Rainfall and Streamflow from Small Tree-Covered and Fern-Covered and Burned Watersheds in Hawaii

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U. S. FOREST SERVICE RESEARCH PAPER PSW- 34 1966

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U.S. Forest Service research in Hawaii
is conducted in cooperation with
Division of Forestry
Hawaii Department of Land and Natural Resources

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116.25(969)

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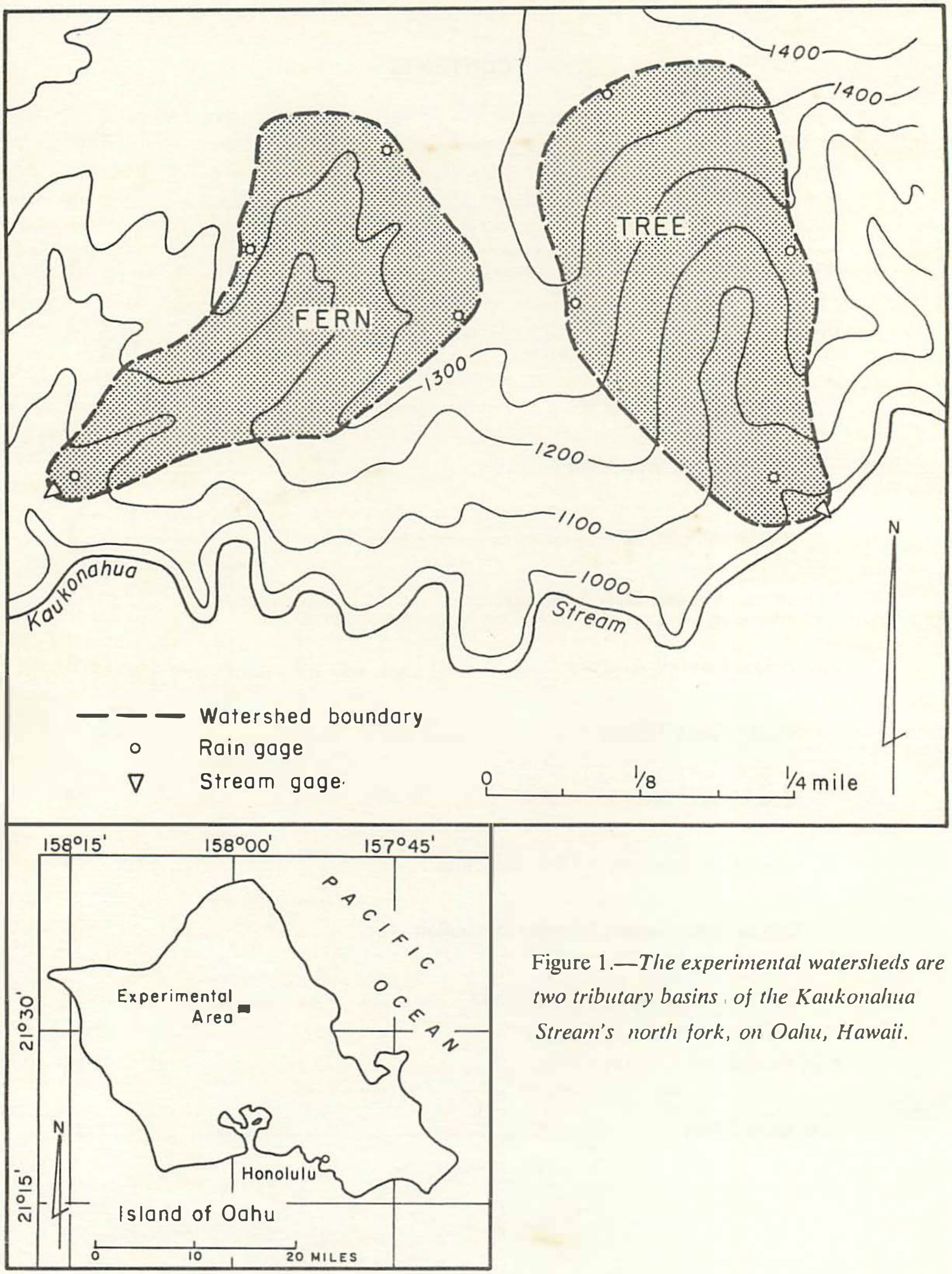

Figure 1.—*The experimental watersheds are two tributary basins of the Kaukonahua Stream's north fork, on Oahu, Hawaii.*

In Hawaii a supply of water may depend on anything from rain on the roof at Kona to elaborate tunneling for water at Honolulu. Historically the people of Hawaii have looked *mauka*—to the mountain watersheds—for much of their water. What they now see are watershed slopes clothed with vegetation that protects the soil and helps deep percolation of water. But 80 years ago, these same slopes were denuded—only rigid protection and widespread planting since then has brought vegetation back to its present state. Now the question is being asked: "Can these mountain watersheds be safely managed to produce even more water and other products to meet the expanding needs of this island State?" (Anderson, Hopkins, and Nelson 1962).

In 1951, the Hawaii Division of Forestry began a study to learn more about the role of mountain watersheds and their vegetation and water supply. Two small watersheds on Oahu were selected and measurements of streamflow and rainfall were made.[1] The sites represent rather critical mid-elevation, moderate rainfall zone, under two rather distinct vegetation covers: planted trees and native false staghorn fern (*Dicranopteris linearis*).

Some foresters believe that a fern cover on a watershed will produce more streamflow than will a cover of native or planted trees. If this were true, fern could be removed in those areas where it is important to increase the water percolation to groundwater storage, such as on the island of Oahu. In other places, such as the above-surface catchment ditches on east Maui, a fern cover might put more water in the ditches. Conversion of native watershed cover, including fern, to introduced hardwoods for timber production, is one of the significant changes now under way on Hawaii's watersheds. Will such conversions be beneficial or detrimental to water supplies? And does a fern cover help or hinder streamflow from a watershed?

This paper provides some answers to these questions by reporting on an analysis of rainfall and streamflow data from two small watersheds in Hawaii. It describes the statistical techniques used, and suggests the principal hydrologic processes in effect under three different watershed conditions.

Watershed Physiography

The watersheds studied are two tributary basins of the north fork of the Kaukonahua Stream, on Oahu (fig. 1). The fern-covered watershed is 29.7 acres, and the tree-covered watershed is 38 acres. They lie on an elevation of 1,000 to 1,400 feet, generally face south, and have slopes of 66 and 56 percent, respectively. They are rather typical of Oahu's streams at that elevation, on the leeward side of the Koolau Range.

The watersheds are situated in the rock-type mapped by Stearns and Vaksvik (1935) as the "Koolau Volcanic Series," a typical olivine basalt of the "aa" or the "pahoehoe" texture. Each lava flow is 10 to 30 feet thick and dips from 5 to 15 degrees to the northwest.

Soils in the experimental watersheds lie within the area mapped as the "Helemano Series." This series is typical of soils found on steep slopes at elevations ranging from 500 to 1,200 feet. Permeability is classed as intermediate, 2 to 6 inches per hour, with medium internal drainage. The watersheds were examined by Chester Wentworth, geologist with the Board of Water Supply, City and County of Honolulu; and by Z. C. Foster, soil conservationist with the Agricultural Extension Center, University of Hawaii. Both scientists reported no fundamental differences in rock or soil between the two watersheds.

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[1] This work was under the direction of staff foresters Collin Lennox, Karl Korte, and Albert MacDonald. In the analysis reported in this paper, we checked their compilations and extracted additional rainfall and streamflow data from their charts.

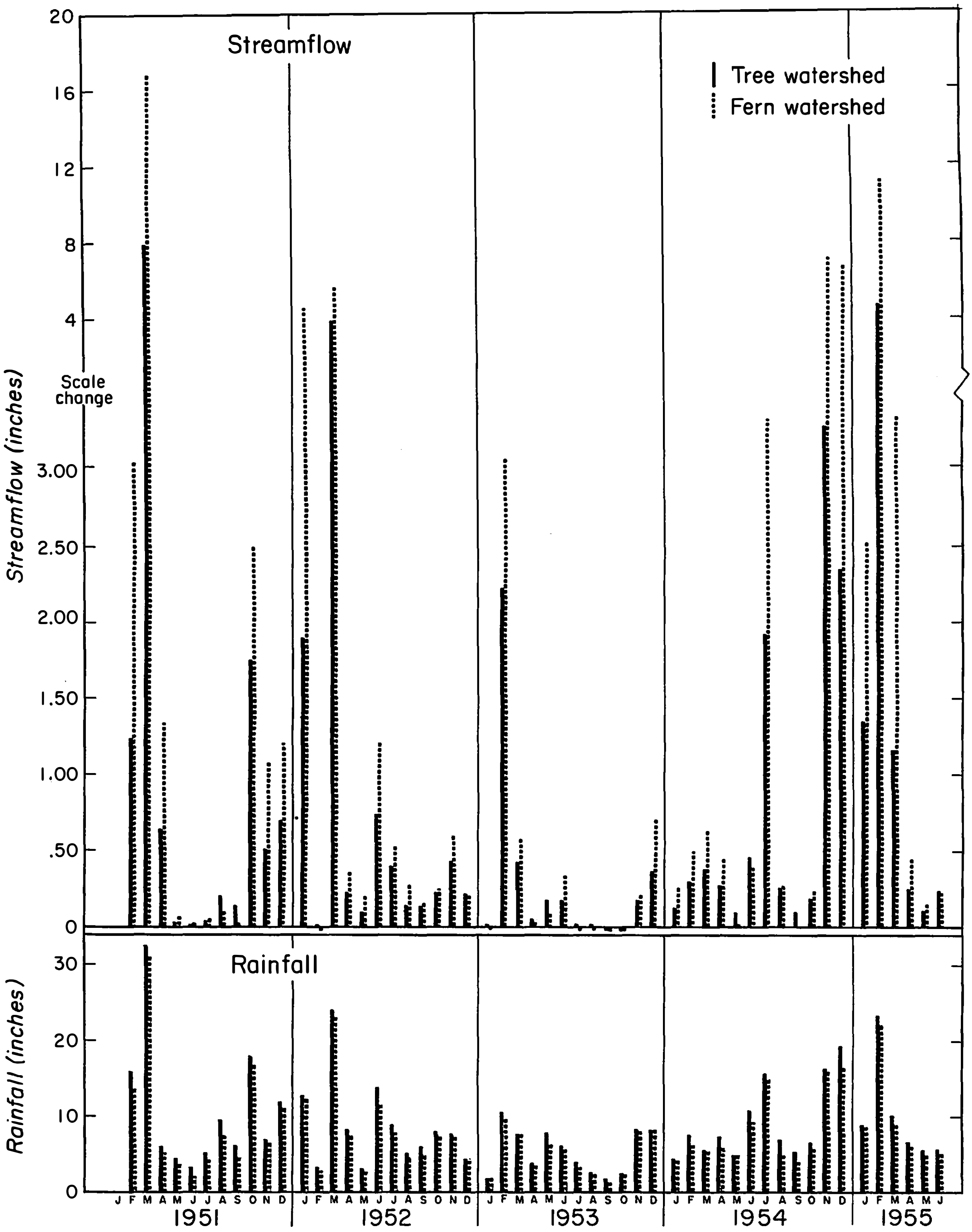

Figure 2.—*Comparison of monthly runoff and precipitation on the tree-covered and fern-covered watersheds.*

Vegetation Cover

The watersheds are usually referred to by their "original" vegetation: predominantly planted trees in the "tree watershed," and mixtures of native trees with large areas of false staghorn fern in the "fern watershed."

Tree-Covered Watershed

When the study was started in 1951, the tree watershed was dominated by turpentine trees, various eucalypts, and rubber trees, originating from plantings in the early 1930's. Tree diameters in 1951 ranged from 12 to 20 inches. About 80 percent of the basin was forested, with vegetation canopy being heaviest on slopes that were most exposed to the northeasterly trade winds.

Fern-Covered Watershed

The vegetation on the fern watershed underwent changes during the period of this study. Originally, the area was dominated by false staghorn fern, with some scattered koa and ohia trees, and patches of kukui trees in the drainage ways. In 1951, about 65 percent of the basin was open forest and 35 percent dense fern. In August 1953, this vegetation was burned, and reburned a month later. From then until March 1954 the entire basin was planted to small trees, mostly brushbox, and blackbutt eucalyptus; some 13,000 trees in all were planted.

Vegetation Changes

Vegetation in both watersheds would be expected to have changed—both with age and with the burn-planting treatment of 1953. Changes would be expected to be small in the tree watershed, for the trees were already 19 years old at the start of the study. Therefore growth in the ensuing 4½ years of the study probably had little effect. In contrast, the burn-planting treatment of the fern watershed would be expected to result in a more drastic change.

Two burnings on the fern watershed affected both the vegetation and the current water regime. The hydrologic effects of vegetation removal might be expected to include (a) reduction in the interception storage, (b) inducing of quicker paths for runoff, and (c) reduction in transpiration. The first effect would be expected to cause runoff to start with less rain and to produce a constant increase in the runoff per storm. The second effect would be expected to increase peak flows. The third effect could increase both percolated water and total streamflow.

Instrumentation and Data Collection

Measurements of streamflow and rainfall on both watersheds were begun in January 1951, and continued through June 1955. Streamflow was continuously measured by an "H" type of flume of 1-foot depth and width made of redwood and set in a concrete cut-off wall. The flume and concrete section were calibrated by the U.S. Geological Survey. Streamflow stage was recorded on a Stevens "L" type recorder, with an 8-day record on each chart.

Precipitation in each watershed was measured by both standard gages and intensity recording gages (fig. 2). Standard gages were set at three sites in each watershed, representing different slope facets. All gages were set below the ridge to avoid excess wind influence on catch. A recording gage was operated on each watershed, with the gage located near but not at the stream-gaging station. Both rainfall and streamflow were recorded on the same chart.

Streamflow-Rainfall Analysis

In analyzing the data gathered, we had the following aims:

- To determine monthly and annual streamflow from the two watersheds.
- To relate by multivariate analysis total streamflow for storms and peak discharges of individual storms to storm-rainfall characteristics and prestorm rainfall.

- To determine the differences between streamflow-rainfall relations in the two watersheds and explore possible causes.
- To determine the effects on streamfall-rainfall relations of burning vegetation on the fern watersheds and of protecting trees on the other watershed.

We assumed that the streamflow was accurately measured throughout the study period, but we tested the rainfall measurements for consistency.

Rainfall Data Testing

Rainfall data from the eight individual rain gages on the watersheds used in the study were tested for consistency with each other and with nearby rain gages. We used the double-mass technique, that is, simple comparisons of accumulations of an individual gage against the means of many nearby gages (Anderson 1955; Kohler 1949). This technique can detect and correct for inconsistencies in precipitation measurements, such as those due to changes in exposure of the gage. Rainfall catches in the six standard gages were found to be consistent throughout the period of record; catches for the two intensity gages were found to have changed throughout the period of record, and were adjusted to give a consistent record throughout the study period.

Seasonal differences in rainfall were found during the testing. Average monthly rainfalls for the wet season (November–April) and the dry season (May–October) together with standard deviation were as follows:

	Wet season	Dry season	Difference
Watershed:	(inches)		
Tree gulch	10.65±7.20	6.91±3.94	3.74
Fern gulch	9.69±6.54	5.84±3.69	3.85
Differences	0.96	1.07	

The tree watershed, which is slightly nearer the Koolau summit received about 1 inch more rain per month in both the wet season and the dry. Annual rainfall was 105 inches for the tree watershed and 93 for the fern watershed. Average rainfall for the study period was about equal to the long-term average as judged by comparison with long-term records from nearby gages.

Monthly and Total Streamflow

Streamflow measurements for the individual watersheds were used when available to obtain monthly and total streamflow (fig. 2). For short periods, streamflow data were not available. Missing records were estimated by simple correlation of streamflow between the study watersheds and nearby streams. In filling in missing records for the tree and fern watersheds, daily discharges from the Poamoho and north fork of the Kaukonahua Streams were used, together with daily rainfall records. The method was similar to that used by the U.S. Geological Survey and probably gives comparable accuracy.

The means and standard deviation of monthly streamflow, by wet season and dry season, were as follows:

	Wet season	Dry season	Difference
Watershed:	(inches)		
Tree gulch	1.307±1.798	0.304±0.472	1.003
Fern gulch	2.704±3.866	0.400±0.777	2.304
Difference	—1.397	—0.096	

Annual streamflow was about 10 and 19 inches for the tree and fern watersheds, respectively. Almost all the difference in runoff between the two watersheds occurred in the wet season. Dry season flow was greater in the fern watershed, but was also more variable. For the 4½ year period of record (fig. 2) the fern watershed had 7 months with no flow, and the tree watershed 2 months. The difference in number of months of no flow is primarily associated with greater rainfall in tree watershed. The driest year was 1953, when July-to-October flow was nearly zero. The wettest months were January and February of 1955, with the largest runoff from a general "Kona storm" in February. Similar streamflow results were reported by Rice (1917) and Mink (1962) for nearby large streams.

Monthly Rainfall-Streamflow Relations

The response of each stream to a given amount of rainfall was different in the dry months (April–October) from the wet months. (November–March). Those differences were reflected in the regression coefficients relating monthly streamflow to rainfall in the month and to rainfall in the month before (equations 1–4, table 1). Explained variance ranged from 85 to 95 percent; errors of estimates ranged from 0.18 inch to 0.94 inch.

The equations imply that, for average watershed wetness, 3½ to 4½ inches of monthly precipitation were necessary to produce significant amounts of streamflow. The equations also show increased proportion of rainfall becoming streamflow for large amounts of monthly precipitation. For example, streamflow doubled when rainfall rose from 10 inches to 15 inches per month.

Further tests were made of the equations 1–4

Table 1.--*Monthly streamflow relations, fern and tree watersheds, Oahu, Hawaii 1951-1955*[1]

Equation No.	Watershed and period	Equation	n	R^2	Syx
(1)	Fern, May-Oct.	$QM=-0.55+0.096P+0.0054PSQ+0.025AP$	26	0.85	0.32
(2)	Tree, May-Oct.	$QM=-0.34+0.056P+0.0028PSQ+0.012AP$	26	.88	.18
(3)	Fern, Nov.-Apr.	$QM=-1.89+0.289P+0.0094PSQ+0.050AP$	27	.95	.95
(4)	Tree, Nov.-Apr.	$QM=-0.62+0.121P+0.0036PSQ+0.004AP$	27	.93	.51
(5)	Fern, prefire	$QHAT=-0.14+1.952Q(Tree)$	31	.94	.55
(6)	Fern, post fire	$QM=0.034+1.065QHAT-0.02SEA-0.31Q(Tree)\cdot SEA$	22	.98	.39
(7)	Fern, prefire	$QM=0.017+0.890QHAT-0.05SEA-0.27Q(Tree).SEA$	31	.98	.53

[1] Equations 1-5 are from regression on principal components (Wallis 1965); equations 6 and 7 are from ordinary full model multiple regression. In the above equations May to Oct., SEA=1; Nov. to Apr., SEA=-1; all other variables are in inches: QM is monthly streamflow, P is monthly rainfall and PSQ is its square, AP is monthly rainfall in the antecedent month, QHAT is QM for tree watershed calculated from equation 5, and Q(Tree) is measured streamflow in tree watershed for a month. n is number of months, R2 is explained variance in percent, and Syx is standard error of estimate in inches.

of table 1 to see if the variance was correlated with the amount of rain and to test for any serial correlation in the flow. We found no correlation between the variance and the size of the flow; nor, in using Durbin-Watson statistics (Durbin and Watson 1951), did we note any trend in flows for the tree watershed. But a possible increase was indicated in the flow of the fern watershed, perhaps associated with the burn of August 1953.

Effects of Burning on Monthly Streamflow

To find out if monthly flows changed after the fern watershed was burned, we first ran a simple regression of monthly runoff against time in months after January 1951. We obtained a highly significant deviation of runoff after August 1953 for the fern watershed, but only a slight deviation, which was not significant, for the tree watershed. Both these tests and the usual double mass comparison of fern and tree monthly flows showed an increase in runoff of about 20 percent after the burn.

A closer estimate of the effect of the burning of the fern watershed on its flows probably can be made by comparing the streamflow of the two watersheds before and after the burning. This technique is the familiar "calibrated watershed approach" (Wilm 1949). We wanted to know not only if the burning had an effect, but also if the effect was different in the wet and dry seasons. First, the pre-fire monthly flows of the fern watershed were regressed against those of the tree watershed (see equation 5, table 1). Next, the values of the fern watershed flow for the post-fire months were regressed against the predicted values (from equation 5) and with seasonal variables included (see equation 6, table 1). As a control, the analysis was run against the pre-fire flows (see equation 7, table 1).

Not surprisingly, quite accurate prediction resulted from direct comparison of streamflow of adjoining watersheds. The explained variances were 98 percent. The equations of monthly flows (equation 6 and 7, table 1) may be simplified by substituting −1 for the wet season and +1 for the dry season:

Wet season:
Pre-fire $Q\ (\text{fern}) = -0.06 + 2.01\ Q\ (\text{tree})$
Post-fire $Q\ (\text{fern}) = -0.10 + 2.39\ Q\ (\text{tree})$
Dry season:
Pre-fire $Q\ (\text{fern}) = -0.16 + 1.46\ Q\ (\text{tree})$
Post-fire $Q\ (\text{fern}) = -0.14 + 1.77\ Q\ (\text{tree})$

The implied effect of the burn was to increase the regression coefficient of the equations by 20 percent in both periods (from 2.01 to 2.39 in the wet season and from 1.46 to 1.77 in the dry season). This increase agrees quite closely with the results of the double mass analysis, reported earlier in this paper.

Storm Streamflow and Flood Peaks

Responses of the two watersheds to rainfall are reflected in the amount of streamflow and the maximum discharge resulting from individual storms. We studied the relation of these two streamflow characteristics to amounts and intensities of rainfall during a storm and to the amount of rainfall in the week immediately antecedent to the storm. Separate analyses were made for each watershed and for the pre-fire and post-fire periods.

In this study the precipitation record was divided into storm events, a storm being defined as "a succession of days with daily recorded rainfall, in which no day had less than 0.10 inch of rain." Storm rainfall for a watershed was a simple average of the four gages in each watershed. And maximum intensities of rain for the storm were taken from the recording gage in each watershed and adjusted to "watershed intensity" by using the ratio of watershed rainfall to catch in the intensity gage.

For each period, pre- and post-burn, a sample of storms was selected to represent as wide a difference in total storm rainfall and intensities as possible—together with a maximum of diversity in the amount of rain occurring antecedent to the storm. A total of 36 storms was used for the tree watershed and 39 storms for the fern watershed for the pre-fire period. For the post-fire period, 43 storms were selected for each watershed.

Variables and Functions Tested

Storm characteristics or variables used in the analyses are defined as follows: [2]

Dependent variables:

QS = total storm discharge, unit, inches depth.
QPI = maximum discharge, unit, inches depth per hour.

Independent variables:

AP7 = total rainfall in 7 days before storm (to index pre-storm soil moisture conditions), units inches depth.
AP30 = total rainfall in 30 days before storm, units inches depth.
P5 = maximum 5 minute rainfall intensity during storm, units, units inches per hour.
P15 = maximum 15 minute rainfall intensity during storm, units inches per hour.
PS = total storm rainfall, units inches depth.
S = seasonal class, dry season S = 1, wet season S = 0.

Means and standard deviations of the streamflow and rainfall variables are given in table 2.

Linear and non-linear expression and logarithmic transformations of the variables were tested. Selection of variables used was based on tests of significance and contributions of the variables to explain variation in streamflow.

Analytical Methods

To determine streamflow response to rainfall, we used multivariate analysis techniques.[3] Important steps in the analysis were as follows: (a) a factor analysis, known as principal components with varimax rotation, to diagnose the adequacy of the rainfall data of selected storms (Cooley and Lohnes 1962; Horst 1965); (b) a regression on principal components to determine quantitative relations between the precipitation variables and streamflow; (c) a determination of factor contribution to explain variation and the variables associated with each factor[4]; and (d) a test for autocorrelation.

To simplify the comparison of rainfall-streamflow relations, we omitted variables that were not significant or added nothing to explain streamflow variation. Eliminated variables were (a) the 5-minute intensity of rainfall (P5), which added nothing to the information not included in P15 (and P15 could also be more accurately determined from the charts); (b) antecedent 30-day precipitation (AP30) and the 7- to 30-day antecedent rainfall (AP30–AP7), which did not improve prediction over use of simple AP7; and (c) logarithmic transformation from the variables, which gave no improvement in relationships that could not be better explained by testing quadratic and joint variables of the non-transformed variables, and therefore arithmetic variables were used as being simpler to interpret and use. Tests for autocorrelation of the data, arranged by storm size, gave non-significant Durbin-Watson coefficients (Durbin and Watson 1951).

Storm Streamflow-Rainfall Relations

The relationship between storm characteristics and storm runoff between the two watersheds in the two periods, together with the seasonal effect

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[2] Units of inches refer to inches equivalent depth of water over the watershed area.

[3] Although most of the techniques used here have been known for many years, only recently have computer programs and certain extensions of the programs made them applicable to hydrology. Initially in our factor analysis we used the University of California BC TRY computer package of Prof. R. C. Tryon. Later we used a program written by J. R. Wallis for principal components analysis (Wallis 1965), which includes mathematical formulation of factor contribution from rotated factor weights contributed by Prof. W. M. Meredith, University of California, Berkeley.

[4] Factors (or dimensions) represent such physical characteristics of the storms as amount of rain, intensity of rain, or wetness of watershed. A factor may consist of one or more variables.

Table 2.--*Means and standard deviations of variables used in storm analyses*[1]

Watershed and period	Statistic	Variable symbol[2]				
		QS	QPI	PS	AP7	P15
Fern, prefire	Mean	0.83	0.11	2.99	1.44	0.86
	S.d.	1.68	.22	3.09	1.25	.93
Tree, prefire	Mean	.26	.07	2.60	1.48	.92
	S.d.	.49	.25	2.71	.99	.88
Fern, post fire	Mean	.49	.11	1.95	1.70	.87
	S.d.	1.19	.41	2.35	1.42	.87
Tree, post fire	Mean	.27	.05	2.04	2.72	.98
	S.d.	.55	.21	2.23	2.68	.76

[1] Listing of all variables for the selected storms are available upon request to Director, Pacific SW. Forest and Range Expt. Sta., P.O.Box 245, Berkeley, Calif. 94701. Original records may be seen in Honolulu, Hawaii.

[2] QS is total storm runoff in inches, QPI is maximum discharge during storm in inches per hour, PS is total precipitation for storm in inches, AP7 is total precipitation in the 7 days antecedent to storm in inches and P15 is maximum 15-minute precipitation intensity during storm in inches per hour.

of the relationships, were evaluated by the following model:

Storm runoff = F (storm precipitation (PS), storm precipitation squared (PSSQ), storm precipitation times 7-day antecedent precipitation (PSAP7), season (S).

The adequacy of the selected storms for evaluation of storm-runoff relations was tested by principal components analyses of the correlation matrices of the precipitation variables. The resulting factor weight matrix after varimax rotation is illustrated for the tree watershed in the post-fire period:

	Dimension number		
Variable:	(1)	(2)	(3)
PS	.98	—.02	.29
PSSQ	.98	—.05	.08
PSAP7	.21	0	.98
Season	—.04	.99	0

Dimension No. 1 consists of the storm precipitation and its square, with heavy loadings occurring only on these two variables. Dimension No. 2 is the season variable; and dimension No. 3 represents the interaction variable, that is, storm precipitation x antecedent 7-day precipitation. Similar factor weight matrices were obtained for other watersheds and other periods. The loadings on the variables and dimensions are such as to indicate that we may well use this set of data to test the effect of these variables on the dependent variable of storm runoff.

When the above variables were related to storm runoff by regression on principal components, explained variance ranged from 78 to 93 percent (for equations 8–11, table 4). The proportion of explained variance associated with each of the dimensions for the two watersheds and the two periods is shown in table 3. In general, the largest part of the explained variance—67 to 87 percent—was associated with the storm precipitation; another 9 to 22 percent was explained by the interaction of antecedent and storm precipitation. Seasonal effects added 1 to 3 percent.

The regressions of storm precipitation, antecedent precipitation, and season on storm runoff from the two watersheds provide some clues to the hydrologic processes in effect in these watersheds and the effects of the burn on these processes (table 4). We see that the seasonal effect on runoff was remarkably uniform, amounting to about one-tenth inch less runoff per storm in the dry season (May to October) than in the wet season (November through April). The interaction of storm and antecedent 7-day precipitation seemed to be quite important in the fern watershed in both the pre- and the post-fire periods, but not important in the tree watershed in either period. Hence, these two watersheds behaved quite differently in their reaction to antecedent wetness conditions. If the different responses to antecedent precipitation were due to soil conditions developed under the fern vegetation, then the effect persisted after the burning of the fern watershed into the post-fire period. The

Table 3.--*Explained variance, storm analyses, by watershed and period*

Watershed and period	Variables and explained variance for dimension number...[1]			
	(1)	(2)	(3)	R^2
	STORM DISCHARGE			
Fern, prefire	PS, PSSQ 67	Season 3	PSAP7, PS 22	92
Fern,post fire	PSSQ, PS, PSAP7 89	Season 1	PS 3	93
Tree, prefire	PS, PSSQ 67	Season 2	PSAP7 9	78
Tree,post fire	PS, PSSQ 87	Season 2	PSAP7 5	93
	PEAK DISCHARGE			
Fern, prefire	P15SQ, PSSQ 54	Season 2	PSAP7, PSSQ 32	88
Fern,post fire	P15SQ, PSSQ 89	Season 1	PSAP7 4	94
Tree, prefire	P15SQ 78	Season 1	PSAP7, PSSQ 3	82
Tree,post fire	P15SQ, PSSQ 90	Season 1	PSAP7 1	91

[1] Definition of variables PS, etc. are given in text. SQ after a variable indicated variable is the square; PSAP7 is PS times AP7.

Table 4.--*Storm streamflow and peak flow relations to storm and pre-storm characteristics, fern and tree watersheds, Oahu, Hawaii, 1951-1955*[1]

Equation No.	Watershed and period	Equations	n	R^2	Syx
		STORM STREAMFLOW			
(8)	Fern, prefire	$QS=-0.26+0.209PS+0.017PSSQ+0.033PSAP7-0.10S$	39	0.92	0.50
(9)	Tree, prefire	$QS=0.00+0.085PS+0.007PSSQ+0.000PSAP7-0.12S$	36	.78	.24
(10)	Fern, post fire	$QS=-0.12+0.200PS+0.012PSSQ+0.036PSAP7-0.11S$	43	.93	.33
(11)	Tree, post fire	$QS=-0.04+0.113PS+0.010PSSQ+0.003PSAP7-0.11S$	43	.93	.16
		PEAK DISCHARGE			
(12)	Fern, prefire	$QP=-0.004+0.032P15SQ+0.003PSSQ+0.004PSAP7+0.00S$	39	.88	.08
(13)	Tree, prefire	$QP=-0.034+0.059P15SQ+0.002PSSQ-0.007PSAP7+0.02S$	36	.82	.11
(14)	Fern, post fire	$QP=-0.039+0.070P15SQ+0.006PSSQ-0.001PSAP7-0.01S$	38	.94	.11
(15)	Tree, post fire	$QP=-0.023+0.039P15SQ+0.004PSSQ-0.001PSAP7-0.03S$	43	.91	.07

[1] Equations are from regressions on principal components, with dimensions set at 3. Variables are defined in text. n is number of storms. R^2 is explained variance in percent, and Syx is standard error of estimate.

effect of storm precipitation was different between the watersheds, but not between the periods within a watershed. About twice as much runoff per storm is indicated for the fern as for the tree watershed. For the fern watershed, no difference in the reaction of storm precipitation occurred between the pre-fire and post-fire periods (equations 8 and 10, table 4).

What then was the source of the increase in monthly flows previously found in the post-fire period in the fern watershed? The answer is suggested by the difference in the regression constant, which may be interpreted as a difference largely in interception storage. The difference of 0.14 inch per storm (—0.12 —(—0.26)) is the equivalent of 17 percent increase in the average storm runoff; that is, of the mean QS of 0.83 from table 2. This increase is consistent with the 20 percent increase found in the monthly flow analysis.

The lack of change in the coefficients relating precipitation to runoff in the pre- and post-fire periods may be interpreted as indicating that the burning of the watershed had little effect on the infiltration or percolating capacity—at least not in the range such as to affect rainfall excess or storm interflow or both. If infiltration or percolation capacity were affected, enough detention characteristics in the watersheds remained to mask the effect of such changes. On the other hand, the increase in the regression constant indicates that the burning of the watershed had its expected effect in reducing any storage that was readily available for evaporation, such as the interception storage. As for the consistent seasonal effect of one-tenth inch less runoff per storm in the dry season, that implies a higher evaporation and transpiration in that season. Local climatological studies indicate greater evaporation potential during the dry period (Chang 1961). The similar coefficient for the seasonal effect between watersheds indicates about equal change in evaporation on the two watersheds with season.

The coefficients and constants for the tree watershed, pre-fire and post-fire, differed only slightly, indicating—as expected—little change in hydrologic conditions. This finding further suggests that the changes in the fern watershed were real and caused by the removal of the fern vegetation.

Peak Discharge-Rainfall Relations

The same storms used in the storm runoff studies were used in the peak discharge evaluations; however, the 15-minute intensity of storm precipitation was substituted as one of the variables. To test the adequacy of the sample of storm and antecedent rainfall, the varimax rotated factor weight matrix resulting from a principal component analysis was studied. For the tree watershed in the post-fire period, the analysis showed the following:

	Dimension number		
Variable:	(1)	(2)	(3)
P15SQ	.96	.01	.06
PSSQ	.95	—.07	.17
PSAP7	.14	0	.99
Season	—.03	.99	.06

We see from this analysis that the 15-minute intensity and storm precipitation load together on dimension No. 1, hence, they both represent storm rainfall characteristics. Again the seasonal effect loaded on the single dimension, dimension No. 2: the variable expressing the interaction of storm size and 7-day precipitation loaded on dimension No. 3. Therefore, we concluded that the sample of storms was adequate for testing these variables for their effect on peak discharges.

The factors contributing to peak discharges were evaluated from the regression on principal components. Explained variance ranged from 82 to 94 percent (table 3), with 54 to 90 percent being associated with the storm characteristic variables. The seasonal contribution was not large—only 1 to 2 percent. The interaction of storm size and 7-day antecedent precipitation was apparently unimportant.

The coefficients relating storm intensity to peak discharges give some clues to the processes of peak discharge development in these watersheds. One clue is the curvilinearity indicated by both storm variables being best expressed as squares of precipitation. This is apparently true curvilinearity and not merely a missing threshold (subtracting a threshold value of 0.25 inch per hour from P15 actually decreased prediction). From the curvilinearity, we may infer that increasing rainfall intensities produce runoff from larger and larger new areas.

The effect of the fire in the fern watershed may be seen in the effect on the rainfall coefficients and on the variability of flow. The variability of the flow was doubled as a result of the burning, as is shown by the standard deviations in table 2. The coefficients of the rainfall-runoff were greater in the post-fire periods (table 4). Both effects suggest changes in the processes affecting peak flows, involving changes in the surface roughness, changes in the time of concentration of runoff from the parts of the watersheds, and local changes in the flow paths, such as changes from interflow through the soil to surface flow. Further clues might come from analysis of the hydrograph shapes; such an analysis was not part of this study.

Conclusions

From this short-term study of rainfall-runoff relations on two small watersheds in Hawaii, we concluded that:

- Streamflow was a relatively small proportion of the average annual rainfall of 93 to 105 inches, being as little as 6 percent and at most 25 percent of the rainfall in individual years and watersheds.
- Rather large differences in runoff characteristics can be expected from adjoining watersheds; streamflow differed by a factor of at least 2.
- There will be less runoff per unit rainfall in the dry season than in the wet season, with runoff per storm of 0.1 inch (12 to 38 percent) less in the dry season.
- If false staghorn fern is removed from watersheds, such as by fire, short-term increases in storm runoff and peak flows can be expected. An increase of 20 percent in storm runoff was found for the first 2 years after the burn. Peak discharges were greater only for larger than average storms.
- Changes in hydrologic processes that result from treatment of these watersheds may be inferred from principal components analyses of rainfall-runoff relations.

The technique of using "paired watersheds" for analysis has one possible weakness: each pair is unique and its response to rainfall—or as in this study, to burning—may in some degree be unique. Therefore, we cannot be certain that the greater streamflow from the fern watershed was due entirely to difference in vegetation. If measurements were made now of streamflow and rainfall—some 13 years after tree establishment on the fern watershed—we might have further evidence of the effect of fern vegetation as opposed to that of trees on a watershed. We recommend such a study be made.

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GPO 973-514