The Annual Rainfall of East Maui

By Luna B. Leopold

ABSTRACT

East Maui Irrigation Company, serving the sugar plantations on the Maui isthmus, must pay for water derived from lands not under the company’s jurisdiction. This payment, which is a substantial sum, is based in part on a map of mean annual rainfall of the East Maui area.

It was mutually agreed by the Territory of Hawaii, represented by the U. S. Geological Survey, and the irrigation company that a revised rainfall map should be constructed by a disinterested third party, and that adjustments of payments would be determined by the new map. The author was asked to prepare the map which accompanies the present paper.

The map of average annual rainfall includes the whole north slope of Haleakula, the 10,000-foot mountain of East Maui. The height of the mountain is sufficient to divert the trade wind flow laterally around it rather than allowing the air to flow over the top as is the case of West Maui. Yet sufficient vertical lifting occurs to provide an annual rainfall of over 400 inches at the wettest place.

The map utilized the records of 116 rain gages, an average of one gage per four square miles. Each gage record was adjusted to a long-term base record to eliminate the effects of differing periods of record at different gages. The annual rainfall at the wettest place near Wailua Iki was determined by this study to be considerably greater than that shown in previously published maps of the area.

Ordinarily when one rain gage experiences a wet year, so also do others in the vicinity. Thus the ratio between gages remains constant from year to year. In the area studied there were found long-period swings in these interstation ratios. Gages in the higher elevation and westward portion (Opana-Olinda area) decreased in rainfall relative to a stable base during the period 1923–1933 and increased relatively in the period 1933–1948. Hana and Waiakamoi, representing the low elevation northern and eastern sectors acted in an opposite fashion, increasing or remaining constant relative to the base during 1923–33. In the later period, 1933–1948, these stations decreased in rainfall relative to the stable base.

This long-term swing in interstation relations is interpreted as an indication that during the period 1923–1933 the stable layer of air at the temperature inversion,

1 Also published with the approval of the Director as Technical Paper No. 189 of the Pineapple Research Institute of Hawaii.

2 Luna B. Leopold is former head, Department of Meteorology, Hawaiian Sugar Planters' Association and Pineapple Research Institute, cooperating.
which marks the top of the clouds (about 7000 feet mean sea level in Hawaii), decreased in height. This decreased the height of cloud tops and caused relative decreases in the rainfall at stations in the 3000–4000 foot elevation zone. At the same time it is conjectured that this phenomenon caused the rainfall at Hana to increase relative to a stable base.

Such long-period changes in the height of the stable inversion layer probably reflect changes in position and strength of the Pacific high pressure cell northeast of Hawaii. Complete upper air temperature data are available for Hawaii only since 1946. Any climatological information on the action of the temperature inversion in years previous to 1946 is of importance in studying the relation of the changes observed in the high pressure cell to local variations in Hawaiian rainfall.

The wettest portions of the Hawaiian Islands rank high in the list of heavy rainfall areas of the earth. These localities of excessive precipitation occur in Hawaii on the windward slopes of the larger volcanic cones or at the summits of the lesser mountains. Their vegetation is truly a jungle forest, the dominant plants being ohia lehua (Metrosideros collina), tree fern (Cibotium chamissoni), and an exotic fern (Gleichenia linearis) which has taken over large portions of the forest floor wherever the upper story allows moderate sunlight to penetrate to the ground.

A nearly unbroken forest canopy, the locally rough surface of lava flows, and the high rainfall prohibit the use of such areas for any purpose except that of water catchments.

The belt of maximum rainfall on East Maui is at 3000 feet, decreasing toward both higher and lower elevations. At approximately 7000 feet the forest ends at a sharp boundary and is replaced at higher elevations by a xerophytic zone of shrubs and grass (4).

The development and maintenance of pipelines, tunnels, and ditches to collect and distribute water for the irrigation of the drier areas has provided both the stimulus and opportunity to maintain a network of rain gages probably unequaled in localities of comparable rainfall.

Isohyetal maps of the Hawaiian Islands have been published by the Territorial Planning Board (8), by Voorhees for Oahu (9), by Halstead and Leopold for Oahu (1), Stearns and MacDonald for Maui (7), and by others. However, all the available maps either used incomplete records or the station rainfall values were not adjusted to a long period base record.

Opportunity to make a detailed study of annual rainfall on East Maui was provided through the desire of East Maui Irrigation Company to obtain a revised isohyetal map of their water catchment area. This company pays for irrigation water derived from land not under its jurisdiction and the payments are based on a mean annual rainfall map.

THE RAINFALL RECORDS

The longest rainfall records of East Maui are for stations located along the main coastal road connecting Hana with the central isthmus. There are numerous gages in the sugar, pineapple, and ranch lands on the isthmus and the west slopes of Haleakala cone. In the rain forest of the windward slopes, the gages have been maintained only with great effort because the interior is accessible only by horse or, in many places, by foot. The few trails have been cut for inspection of
TABLE I

<table>
<thead>
<tr>
<th>Years</th>
<th>No. of Cages (in)</th>
<th>No. of Cages Having Various Lengths</th>
</tr>
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<tbody>
<tr>
<td>0</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>11-01</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>61-12</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>62-02</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>69-48</td>
<td></td>
</tr>
</tbody>
</table>

No. of Cages

In the columns under the headings 0, 1, 2, 3, 4, 5, and 6, the figures represent the number of cages having various lengths. The figures in parentheses indicate the number of cages with lengths of 0 to 1 foot, 1 to 2 feet, 2 to 3 feet, 3 to 4 feet, 4 to 5 feet, and 5 to 6 feet, respectively.
the area of about 400 square miles, or an average of one gage per four square miles. Key maps showing locations of gages operating in 1948 have been published (4). The gage numbers adopted in the key have been used in Table 3 to help identify the currently operating stations in the East Maui area. Old gages now discontinued do not have assigned numbers but the locations of all gages are indicated on the map of Figure 2.

A frequency distribution of length of record of gages used in this study is summarized in Table 1.

**ADJUSTMENT OF RECORDS TO A LONG-TERM BASE**

As in most isohyetal problems, it is necessary to adjust records of various lengths to a long-term base record. Failure to do so can distort the isohyetal pattern because certain short records may have run only during unusually wet or dry years.

The choice of a base station or group of stations is usually simple because in most areas secular changes in rainfall can occur without varying the ratios between stations. However, in an area such as East Maui, known secular changes of weather elements such as wind direction may alter interstation ratios in a systematic manner. For example, the surface wind at Honolulu has progressively changed direction during the 43-year record (10) and it is conceivable that certain stations would therefore systematically be subjected to progressively more windward exposure while other stations simultaneously would become more leeward. Examination of the records for such influences has, in the present study, been a major problem, which will be discussed below.

**CONSTRUCTION OF THE ISOHYETAL MAP**

The mean annual isohyetal map of Figure 2, based on the adjusted annual means, is different from the previously published maps in small but interesting ways. The isohyetal map of Maui included in the Territorial Planning Board Report (8) showed the maximum rainfall on East Maui to be 280 inches. The present study indicates a maximum of 400 inches located at a much more easterly position. The map of Stearns and MacDonald (7) showed two separate isohyetal maxima, the easterly one reaching 350 inches. An unpublished map of the U. S.

<table>
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<th>Station No.</th>
<th>Station</th>
<th>Mean Annual Rainfall, Inches</th>
</tr>
</thead>
<tbody>
<tr>
<td>442</td>
<td>Lupi</td>
<td>177</td>
</tr>
<tr>
<td>447</td>
<td>Punalu</td>
<td>126</td>
</tr>
<tr>
<td>450</td>
<td>Honoumau</td>
<td>221</td>
</tr>
<tr>
<td>456</td>
<td>Keanoe</td>
<td>266</td>
</tr>
<tr>
<td>450</td>
<td>Paioea</td>
<td>214</td>
</tr>
</tbody>
</table>

It was decided that the long-term base record to be used for station adjustment and for comparison with individual records should include stations of both relatively windward and relatively leeward location, and should include both relatively wet and dry stations. This would tend to balance secular changes in one station by changes of the opposite direction in other stations. Five stations, each having records for 42 identical years, were chosen, representing at least some range in annual rainfall and nearly uniform distribution geographically about the critical high rainfall area. (Table 2.)

The rainfall averages before and after adjustment to the base group are presented in Table 3.

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3 Station numbers are those used in The Key to Rain Gages in Hawaii (see reference 4).
Weather Bureau (date unknown, scale one inch = 21/2 miles), showed a long narrow area of heaviest rainfall connecting the areas where Stearns and MacDonald had drawn two maxima. The shape and position of the isohyetal maximum is of some interest because it bears on the interpretation of causes of observed rainfall.

Interpolation in ungauged areas was facilitated by the construction of profiles on which rainfall was plotted against distance, examples of which are presented in Figure 3. Numerous profiles of this kind drawn for stations in the Hawaiian Islands show a tendency for logarithmic increase of rainfall with distance (straight line plot on log paper) except in the vicinity of the rainfall maxima where the profiles round off. This feature can be seen in a number of the profiles of Figure 3. Because it helped determine the location and value of the isohyetal maximum near Waialua Iki, profile J-G-E (see Figure 3) was of particular significance.

It can be seen that this profile is nearly symmetrical in slope on both sides of the isohyetal maximum. Two straight lines drawn through the station points would intersect to the left (southwest) of Waialua Iki, indicating a maximum rainfall even higher than measured at Waialua Iki. When the crest of profile J-G-E of Figure 3 was rounded off in accordance with observed profiles elsewhere, one can read from the profile two points indicating the probable position for each isohyetal line. In this manner the position and value of the highest isohyetal line, 400 inches, was determined.

In a similar manner, profile lines were used to determine the position of isohyets in other ungauged areas, as shown by Figure 3. Such profiles also help determine isohyetal patterns in areas where, due to some unknown local factor, a particular gage may be inconsistent with surrounding ones. An example is Erehwon Makai on Profile A-H-M. All gages except this one align themselves nicely. For this reason the Erehwon Makai record of only one year was disregarded.

A disconcerting problem was posed by the 26-year record of Honomanu Mauka. Owing to its position between Puohakamoa No. 2 (291 inches) and Waialua Iki (391 inches) it is surprising that the rainfall of Honomanu Mauka is as low as the 261 inches which the gage recorded. This relatively low value led Stearns and MacDonald to draw two closed isohyetal centers enclosing Puohakamoa No. 2 and Waialua Iki, respectively.

To seek a physical explanation for the low rainfall recorded at Honomanu Mauka, Robert P. Bruce and the writer made a field inspection of the gages along the Kailiili-Honomanu Mauka line. Each gage appeared moderately well exposed at the present time. However, Honomanu Mauka is situated at the top and near the brink of a cliff at the head of a mile-long straight reach of the deep valley of Honomanu Stream. This reach is oriented NE-SW and which the trade wind probably funnels.

The gage is placed about 50 feet southwest (leeward) of a planted line of eucalyptus trees which marks a land boundary. At the time of our inspection (June 1949) the trees immediately upwind from the gage were 25 feet high. These trees were actually sprouts from eucalyptus trunks measuring about 16 inches diameter breast height. The sprouts were 4-5 inches in diameter, and though the growth was too uniform to produce clear-cut annual rings, the age of the sprouts was estimated to be 6-8 years. There is no doubt that the eucalyptus trees were planted about at the time the trail was built and the gage installed, and about a decade ago the trees near the rain gage were cut down to provide better exposure for the gage.

The exposure near the brink of the
cliff resembles in principle that of a rain gage placed at the ridge of a peaked roof. Under conditions of prevailing trade wind, C. K. Wentworth (unpublished data) has shown that a gage at the roof peak collected less rain than normally exposed gages in the vicinity. This is due to the fact that rain tends to blow over the roof ridge and give abnormally large values on the eaves and ground to leeward.

Proceeding eastward from Puohakamoa No. 2, tree fern increased perceptibly and the general aspect of the vegetation indicated an increase in rainfall, not a decrease. This fact, together with the gage exposure at Honomanu Mauka, led to the conclusion that the mean annual rainfall recorded by that gage is too low. Judging from the relation of this gage to the five-station group as shown by its curve in Figure 5 and discussed below, its catch was not radically influenced by the cutting of the eucalyptus trees.

**RELATION BETWEEN INDIVIDUAL GAGES**

It is accepted hydrologic practice to test the homogeneity of a rainfall record by "double mass curve" plotting (2). A base station or group of stations is chosen and the annual rainfall values are accumulated from the beginning to the end of the record. The annual values for the station to be tested are also accumulated, and for each year, the accumulated value of the base is plotted against the corresponding accumulated value for the station. This results in a nearly straight line, the slope of which is the ratio of the annual rainfall of the base to the annual rainfall of the station. An example is presented in Figure 4a.

The points plotted on the diagram should vary in a random manner about the line of best fit. Any sharp break in slope is interpreted as a change in exposure or position of the station being tested.

The same principle is used here for a different purpose: to determine if there are well-defined secular changes in relations between stations. We will plot an enlarged diagram of the double mass curve, exaggerating the variation of the points about the straight line. A diagrammatic sample is shown in Figure 4b. In the present study the straight line was drawn from the origin through the point representing the latest year of record. The slope of this line is then the ratio

\[
\frac{\text{average annual rainfall of station}}{\text{average annual rainfall of base group}}
\]

On Figure 4b let point B represent the plotted position of accumulated rainfall of station X vs. the base group at some particular year. It can be seen that in the example, station X has accumulated rainfall at a higher than normal rate during the period from the initial year to year B. The accumulated deviation in inches of rainfall at year B is the distance \( d \), which can be computed by the formula

\[
[S_b - (G_b R)] \cos \theta = d
\]

where:
- \( S_b \) = actual accumulated rain of station X at year B
- \( G_b \) = actual accumulated rain of base group at year B
- \( R \) = ratio of mean annual rain at station X to mean annual rain at base group.

Since the angle \( \theta \) is constant for each year it is possible to plot a curve of accumulated deviation against years by using the distance \( d \) instead of \( d \). Also, since the deviation curves for a number of stations will be plotted against the same time scale for interstation comparison we will divide each deviation by the mean annual rainfall of the individual station. This yields the curves in Figure 5, in which the ordinate of any point is the accumulated departure in
percentage of the average annual precipitation of the respective station.

Positive slopes mean relatively large increments of rainfall at the station compared with the increment at the five-station group. Negative slopes mean relatively small increments compared with the five-station group. Comparison of slopes of curves of different stations then can be interpreted as relative rates of accumulation, and since each station curve is expressed as a percentage, the curves are directly comparable in quantitative terms.

It should be emphasized that the accumulated deviation at a given station, which is plotted as the ordinate of Figure 5, is not a measure of rainfall amounts at the station. Year-to-year variations in rainfall have been eliminated. Slopes of the lines represent rates of accumulation relative to the concomitant accumulation at the base group. Correlation coefficients were computed between the ratio

\[
\frac{\text{rainfall for a given year at station } X}{\text{rainfall for same year at base group}}
\]

and rainfall for the year at the base group. Using Hana, Waiakamoi, and Kipahulu as samples in this computation, correlation coefficients were in no case significant.

Looking at the stations in Figure 5 whose records begin in 1907, it can be seen that Puohakamoa No. 2 and Waiakamoi are the most contrasting, one increasing while the other decreases, and vice versa. Owing to the small number of stations with long records, interpretation is difficult when we confine our attention to the whole 1907–1948 record. It is somewhat clearer when the 1923–1948 record alone is inspected. Relative to the base group, the period 1923 to 1933 is marked by low rates of accumulation (negative slopes) at Puohakamoa No. 2, Honomanu Mauka, Kailua Mauka, Ukulele, and Kailua, normal rates (near zero slopes) at Waiakamoi, and moderate (positive) rates at Hana. In the period 1933 to 1948, Hana and Waiakamoi are decreasing with respect to the base group while the other stations tend to increase.

We see that the latter stations near the coast to the north and east of the center of maximum rainfall act in an opposite manner to coastal stations to the west, and to high elevation stations west and south of isohyetal maximum. This suggests a secular trend in the position of greatest rainfall activity; that is, a shifting of position of isohyetal pattern without regard to absolute value of the isohyets. This could be caused by a downhill and easterly movement of the isohyetal pattern during the period 1923–1933 and a subsequent reverse movement.

Kipahulu lies on the southeast coast of Maui, outside the area concerned here and is probably affected in a different way by storms with southerly winds. It is interesting, however, that its deviation curve with respect to the five-station group is in phase with and similar to the Puohakamoa curve, with even larger amplitude.

If the shifting of isohyetal pattern is real, a fact which the short records do not completely establish but merely suggest, a possible explanation might lie in secular changes in the height of the trade wind subsidence temperature inversion. A lower inversion could explain the relative decrease of rain in the Ukulele–Puohakamoa No. 2 area. It is possible that this decrease in inversion height change would tend to increase relatively the rainfall at Hana. The possibility is of particular interest because of the paleoclimatic work of Selling (6). He finds evidence in the pollen hogs of Hawaii that xerophytic species grew at the top of West Maui in the early portion of “Period III,” which he tentatively sug-
SELECTED PROFILES OF ANNUAL RAINFALL VS. DISTANCE EAST MAUI

THE HAWAIIAN PLANTERS' RECORD

DISTANCE IN MILES

RAINFALL IN INCHES

- WAILUA IKI
- MAKAPO
- PUNALUU
- HONOKAA
- WAILUA IKI

HALEAKALA
- KAMAKAHEA
- MOUNTAIN
- UKULELE
- MAUI INTAKE
- WAIAKAMO GULCH
- HAIPIENA
- PUCHAKAMOA
- PUCHAKAMOA
- HONOMANU UPG
- HONOMANU VALLEY
- KAPAA VALLEY
- WAILUA IKI
- HONOKAA
- PUNALUU
- HAIPIENA
- MAUI INTAKE
- WAIAKAMO GULCH
- PUCHAKAMOA
- PUCHAKAMOA

RAINFALL IN INCHES

- 600
- 400
- 200
- 100
- 60

HALEAKALA
- KAMAKAHEA
- MOUNTAIN
- UKULELE
- MAUI INTAKE
- WAIAKAMO GULCH
- HAIPIENA
- PUCHAKAMOA
- PUCHAKAMOA
- HONOMANU UPG
- HONOMANU VALLEY
- KAPAA VALLEY
- WAILUA IKI
- HONOKAA
- PUNALUU
- HAIPIENA
- MAUI INTAKE
- WAIAKAMO GULCH
- PUCHAKAMOA
- PUCHAKAMOA

THE HAWAIIAN PLANTERS' RECORD

DISTANCE IN MILES

RAINFALL IN INCHES

- 600
- 400
- 200
- 100
- 60
Figure 3. (Left) Rainfall-distance profiles and (above) map showing profile locations on East Maui.

suggests is correlative with a geochronologically dated period of about 1000 B.C. in northern Sweden. To have xerophytes on top of West Maui, Selling suggests that the height of temperature inversion decreased until it lay near 4000 feet mean sea level. Its present height is about 7000 feet. Without attempting to discuss the details of Selling's post-glacial history of Hawaiian vegetation, it is possibly significant that there are indications within the period of rainfall record that secular changes in inversion height have occurred.

The secular shift of wind direction at Honolulu discussed by Wentworth (10) was examined for possible coincidence with the interstation relations discussed here, but no clear-cut correlation was observed.

The causes of the secular changes observed here are at present unknown but their description is a first step toward better understanding of the processes involved which will no doubt be of importance in paleoclimatology and long-range forecasting.

THE ISOHYETAL PATTERN

Mountains reaching high enough to penetrate the temperature inversion (whose mean height is 7000 feet) tend to split the trade wind laterally. Mountains whose tops lie below the inversion allow air to surmount their summits, as has been mentioned by Selling (6) and Leopold (3). In the latter case the maximum isohyet will lie nearly at the summit. The higher mountains receive the maximum precipitation at a lower elevation, about 3000 feet.

Splitting of the winds by Mauna Kea and Mauna Loa has been demonstrated by noting directions of movement of the cloud bases at various points around the mountain base (3). Similar action of the winds around Haleakala is shown by the direction of motion of cloud bases presented in Figure 6.

The dynamics of the splitting process by which the maximum rainfalls at the
Figure 4. (Top: 4A) Accumulated annual rainfall at five-station base group in relation to accumulated annual rainfall at Hana. This type of plot is called a "double mass curve." The nearly straight line relation indicates an approximately constant ratio of annual rainfall catch at the two locations. (Bottom: 4B) Diagrammatic representation of double mass curve shown above exaggerating the deviations of the cumulative curve from the straight line.
3000 feet level have not developed. It is noteworthy that the maximum rain area lies somewhat higher than the level of the normal cloud base on East Maui, which is approximately 2000 feet.

The isohyetal lines of the wet portion of East Maui (Figure 2) are nearly triangular in shape. On the NE the isohyets closely parallel the topographic contours. On the west the isohyets are perpendicular to the local topographic contours at nearly every point. On the upper slopes of the mountain, the south edge of the high rainfall zone, the isohyets are parallel to the contours. The zone where horizontal and vertical convergence combine to a maximum value is indicated by the isohyet of largest value, at the center of the northeast facing slope, and it would be illogical that wind flowing around the mountain should result in two centers of maximum rainfall as some earlier maps showed. Winds observed on the northeast slopes of the mountain tend to parallel the topographic contour. As these winds reach the place on the north flank of the mountain where the topographic contours break suddenly from their WNW–ESE orientation to a north–south orientation, the winds will there acquire a downslope component. For this reason, it is qualitatively reasonable that the isohyets in that place should be perpendicular to the contours.

Thus in a general way the isohyetal pattern derived on Figure 2 seems in accordance with the simple topographic pattern of the north and northeast slopes of the mountain.

In the western portion of the area where the slopes of Haleakala give way to the smooth flat isthmus, there is smooth gradation of rainfall, decreasing to the west. In the vicinity of Pukalani and Pulehu Camp, there is an area of sharp bending of the isohyets, with a prong of higher rainfall jutting westward. This is a logical result of the interaction of the sea breeze and the trade wind as explained elsewhere by the writer (3). The southwesterly sea breeze meets the northeast trade along a sharp boundary.
Figure 6. Wind direction at about 2000 feet as indicated by movement of cloud bases, East Maui. Wind directions represent the mean during the period mid-morning to mid-afternoon on two days of observation, July 12 and 13, 1949.

oriented ENE–WSW passing north of Pukalani Junction. The jutting area of higher rainfall there is a result of the naulu rains caused by the interaction of the two wind systems.4

ACKNOWLEDGMENTS

It is a pleasure to acknowledge the cooperation and interest of Robert P. Bruce, manager of East Maui Irrigation Company at Paia, who helped by arranging numerous field trips. George Moriguchi was of inestimable assistance in the computation, drafting, and field work. The pineapple and sugar companies of central Maui kindly furnished rainfall records for use in this study. The manuscript was read by my colleagues W. A. Mordy and C. K. Stidd who offered valuable suggestions.

4 The original computation sheets and the tracing of the isohyetal map have been placed for permanent record in the files of the Library of the Experiment Station, Hawaiian Sugar Planters’ Association, Honolulu.
LITERATURE CITED


3 Leopold, Luna B. The Interaction of Trade Wind and Sea Breeze, Hawaii. (in press).


