on Oahu, for example, has shown that the danger with regard to the encroachment of sea water here is the same as has been encountered in many other localities. Geologists and engineers have known for a long time that in a porous rock formation fresh water, owing to its lower specific gravity, will float on salt water without mixing with it to any large extent and that when water from such a source is pumped faster than it can be replenished laterally the salinity of the water will increase. Lindren, (56) in his studies of the ground waters on Molokai, found that there was a sheet of fresh water floating on underlying sea water and that even moderate pumping on wells drilled below sea level caused the chloride content of the water to increase rapidly. He makes a vague reference to the counter pressure of sea water, but the Alexanders (57) were the first to develop a clear concept of the relation of sea water to fresh ground water. Because the artesian head in the central Honolulu district was more than forty two feet when the first wells were drilled, and only a small part of this head could be accounted for by the frictional resistance of the aquifer, Prof. W. D. Alexander and his son, A. C. Alexander, of Honolulu, came to the conclusion some time before 1908 that the seaward end of the aquifer was not covered, that the fresh water was in equilibrium with sea water, and that the head was caused by the difference in density between the sea and fresh water. On Maui the same situation exists. Several of the plantations on that island originally developed ground water by drilling wells down into saturated rock, but when the water was pumped the salt content rose so high as to render it unfit for use. They found that by sinking tunnels that would skim off only the top, water of much better quality was obtained.

Along the coast of Florida Sanford (58) also found a sheet of fresh water floating on sea water. He noted that there was a zone of diffusion between the two waters and that the more open-textured the rock the greater the admixture of salt with fresh water . On the coast of Maine and on adjacent small islands Clapp (59) found that some wells drilled into water-bearing rock first struck fresh water but when drilled deeper struck salt water. He also stated that in some wells fresh water was obtained at first but continued pumping rendered them salty. Thompson (60) states that what he believes to be a continuous sand formation lying at a depth of 800 feet at Atlantic City yielded excellent water, whereas Lewes, Del., about 55 miles away, at depths of 891 to 950 feet, the formation contained water that was too salty for use. Brown (61) found that along the Connecticut coast near New Haven if wells were drilled too deep contamination by sea water would result. Also he found that continued draft on some wells that originally yielded water of good quality caused the salinity of the water from them to increase so much that many had to be abandoned. Spear (62) in his description of the Brooklyn water supply on Long Island stated that a group of deep wells near the shore became seriously contaminated by sea water after continued heavy pumping but that other groups of wells similarly situated, some of which were used only a few months each year during dry weather and the rest pumped continuously but rather lightly, continued to yield good water.

Most of the ground water developments on Oahu consist of artesian wells drilled down into the water bearing basalt that forms the main body of the island. The depth of these wells ranges from 97 to 1,500 feet, depending on location. As the top of the water bearing basalt or aquifer dips toward the sea, wells drilled near the shore must pass through considerable thicknesses of alluvium and marine deposits before striking the top of the aquifer. In some localities the logs of wells have shown that the underlying aquifer is 700 or more feet below the ground surface and that even the top of it contains brackish water. In general, as the distance to the top of the aquifer below sea level decreases the chloride in the water that occurs in it also decreases. As the salinity of the water varies vertically but remains fairly uniform horizontally, wells driven deeper than others in the same area will yield brackish water of much higher chloride content. The contamination by sea water progresses upward from beneath rather than laterally from the shore line, and therefore wells that are drilled too deep will yield brackish water even though they are at considerable distances from the shore.

Another factor that affects the salinity of the water is the intensity of draft on a well. In a well that penetrates the transition or mixture zone the chloride content of the water will increase with the rate of discharge. The removal of water surrounding a well when discharging will cause a reduction in hydrostatic pressure in its immediate vicinity, even in a very permeable aquifer, and this will cause the formation of a cone of the more brackish water below the bottom of the well, which will rise into the well, thereby increasing the salinity. The distance to the top of the cone from the bottom of the well is dependent on the rate of discharge from the well. In many wells that show only slight contamination or none at all the effect of the cone of brackish water is not noticeable, because of comparatively light drafts or distances greater than the height of the cones between the top of the zone of mixture and the bottom of the wells.

It has often been stated that when a well goes salty from over-draft it will not freshen if pumping is reduced. Wells will freshen however, if pumping is halted in order to permit the rise of the water table again. Small clinker particles derived from the unlined floor and walls of the tunnels may gradually freshen wells by sealing cracks in the sump and tunnel floors, and thereby reducing the direct upward flow of saltier water from below.

One method used in improving the quality of the yield is to reduce the depth by filling the lower portion of the well, so that only water from the upper part of the zone of mixture, which is less brackish, will enter the well. The filling consists of iron punchings, lead, crushed rock, concrete or neat cement. Often several of these materials are combined. The methods used in depositing the materials at the bottom of the wells are the same as those used in sealing wells except that in a few wells the materials have been dumped in at the top. The amount of chloride in the water is determined both before and after the lower part of the well is plugged in order to find out where the filling should stop.

Methods of Recovery

The wells in Hawaii are classified below:

A. Drilled Wells (There are seventy nine drilled wells on Kauai)

1. Artesian and sub-artesian

   a. Water confined in basalt flows under residual or sedimentary caprock and in counter poise with salt water.

   b. Water confined in the dike complex under a sedimentary caprock

c. Water confined in water bearers in the caprock series

2. Non-artesian

a. Water in basalt

b. Water in basalt, limestone or permeable earthy sediments in the caprock series.

B. Dug Wells (non-artesian)

1. Supplies by the unconfined water bearers of the caprock series

2. Supplied by basalt

a. Maui-type involving the skimming principle and not in the dike complex (Two of this type on Kauai)

b. Lanai-type in the dike complex and not involving the skimming principle

c. Oahu-type in the dike comples but involving the skimming principle

The ancient Hawaiians obtained water from springs, natural water holes, and wells near the beaches. They spread sheets of oiled tapa cloth made from the bark of trees to catch the dew and rain. The sites for wells were presumably located by noting springs at low tide along the coast or by tasting water in cracks along the coast. Two types of wells were made. One type was made by blocking crevices in the lava with rocks, mud, and straw on the seaward side to prevent the inflow of sea water. Large rocks were placed in position for steps to make access easier.

The other type was made by excavating loose clinker in aa to the basal water near the beach. Such wells were lined with big boulders if necessary to keep the clinker from caving in. The water in many Hawaiian wells is too brackish to drink if one is not accustomed to it, but the Hawaiians are noted for their ability to drink brackish water.

The Maui type well is the name applied throughout Hawaii to a mine-like shaft to the basal water table with one or more infiltration tunnels skimming the fresh water off the underlying sea water. This type of well consist of either a vertical or an inclined shaft, driven to a point a few feet below the water table, with one or more horizontal tunnels driven from the bottom of the shaft to skim fresh water from the upper part of the zone of saturation. Although it is not essential for the shaft to be in a water bearing rock, the tunnels are always driven into permeable basalt, the location of which is often predetermined by test holes. The most effective direction to drive these tunnels is generally at right angles to the strike and inland across the dip of the lavas. Where the zone of fresh water is thick, as it is under most of Oahu, tunnels may be unnecessary. The pumping machinery is placed in a chamber at the bottom of the shaft, and the shaft is locally deepened to provide sump for the suction pipes. The well is usually dug at the altitude from which the water is to be distributed, thereby saving pipe line. The shaft is either lined or unlined according to the character of the materials encountered, but the tunnels are not lined. A well of the Maui type encounters a much greater amount of pervious rock than a drilled well, but the essential difference is that the Maui well skims the fresh water from the top of the zone of saturation, whereas the drilled well passes through may feet of non-water-bearing rock and then must penetrate deep into the zone of saturation in order to have an effective yield. The drilled well therefore derives its supply from the lower part of the zone of fresh water rather than from the upper part..

With wells of the Maui type it is safe to lower the water level either to or a little below sea level, and because the aquifer are highly permeable the cone of influence is greatly extended. This lowering of head would decrease the natural discharge from the basin now occuring through overflow and upward percolation through the confining beds. Because of the low gradients of the water table this lowering of the head would greatly increase the flow into the pumped area. As it costs less to build a well of the Maui type than to drill a battery of artesian wells, the safe yield of the basin can be increased economically. The Maui wells likewise recover greater amounts of water safely in the areas being pumped by the plantations.

The first well of this type was excavated in 1900 on the old Kihei plantation on Maui. The fact that this well is still in operation and that wells of this type have been utilized so successfully, even to the extent of replacing the artesian wells in the Honolulu city supply, establishes the soundness of this method for recovering basal water in Hawaii.

The Lanai type is a shaft that penetrates as deeply as feasible into water confined at high altitude between dikes and is supplied from either an infiltration tunnel cutting across the saturated dike compartments, or from drilled wells in the bottom of the shaft. It may be identical in appearance to a Maui type well but differs greatly because the skimming principle and salt-water contamination are not involved. The water level in such wells may vary widely compared to that in the Maui type well.

Perched Water

Perched or high-level ground water is exceedingly valuable. It is used to irrigate lands too high to be economically supplied by pumped water, to supplement low-level ground water supplies where they are insufficient, to generate power, and to dilute brackish, low-level pumped water thereby increasing the water supply and hence the irrigable acreage. It is utilized for domestic supplies and on the islands of Hawaii and Maui it is used to flume the sugar cane.

The four types of occurance of perched ground water are (1) water confined by intrusive rocks, (2) water perched on ash or tuff beds, (3) water perched on soil beds, (4) water perched on alluvium. They are all the known quantitatively important occurances of high-level ground water in the basalts of the Hawaiian Islands. On Maui an andesitic mantle is sufficently impermeable to hold up water perched on Haleakala..

Dikes and sills constitute the more important intrusive rocks. On Oahu the sills are so small and so few that they serve as restraining members in a few places only. The conception of ground water occurring in reservoirs of permeable flow lavas confined on the sides by dikes and on the bottom by sills and ash beds has become general. On Oahu, however, such structures are not found necessary in conjunction with the dike systems to hold the water at high levels as the indefinite floor of the reservoir may be formed by the dike complex itself. The water entering this vertical zone of saturation is disposed of in several ways. A large part overflows as springs; some reaches the sea by flowing at the base of the alluvium; and the remainder leaks through joint cracks in the dikes along the margin of the rift zone and joins the basal zone of saturation supplying the artesian basins. Thus deep percolation and overflow account for all the water.

In a general way, the dikes in the rift zone are roughly parallel and nearly vertical, so that a tunnel driven at right angles to them drains the water confined by them for a considerable distance on each side and above the tunnel. In some tunnels the drainage will be from an area of 2000 feet on each side. However, in dikes of low dip and irregular trend it would be perfectly possible for a tunnel not to drain areas around it. Almost invariably the lower the tunnel the more successful it will be. Largest yields per foot of tunnel will be obtained by driving at right angles to the prevailing dike trend and under the highest and wettest mountain mass. If possible, tunnels should be driven in dike areas below springs, which indicate that a water table is present.

Water is commonly perched in lava by underlying fine textured red or reddish yellow vitric tuff beds or ash beds. Some beds may be baked to a friable brick by the overlying lava and some weathered to a clay-like soil before burial. In places some of these soils are probably loess, dust blown from ash-covered lands to the windward. An interesting lesson in the relation of the amount of rainfall to the effectiveness of interstratified tuff or ash beds in perching water is found in East Maui. Numerous tuff beds are exposed in the canyons cut in the Kula lavas on the dry slope, yet only a few perch water, and then only in quantites of a pint or less per minute. On the wet north slope, similar tuff beds in the same formation perch hundreds of small springs and give rise to perennial streams. This difference shows that the tuff beds are permeable and discontinuous to allow great quantities of water to percolate through them. But when the rainfall exceeds about forty inches a year, loss by seepage is exceeded by recharge, and sufficient water moves laterally along them to make perched springs. Numerous tunnels at the contact of tuff beds and the overlying lava have shown that usually small amounts of water only can be recovered from such structures unless the ash mantled a terrace cut by shallow gullies or containing swales in which water will collect. Another essential is that the ash be buried by lava before it is cut through in too many places by streams. The water enters tunnels when they penetrate the bottom of such gullies. Wide buried plateaus mantled with ash yield little water to tunnels even in regions of high rainfall.

Most of the buried lava flows that remained uncovered sufficiently long to decompose to soil, received numerous ash showers. Also many of the ash beds were weathered to a soil before burial. This it is difficult to separate the occurance of water perched on interstratified soil and ash.

Water is found in valley-filling lavas in many places where they overlie older alluvium and silted stream beds. The water is recovered by tunnels driven to the floor of such buried valleys. At first thought it would seem that perched water could be recovered from the younger alluvium where it is underlain by older alluvium. In some places water occurs in this manner, but the deposits of younger alluvium in the upper parts of the valleys are too small in area and occur practically only in the stream bed. It is only near sea level that the younger alluvium widens out, and there water can be developed more readily from the basal water table..

Perched water in general is of good quality. Salt carried inland as spray amounts usually to less than two grains of salt per gallon. In general on the islands, the total dissolved solids range from 150 to 250 parts per million in the smaller leeward springs and 50 to 175 parts per million in the windward springs.

The Lanai type of well is most frequently used in recovering water from the dike complexes. It is a shaft that penetrates as deeply as feasible into water confined at high altitude between dikes and is supplied from either an infiltration tunnel cutting across the saturated dike complex or from drilled wells in the bottom of the shaft.

On Kauai there are nine tunnels in seven locations in operation for the recovery of perched waters. (see Figure 19)

Summary

In summarizing the potential yield of water resources for the island of Kauai it is not possible to compute more than average values for rainfall, evaporation, transpiration, and deep percolation. Records of rainfall are available for many lowland stations but for few stations in the mountains where the heavy rainfall occurs. Streamflow records are only available for a limited number of streams and positions on the streams. Great care must be used in using the available streamflow data because of diversion ditches that may divert water supply before the gaging station. Consequently only the stations close to the watershed are reliable in general. Evaporation and transpiration data are not available and only approximate magnitudes of these quantities may be gained from records taken on Oahu.

In order to compute the relative magnitude of the various dispositions of rainfall a number of watersheds were investigated and may be summarized as follows:

Windward side of Kauai:

Hanalei River, above elevation of 625'

Area of watershed -- 7.4 sq. miles

Average yearly rainfall -- 300 inches

Average rainfall--105 m.g.d.

Average streamflow -- 56.2 m.g.d.

Runoff -- 53%

Kalalau Stream, above elevation of 960'

Area of Watershed -- 1.6 sq.miles

Average yearly rainfall -- 125 inches

Average rainfall -- 9.5 m.g.d.

Average streamflow -- 4.7 m.g.d.

Runoff -- 49%

Leeward side of Kauai:

Hanapepe River, above elevation of 150'

Area of watershed -- 18.8 sq. miles

Average yearly rainfall -- 170 inches

Average rainfall -- 152 m.g.d.

Average streamflow -- 57.6 m.g.d.

Runoff -- 38%

Waimea River, above elevation of 490' (using streamflow of Waimea River and Kekaha Ditch)

Area of Watershed -- 45.0 sq. miles

Average yearly rainfall -- 100 inches

Average rainfall -- 214 m. g.d.

Average streamflow -- 84.5 m.g.d.

Runoff -- 39%

These indicate an average runoff of 45% for the watersheds in the mountains. Assuming that on the lowlands where rainfall is less the runoff is less, approaching 5 to 15% as found by Stearns on Maui and already noted we might use as an overall figure for runoff of 25% which would roughly correspond with that found on Oahu.

For evaporation and transpiration an average value is in the order of magnitude of forty inches per year as is indicated in the summary of results for the consumption on the tests of Vaksuik on Oahu.

The average yearly water supply on the island may then be summarized:

Average Rainfall, 88 in.	2,320,000 gallons	76,000 acrefeet
Evaporation and Transpiration, 40 in.	1,060,000	34,500
Runoff, 25%	580,000	19,000
Additions to ground water	680,000	22,500

The additions to ground water, like the runoff, are continually emptying into the ocean unless utilized as the water table rises in the lavas creating a flow toward the lower head and discharging into the sea.

Water Development

For future development three sources should be investigated:

1) Perched Water
2) Ground Water
3) Further utilization of surface streams

There is a plentiful supply of water for Kauai. Development will be limited only by the price necessary to utilize the water and for this reason perched water should be investigated first. Large quantities of water are believed to exist as have been found on Maui and Oahu. These waters, confined by vertical dikes and sills, can be tapped by tunnels and large supplies utilized. Gravity flow to the point of utilization is possible.

Ground water may be exploited more freely than at present. In order to determine the quantity that might be pumped the safe yield of supply should be determined. One method would be to place observation wells between the pumping wells and the sea well beyond the circle of influence of the pumped well. The observation well should penetrate to a depth giving salt or brackish water. The observation well would then be used to check any inflitration of sea water by checking the water level and noting the chloride content at various depths every half year. The observation well would give warning of any overpumping.

In order to utilize the total ground water wells should run in a ring around the island parallel to the shoreline to intercept as much as possible of the basal ground water escaping into the ocean. Ground water has the disadvantages of the expense of pumping but may be utilized efficiently during periods of low stream flow to supplement surface water supplies.

Further utilization of surface streams will require storage of water so as to utilize the high water stage flow. Storage may be in reservoirs or as ground water. Surface reservoirs have no problem of evaporation as precipitation is larger than evaporation. Impermeable reservoir sites are difficult to obtain and the cost of developing them may be excessive.

The surface flow may be put into the ground by running the water at slow rates over pervious material in spreading basins. This will increase the percolation of surface streams greatly. Wells may be used to put the water underground although at the present this type of ground water recharging has been disappointing in Southern California.

If the surface flow is added to perched water supplies at a higher elevation, gravity flow may still be utilized in collecting the water and transporting for irrigation. Otherwise the surface flow could be added to the basal water supplies and taken from storage by pumping.

Ground Water Draft, in millions of gallons, from wells for irrigation, domestic, and industrial use on Kauai, 1941 (Data furnished by the owners) (63)

Well	Pumpage
County of Kauai	
Waimea Water Works	155.48
Hanapepe Water Works	104.03
Kekaha Sugar Co.	
Wells 12-14, 16, & 19	150.00
Well 9	516.00
Wells K-1 to K-5 (inc. 5, 7, & 11)	764.00
Wells M-1 to M-12	1,743.00
Kekaha Pump	730.00
Mana Pump	118.00
Waiawa Pump	623.00
Koloa Sugar Co. (3 pumps)	978.15
Lihue Plantation Co.	
Shaft	467.00
Kealia Wells	200.00
Total	6,548.66

McBryde Sugar Co. not included. Three pumps in Hanapepe Valley and one pump at Lawai Valley pump ground and surface water. It is not possible to separate them.

Head, in feet, and chloride content, in parts per million, in typical artesian wells in Kauai, 1941 (64)

Well 2F. Kealia, Kauai (Records by East Kauai Water Co.)

Date	Head	Chloride	Date	Head	Chloride	Date	Head	Chloride
Jan. 21	10.74	46	May 21	10.52	45	Sept. 22	10.47	45
Feb. 20	10.36	41	Jun 21	10.04	43	Oct. 20	10.39	41
Mar. 25	10.46	43	Jul. 25	10.25	43	Nov. 19	10.50	42
Apr. 21	10.32	42	Aug. 20	9.89	43	Dec. 22	10.36	43

Well 7. Wailua, Kauai (Records by Lihue Plantation Co.)

Date	Head	Chloride	Date	Head	Chloride	Date	Head	Chloride
Jan. 16		131	May 16		140	Sept. 16		130
Feb. 18		131	Jun. 16		128	Oct. 16		128
Mar. 17		132	Jul. 15		125	Nov. 17		127
Apr. 15		126	Aug. 15		128	Dec. 16		132

Well 8. Wailua, Kauai (Records by Lihue Plantation Co.)

Date	Head	Chloride	Date	Head	Chloride	Date	Head	Chloride
Jan. 16	12.75	105	May 16	12.50	---a	Sept. 16	12.85	125
Feb. 18	12.74	100	Jun. 16	12.58	112	Oct. 16	12.99	122
Mar. 17	12.54	100	Jul. 15	12.61	111	Nov. 17	12.93	97
Apr. 15	12.53	95	Aug. 15	12.69	116	Dec. 16	12.73	101

Well 14N. Koloa, Kauai (Records by Koloa Sugar Co.)

Date	Head	Chloride	Date	Head	Chloride	Date	Head	Chloride
Jan. 30	11.94b	453	May 30	10.69b	453	Sept. 29	8.35b	453
Feb. 27	10.85b	453	Jun. 26	8.77b	453	Oct. 30	28.60	453
Mar. 28	10.10b	453	Jul. 30	10.02b	464	Nov. 27	11.27b	432
Apr. 28	10.69b	453	Aug. 29	8.19b	453	Dec.	------------	c

Well 35. Kekaha, Kauai (Records by Kekaha Sugar Co.)

Date	Head	Chloride	Date	Head	Chloride	Date	Head	Chloride
Jan. 19	10.67	194	May	----------	----	Sept.	----------	----
Feb. 15	9.80	425	Jun. 16	9.22	479	Oct.	----------	----
Mar. 18	9.64	322	Jul. 15	9.22	571	Nov.	----------	----
Apr. 22	9.52	419	Aug. 16	-------	----	Dec.	----------	----

Well 37. Kekaha, Kauai (Records by Kekaha Sugar Co.)

Date	Head	Chloride	Date	Head	Chloride	Date	Head	Chloride
Jan. 19	9.66	158	May	----------	----	Sept.	----------	----
Feb. 15	9.77	152	Jun. 16	9.32	115	Oct.	----------	----
Mar. 18	9.51	327	Jul. 15	9.33	194	Nov. 20	9.98	194
Apr. 22	9.63	109	Aug. 16	9.68	261	Dec.	----------	----

Well 56. Kekaha, Kauai (Records by Kekaha Sugar Co.)

Date	Head	Chloride	Date	Head	Chloride	Date	Head	Chloride
Jan. 19	9.89	218	May	----------	----	Sept.	----------	----
Feb. 15	9.96	218	Jun. 16	9.55	118	Oct.	----------	----
Mar. 18	9.52	231	Jul. 15	9.52	218	Nov. 20	9.72	212
Apr. 22	9.70	207	Aug. 16	9.52	194	Dec.	----------	----

a. Bottle broken in mail
b. Pumps running

Mineral Analyses of Water from Oahu

Location--Kaimuki Pump
Date Collected--Sept. 25, 1944

Hour Collected--0905
Lab. Number--26455

Head above sea level, feet---20.07
Specific conductance at 25°C., mho/ccm. x 10^4--3.33
pH value (by glass electrode)--7.95
Turbidity--0.5
Color--1

Analyses, in parts per million

Dissolved oxygen		8.00
Free carbon dioxide		2
Silica		35
Calcium		4.2
Magnesium		4.7
Sodium		51
Potassium		3.8
Bicarbonate		74
Sulfate		9.4
Chloride		53
Fluoride		.40
Nitrate		1.0
Phosphate		.45
Iron		.07
Manganese		.02
Aluminum		.10
Zinc		.10
Copper		.05
Lead	less than	.05
Arsenic		.01
Selenium		.02
Residue at 103°C.		195
Total dissolved solids		237
Alkalinity		61
Total hardness		30
Non-carbonate hardness		0

In milliequivalents per liter:

Calcium (Ca)	.210
Magnesium (Mg)	.387
Sodium (Na)	2.217
Potassium (K)	.097
Error	.044
Total	2.955
Bicarbonate (HCO_3)	1.213
Sulfate (SO_4)	.196
Chloride (Cl)	1.495
Fluoride (F)	.021
Nitrate (NO_3)	.016
Phosphate (PO_4)	.014
Total	2.955

References

1. United States Census Records, 1940
2. Statistical Abstract for the United States, 1944
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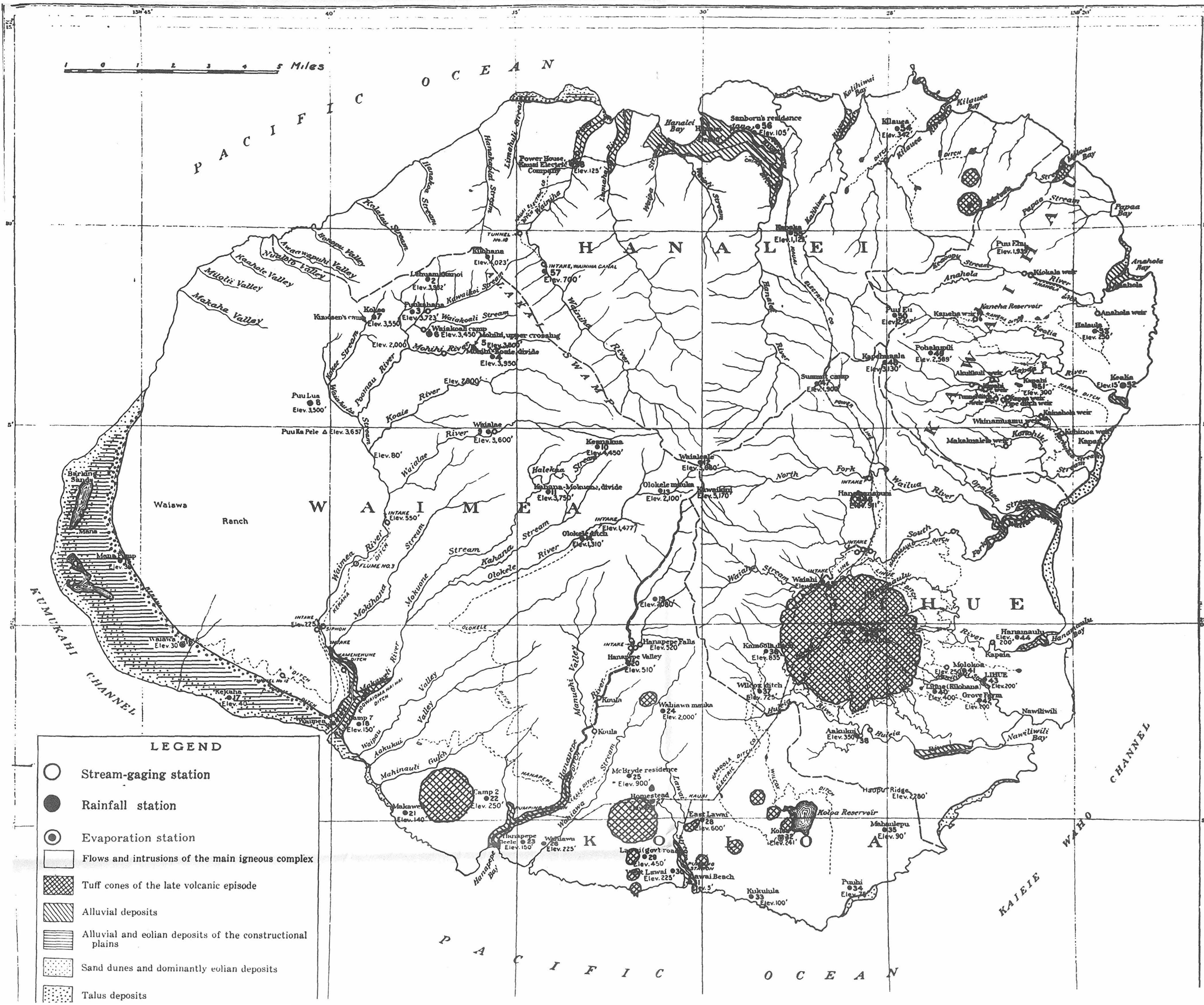
PACIFIC OCEAN
KUMUKAHI CHANNEL
KAIEIE WAHO CHANNEL
HANALEI
WAIMEA
KAWAIHAU
LIHUE
KOLOA
ALAKAI SWAMP
Walawa Ranch
Barking Sands
Hanalei Bay
Kilauea Bay
Nawiliwili Bay
Hanapepe Bay
Kolopa Reservoir
LEGEND
Stream-gaging station
Rainfall station
Evaporation station
Flows and intrusions of the main igneous complex
Tuff cones of the late volcanic episode
Alluvial deposits
Alluvial and eolian deposits of the constructional plains
Sand dunes and dominantly eolian deposits
Talus deposits