HYDROLOGIC ANALYSIS USED TO DETERMINE EFFECTS OF FIRE ON PEAK DISCHARGE AND EROSION RATES IN SOUTHERN CALIFORNIA WATERSHEDS

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Contents

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INTRODUCTION

Forest fires in southern California cause several kinds of damage. Many of the damages, such as destruction of structural improvements, destruction of forage and timber crops, and disruption of recreation and other land use are immediately apparent. Evaluation of these damages in dollars can be made with little difficulty by field examination.

Destruction of vegetative cover by fire may also change the runoff and erosion characteristics of watersheds. Damages resulting from this effect of fire are not immediately evident, but accumulate over a long period of years. Their evaluation, however, is essential if an adequate appraisal of the total effect of fire and of the value of fire prevention is to be obtained. It was for this purpose that the study of fire damage in southern California watersheds was undertaken.

The hydrologic analysis described in this report was made to determine the effect of fire on storm runoff and erosion rates and thus provide a basis for estimating probable damage from this source.

BASIC CONCEPTS OF WATERSHED FIRE DAMAGE

Damages from surface runoff and channel flows and from erosion and deposition of debris are a common occurrence in southern California. The amount of damage varies among watersheds and from year to year and storm to storm. The amount of damage also appears to vary with the age and condition of the watershed vegetation, tending to decrease as the age and density of the vegetation and litter cover increases. Because of the physiographic features of the region some damage may be expected during severe storms even with the best "normal" conditions of vegetation. This normal damage for individual watersheds, averaged for a long period of time, remains relatively constant, as illustrated by curve A of figure 1. Probable normal damage for a given period of time would be the sum of damages shown by curve A for the years included in the period considered.

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Experience has shown that the removal of the vegetative cover by fire may greatly increase runoff and erosion with a consequent increase in the amount of damage. These damages may be expected to continue at a greater than normal rate from the time the watershed cover is burned until it has recovered sufficiently to exert its normal control over runoff and erosion. The damage rate during this recovery period--termed "burn to recovery damage"--is represented by curve B of figure 1. The sum computed from this curve from the time of burn to watershed recovery represents the total damage, including the normal, for the recovery period. The part of the total damage attributable to the fire, or "fire damage," would then be this total damage less the normal damage.

Many of the southern California watersheds are in the process of recovery from past fires. Damage in these watersheds will hence be above normal until recovery is complete. This condition is represented by curve C of figure 1. The damage from past fires, called "present to recovery damage," is determined by the differences in the values shown by curve C and the corresponding values of the normal damage curve. This damage must be deducted from the fire damage determined from curve B when calculating the damage from a new fire in the watershed.

The watershed cover may thus be considered as varying in value for protection purposes after a fire, having a minimum value immediately after the fire and a maximum and constant value when fully recovered and normal soil-water relations have been established. The probable damage that will be caused by any single fire in the watershed will depend upon the condition and age of the vegetative cover at the time of the fire.

Since watershed damage is in large part dependent upon runoff and erosion, the frequency and size of peak runoff flows and the erosion rates will govern the amount of damage for any given watershed. If the relation between discharge size and damage is known and the costs of handling debris established,[2] then the calculation of watershed fire damage is dependent upon having the following hydrologic information:

1. The most probable frequency and size of normal runoff flows.
2. The effect of fire on the size of these flows.
3. The residual effects of past fires on runoff flows.
4. The normal annual erosion rates.
5. The effect of fire on erosion rates.
6. The residual effect of fires on erosion rates.

The basic purpose of the hydrologic analysis described in this report was to provide this information. The procedures and methods used were thus necessarily designed to permit compilation of the required data in the form prescribed by the needs of the Fire Damage Appraisal Project.

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[2] The relation of damage to peak discharge and erosion rates and the costs of debris disposal were established in the economic analysis phase of the fire damage appraisal study.

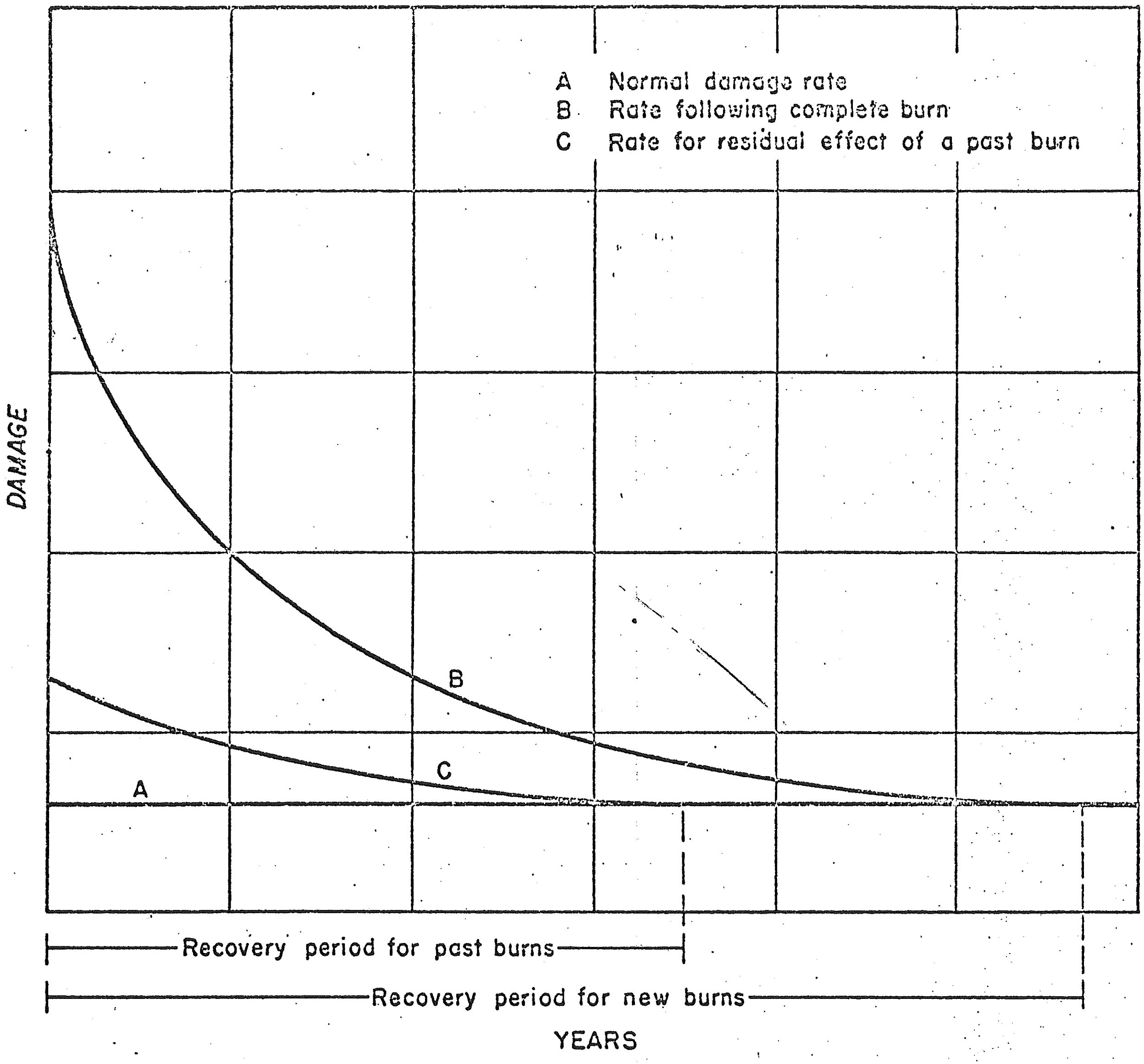

Figure 1.-Theoretical flood and erosion damage.

PHYSICAL CHARACTERISTICS OF THE STUDY AREA

The area covered in the study embraces the major portion of the higher mountain drainages in a 20- to 80-mile wide strip extending along the coast from the Mexican border to watersheds a few miles north of San Luis Obispo. This area includes 256 watershed units with a combined area of 6,800 square miles.

Long dry seasons and short winter rainy seasons characterize the climate of the region. The mountain ranges, which lie across the path of the principal storms, are a major influence on the rainfall of the area. They lift and cool storm air masses moving inland from the ocean, an action often resulting in a very intense precipitation. Rates of rainfall as high as 1.02 inches in one minute, 11.50 inches in 1 hour and 20 minutes, and 26.20 inches in 24 hours have been recorded. Average annual precipitation varies widely over the area, ranging from 10 inches in the interior valleys to more than 38 inches in the higher mountain drainages.

Most of the drainages are small and generally fan-shaped, with short, steep stream channels and precipitous side slopes. Such topographic characteristics are conducive to rapid concentration of runoff and, when combined with intense rains, are a primary cause of the high peak discharge and erosion rates of the region.

Watershed soils are nearly all residual, and as a rule merge into the underlying and generally deeply weathered parent rock. For the most part the soils are moderate to coarse textured, are unstable, have little profile development, and average less than 3 feet in depth.

Igneous and metamorphic rock types predominate in the three southernmost forests. These rock formations are usually highly fractured, thus providing numerous channels for the movement and temporary storage of water. The sedimentary rocks, which occur largely in the northernmost watersheds, are less fractured than are the more crystalline igneous and metamorphic types. These sedimentary rocks include some very pervious as well as some highly impervious formations.

Brush, or chaparral, is the most extensive cover type of the region, occupying nearly 68 percent of the area. Open woodlands cover about 21 percent of the area, and coniferous forests nearly 11 percent. Fires are usually less frequent and less severe in the woodland and coniferous forests than in the brush types.

DETERMINATION OF NORMAL PEAK DISCHARGE

Procedures and methods used in the analysis were frequently limited by the kinds and amount of basic hydrologic data. Stream flow data were available for about one-third of the watersheds studied. Many of these records were incomplete or of short duration. Fortunately large amounts of precipitation data were available that could be used to supplement and extend the streamflow records. Results of experimental work were also used for this purpose.

USE OF STORM PEAK FLOWS

The instantaneous peak discharge of each storm[3] was used as the basic measure of watershed discharge. Preliminary analyses and examination of streamflow records indicated that peak discharge was the best indicator of watershed performance and was particularly sensitive to fire effects. Use of the storm peak discharge also permitted the use of the longer period of precipitation records to establish a more reliable time base for streamflow frequency computations. Because the maximum damage for each storm is caused by the highest peak flow the use of instantaneous peaks fitted well into the specifications of the damage appraisal project.

DELIMITATION OF WATERSHED UNITS

The unit of area for which estimates of peak discharge were made was the "watershed unit" (fig. 2). Each watershed unit was the upstream portion of a single stream or major tributary, or two or more similar small adjoining front drainages with separate discharge channels. The lower boundaries of the units were established by the specifications of the economic phase of the fire damage study, and generally followed the boundary between inflammable watershed cover and valley agricultural lands.

STORM FREQUENCIES

Storm frequencies were developed to supplement the meager stream flow data used in determining the storm peak discharge frequencies. Precipitation records were available for periods of 60-70 years, two or more times the length of stream flow records. By determining the relation between storm precipitation and peak discharge it was possible to compute discharge frequencies using the longer time base of the precipitation records. Such extension was based on the assumption that the relation between storm precipitation and peak discharge would be the same for the period of precipitation records as for the shorter period of stream flow measurements.

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[3] A storm as used in this study may be either a single day or several consecutive days of precipitation. When precipitation occurred on consecutive days, if the precipitation for any day was less than .02 inch the following day was considered as the beginning of a new storm.

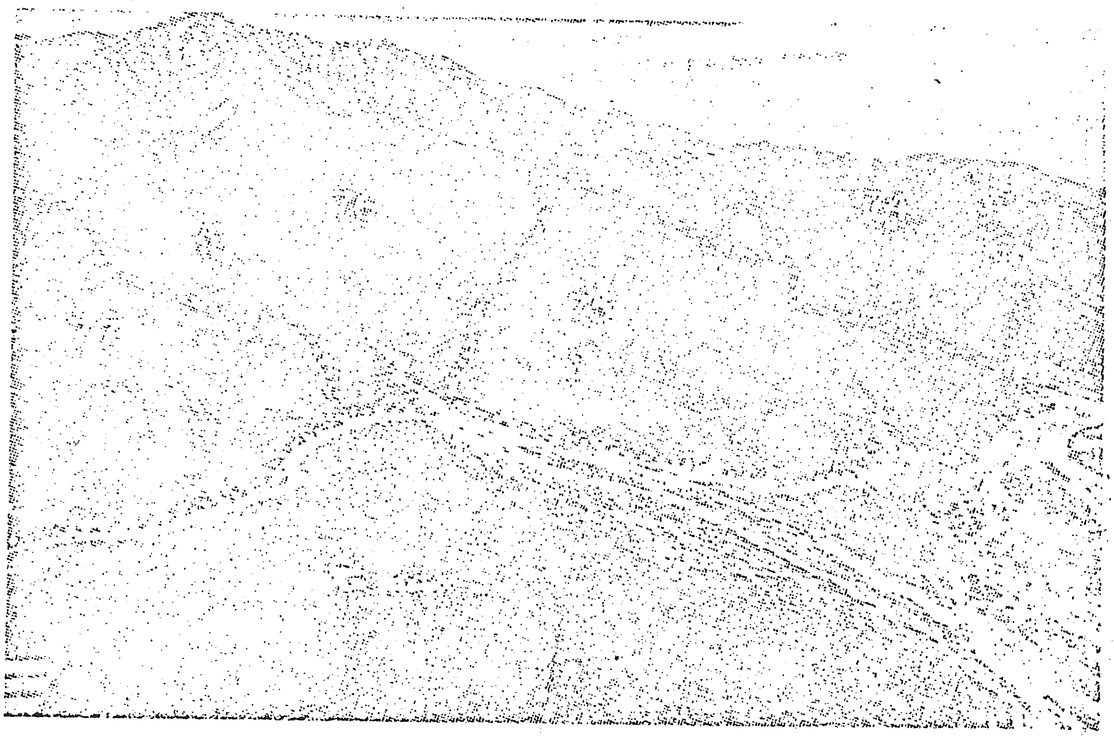

Figure 2.- Typical watershed units. Units 74 and 76 illustrate watershed catchment areas converging into a single major stream at the point of discharge. Units 75 and 77 illustrate watershed front areas.

To facilitate determination of storm frequencies, the watershed units were grouped into five "storm zones." Each zone consisted of a series of adjacent watershed units in which there were an approximately equal number and reasonably uniform occurrence of storms.

A key precipitation station was selected in each of the storm zones. The stations selected had reliable precipitation records of 60 years or more, and the storm frequency of each station was judged to be representative of its zone. The average number of storms per year and the mean annual precipitation were computed from the precipitation records of the key station. The individual storms were then segregated into 1/2-inch size classes. The maximum 24-hour precipitation[4] in each storm as reported by the observer (maximum amount between two consecutive daily readings) was used to establish the size of the storm. The average number of storms per year in each size class and the average storm precipitation within the class were determined. The number of storms by precipitation classes were then plotted against the upper limit of the class on semi-logarithmic paper as shown for the key station of the Los Angeles storm zone in figure 3. Irregularities in the observed number of events of individual precipitation classes were eliminated by drawing a smooth curve through the plotted data. In the lower classes containing the larger number of storms the computed mean precipitation of the classes was also used to establish the slope of the curve between class boundaries. To meet the requirements of the economic phase of the damage study, the curve was extrapolated to give the size of storm that would be equaled or exceeded once in one hundred years.

The number of storms per year given for each size class by the key station frequency curve was used as the base for all storm frequencies of the zone. The amount of precipitation for any given storm, however, varied among the watershed units. It was thus necessary to adjust the precipitation scale of the key station frequency curve when this information was needed for an individual watershed unit. This was done by multiplying the key station precipitation class limits by the ratio of the key station annual mean to the areal mean[5] of the watershed unit. For example, in a watershed unit with an areal mean 1.3 that of the key station mean, the first precipitation class would be .01 to 0.65 inches, the second 0.66 to 1.30 inches, etc., instead of the even one-half inch classes used for the key station. Assuming that the ratio of precipitation amounts between the key station and the watershed unit was the same for individual storms as for the mean annual amounts, any given storm would fall in the same frequency class for both the key station and the watershed unit.

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[4] Preliminary analysis showed a closer correlation between this value and peak discharge than between total storm precipitation and peak discharge.

[5] The areal precipitation means were computed from isohyetal maps of 60- to 70-year mean annual precipitation. The maps covered the same period of record as that of the key station.

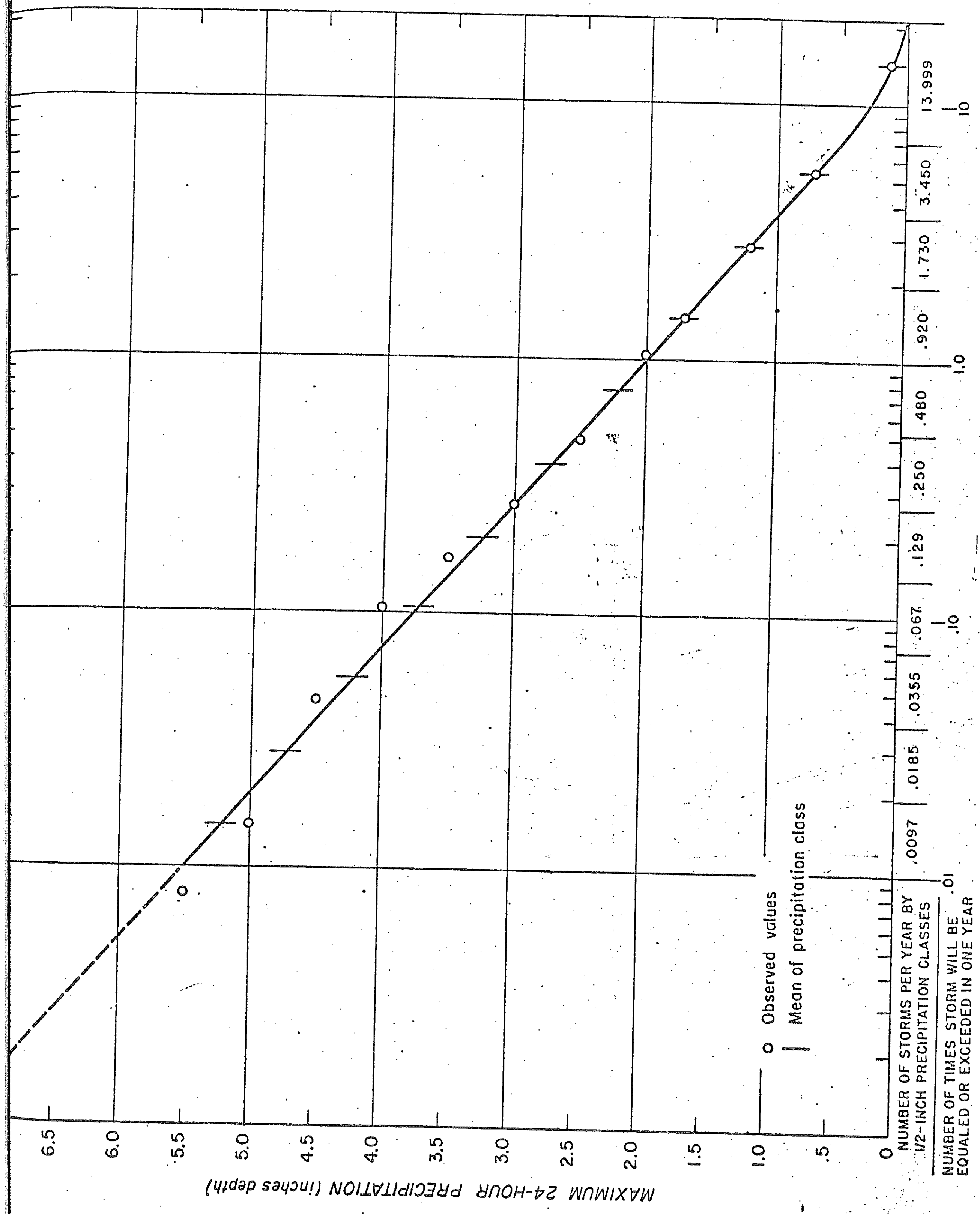

Figure 3.- Storm frequencies for key precipitation station--Angeles storm zone.

A test was made of the validity of using a constant precipitation ratio by checking the ratio of precipitation amounts, storm by storm, and year by year, between the key station and representative stations within various watershed units of each storm zone. These checks were made for all units for which there were reliable precipitation data.

As would be expected, there were greater variations in the ratios between small than between large storms and greater variation between storm precipitation than between yearly amounts. These variations were small and time-wise tended to be compensating. Thus use of a constant ratio gave results well within the accuracy obtainable in the analysis.

PEAK DISCHARGE FREQUENCIES FOR KEY WATERSHEDS

A key watershed was selected in each storm zone to establish for the zone the frequency of normal storm peak discharges of various sizes. Each key watershed was selected as being generally representative of the other watersheds of the zone. A long record of precipitation and stream flow, and a long unburned vegetation cover were other essential requirements of the key watershed.

Peak discharges of the key watershed were grouped into size classes expressed in terms of cubic feet per second per square mile (c.s.m.) and the average number of storm peak discharges per year in each size class determined. The average number of storms per year in each discharge class was also determined for each storm frequency class.

The number of observed peak discharges in each storm frequency class was then checked against the corresponding number of storms given on the storm frequency curve. When these differed the observed number was adjusted to conform to the number given by the longer period of record represented by the storm frequency curve. These adjustments were made by computing the ratio of the number of storms in each size class of the storm frequency curve to the observed number for the period of the discharge record. The number of storms in each storm frequency class within the peak discharge class was then multiplied by the ratio for the class.

The adjusted data were tabulated by peak discharge classes and plotted on logarithmic paper using the same procedure as employed in developing the storm frequency curve. Irregularities in the number of events between size classes were eliminated by fitting a smooth curve to the plotted data (fig. 4). The mean peak discharge of each frequency class was read at the logarithmic mean of the class. The number of events per discharge class given by this curve was used as a base for establishing the peak discharge frequencies for all watershed units within the storm zone.

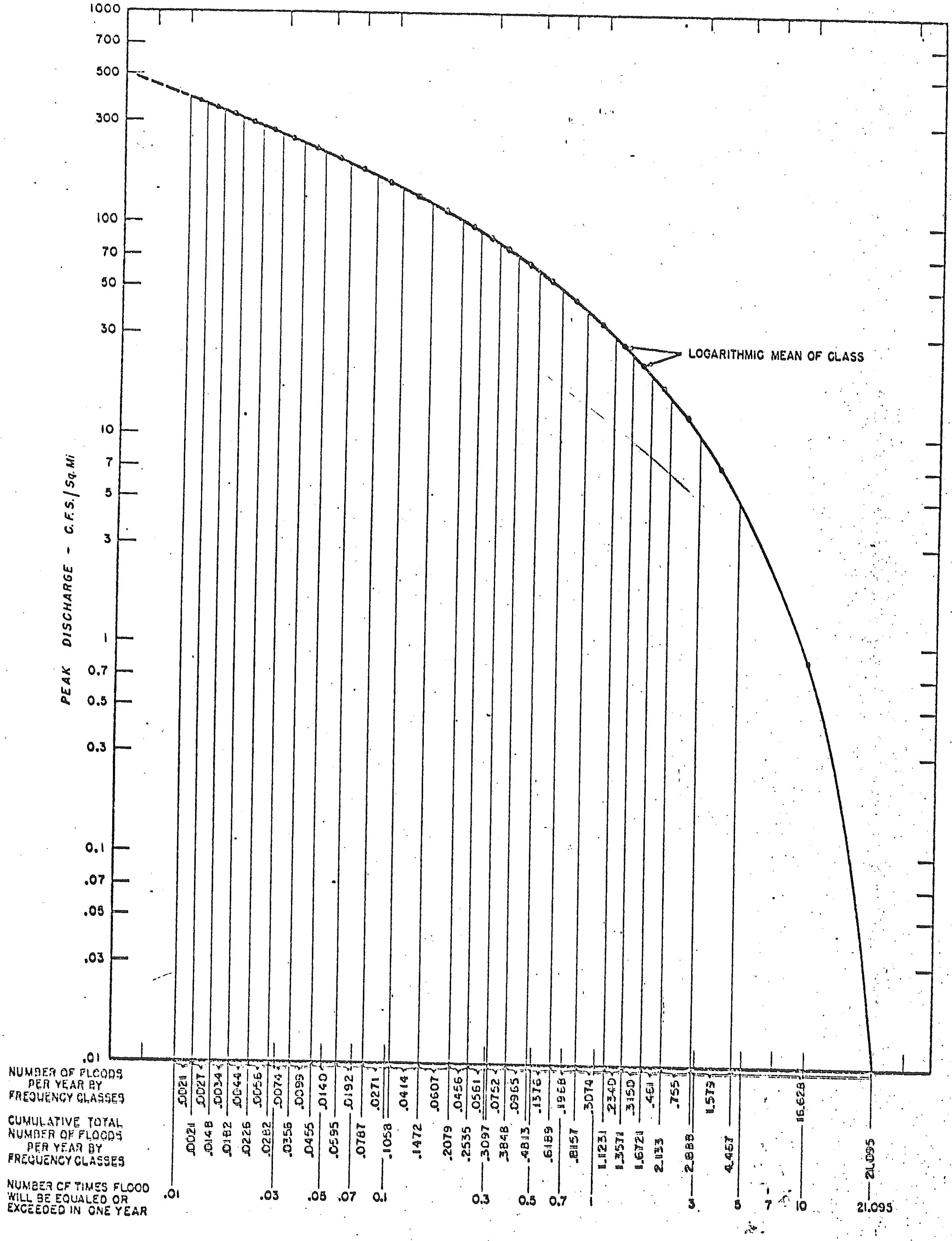

Figure 4.- Peak discharge frequencies for key watershed--Santa Anita Canyon, Angeles storm zone.

Unfortunately, the chaparral-covered watersheds of southern California have all been subjected to fire in the past. There are comparatively few in which the vegetation has not been in part or completely burned within the last 50 years. In developing the normal peak discharge frequency curves from stream flow data a correction was sometimes necessary to compensate for effects of past burns. However, for watersheds unburned for 30 years or more the adjustments were small and only necessary for the larger, infrequent peak discharges. Analyses to show the effect of fire on peak discharge were carried on concurrently with the development of normal peak discharge frequencies. The preliminary results of these fire-effect analyses indicated the approximate effect of fire and provided the basis for correcting for past fire effect when developing normal peak discharge frequencies.

PEAK DISCHARGE FREQUENCIES FOR WATERSHEDS HAVING STREAM FLOW RECORDS

Frequencies of normal peak discharge for watersheds for which stream flow records were available were developed to (1) determine the average size of storm peak discharges for these units by frequency classes of the storm zone and (2) for use as an aid in developing a system of watershed ratings for units for which stream flow data were lacking or inadequate. Stream flow data from watersheds with recent burns or for which the adjustments for past fires were estimated to be in excess of 10 percent of the observed discharges were not used in determining these normal peak discharges.

The frequencies of normal peak discharge for watersheds for which stream flow records were available were based on the relation of the observed peak discharges of the individual watersheds to the corresponding discharges of the key watershed. Within discharge classes there was a relatively consistent relation between the size of the peak discharges and those of the key watershed. However, this relation often varied appreciably from discharge class to discharge class as shown in figure 5. This was due to differences in such things as precipitation, soil, geology, and topography of the watersheds.

Relations of peak discharges of the individual watersheds to the corresponding discharges of the key watershed were determined storm by storm or, if sufficient observations were available for establishing class means, discharge class by discharge class. This was done by plotting the observed peak discharges of the watershed for which the peak discharge relations were being determined over the frequencies of the corresponding discharges of the key watershed as read off its frequency curve. A smooth curve fitted to these plotted data, as shown in figure 5 then established the frequency curve of normal peak discharge for the watershed. Thus the number of peak discharge events per peak discharge class were the same for all watersheds within a storm zone. The average size of the peak discharges varied, however, with differences in the hydrologic characteristics of the watersheds.

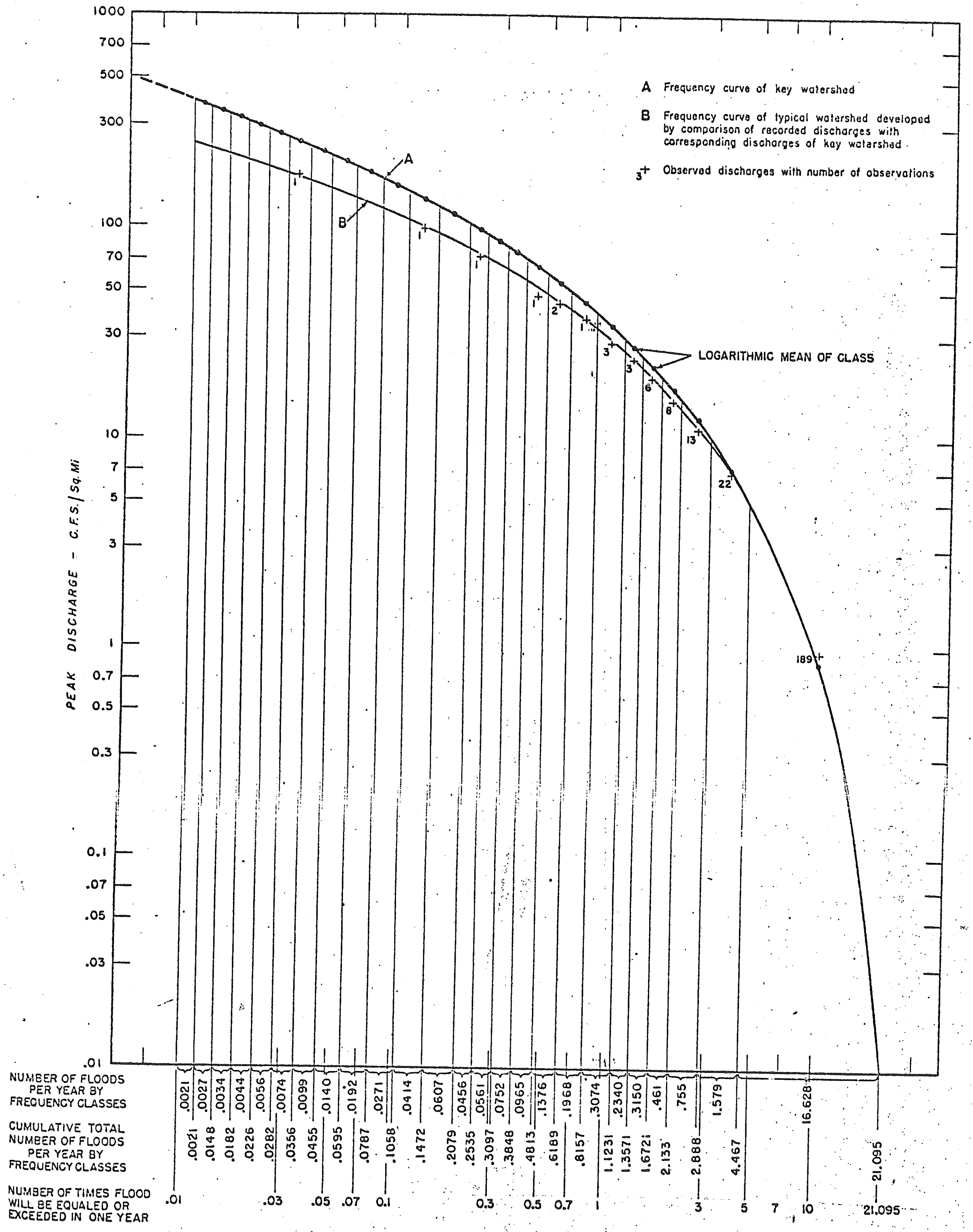

Figure 5.- Determination of peak discharge for watersheds having streamflow records.

EFFECTS OF WATERSHED CHARACTERISTICS ON PEAK DISCHARGE

Discharge measurements adequate for determining frequencies of normal peak discharges were available for only about one-third of the watersheds included in the present study. Estimates of normal peak discharges for the other watersheds were based on numerical ratings of the effect of various watershed physiographic factors on peak discharge. The ratings were derived from analyses of discharge data and the physiography of watershed units with stream flow records. The ratings were determined by storm zones, and were an expression of the effects upon peak discharge of local differences in watershed topography, soil, geology, and precipitation.

The determination and application of the watershed ratings were aided by several conditions of the study. (1) Peak discharge was expressed in terms of unit area (cubic feet per second per square mile), thus permitting direct comparison of the effects of differences in watershed characteristics on these discharges. (2) Although rates of peak discharge varied with local differences in the watersheds, the general pattern of hydrologic behavior was similar, particularly for watersheds within the same storm zone. (3) Records of stream flow were available for nearly all of the larger, more important watersheds for which peak discharge was the most variable and difficult to estimate. (4) Watersheds for which discharge records were available were rather evenly distributed throughout each storm zone, thus providing a reasonably complete sample of conditions existing in the watersheds included in the study.

Each of the watershed factors to be rated was subdivided into classes. Class division of some factors, such as watershed size, were based on actual areas of the units involved. Many of the factors, such as watershed shape, could only be classified qualitatively. The classes of these factors were assigned numbers, the class numbers indicating the relative effect of the class on peak discharge. Thus Class I would indicate effects tending to produce the highest discharges; Class II, effects tending to produce next highest, etc. The number of classes in each breakdown, except those in which the actual dimensions were used, was contingent upon the range of conditions encountered and their estimated effects on normal peak discharge. A representative watershed of each class was selected as a model to facilitate the classification of other watershed units.

When the range in peak discharge within a rating class proved large the upper values of the class, as for example Class II, were indicated as II^{+}, the intermediate as II, and the low as II^{-}. If, on the other hand, the range in peak discharge within the rating classes of a factor was sufficiently small to prove insignificant, the factor was dropped from the ratings of that zone.

Topographic factors considered in the watershed ratings included (1) size in square miles, (2) shape (fan, rectangular, etc.), (3) density of surface water courses (number and length of channels per unit area), (4) average gradient of side slopes, (5) flow characteristics of principal stream channels (shape, roughness, etc.), and (6) average gradient of principal stream channels. The effects of some factors like length of stream channels were excluded from individual consideration because they were reflected in other ratings, such as those of watershed size and shape.

Soil factors considered in the watershed ratings included (1) relative infiltration capacity, and (2) water storage capacity (wilting point to field capacity plus 1/4 storage between field capacity and field saturation).

The limits of the infiltration and water storage classes of the different soil formations were established on the basis of soil textures, depths, and the results of past infiltration and soil moisture sampling (4) (7).

Geologic factors included (1) relative permeability (infiltration capacity), (2) water storage capacity (maximum retention), and (3) amount of rock outcrop. Other differences in the soil and geologic factors, such as drainage characteristics, also influenced peak discharge, but these effects were small or were reflected in other ratings.

Relative permeability of the different geologic (rock) formations was determined by comparing the amounts of penetration of storm precipitation in watersheds containing rock substratum representative of the different formations but with other factors such as slope, topography, cover, etc., approximately the same. Only major storms with high amounts and rates of rainfall were used for this purpose. Rainfall penetration into the substratum during a storm (F_s) was assumed to be equal to the "storm rainfall" (P_s) less the sum of any "increase in soil water storage" (M_i) plus "storm interception loss" (I_s) plus "storm run off" (Q_s), all expressed in inches depth, or $F_s = P_s - (M_i + I_s + Q_s)$. The results of a series of such calculations for the different geologic formations permitted determination of their relative permeability and establishment of permeability classes.

Preliminary analysis indicated that most watersheds included in this study neither reached nor closely approached saturation during the period of record. Direct determination of total water storage capacities was hence impossible. Analysis of the disposition of watershed precipitation for the 1940-41 season, however, permitted estimates of the relative water storage capacities of the various soil and geologic types. Precipitation this season was about twice normal and occurred for the most part in prolonged storms at comparatively low rates. This permitted a high infiltration and retention of rainfall in the various soil and geologic types sampled. Comparisons of the maximum retention of rainfall by the different types during the year, then, permitted estimates of their relative water storage capacities.

As illustrated in table 1, retention of rainfall M_r (column 10) at any time during the year was computed as the difference between the accumulated or mass precipitation P (column 3), and the sum of the accumulated stream flow or yield Y (column 5), accumulated interception loss I (column 7), and accumulated evapo-transpiration E (column 9), or $M_r = P - (Y + I + E)$. Stream flow included the surface runoff from all preceding storms of the season plus the accumulated ground water yield to stream flow from these storms, but excluded the ground water depletion flow of the preceding season. Interception and evapo-transpiration estimates were computed from the results of interception and soil moisture studies carried on in central and southern California (3) (5) (6). The amount of greatest retention during the year (in the present example, 33.7 inches, table 1, column 10), adjusted for differences in precipitation and permeability among the sample watersheds, was used as the relative storage capacities of the different soil and geologic types and for establishing the water storage classes. This retention, however, includes not only that portion of the year's rainfall retained in the watershed, but also any that may have drained from the watershed as unmeasured subsurface flow.

The degree to which the water storage capacity of a watershed was utilized was estimated by determining the proportion of the storm precipitation leaving the watershed as storm runoff, Columns 11 to 13, table 1. Irregularities in the proportion of precipitation appearing as storm runoff often reflect the infiltration capacity or permeability of the watershed and not the degree of its saturation. This is illustrated by the storm of March 1-7 in which a relatively large proportion of storm runoff was the result of rainfall rates in excess of permeability, since the amount of water retained in the watershed after this storm was less than that of succeeding storms. The generally small proportion of the storm precipitation contributed to storm runoff in the present example, column 13, indicates not only the relative water storage capacities of the soil and geologic types represented but also that these were far in excess of the storage utilized during the year.

Table 1.-Computation of rainfall retention--Santa Anita Canyon, Angeles storm zone
1940-41 hydrologic year

Date (1) By storm periods	Rainfall (2) By storms	Rainfall (3) Accumulated	Streamflow1/ (4) By periods	Streamflow1/ (5) Accumulated	Interception loss (6) By storms	Interception loss (7) Accumulated	Evapo-transpiration2/ (8) By periods	Evapo-transpiration2/ (9) Accumulated	Retention (10) Col.3-(cols. 5+7+9)	Storm rainfall-runoff-relation (11) Date	Storm rainfall-runoff-relation (12) Rainfall In.	Storm rainfall-runoff-relation (13) Storm runoff3/ Pct. of ppt.
	- - -	- - -	- - -	- - -	Inches depth	- - -	- - -	- - -	- - -			
10/ 1-10/24	.03	.03	0	0	.02	.02	.01	.01	0			
10/25-10/28	2.76	2.79	.02	.02	.14	.16	.18	.19	2.42	10/25-27	2.76	.4
10/29-11/16	0	2.79	.03	.05	0	.16	.81	1.00	1.58			
11/17-11/19	2.07	4.86	.02	.07	.12	.28	.07	1.07	3.44	11/17-19	2.07	.5
11/20-12/15	.44	5.30	.09	.16	.08	.36	.95	2.02	2.76			
12/16-12/18	4.42	9.72	.11	.27	.19	.55	.05	2.07	6.83	12/16-18	4.42	2.0
12/19-12/25	4.43	14.15	.27	.54	.19	.74	.18	2.25	10.62	12/23-25	4.43	3.2
12/26- 1/21	2.27	16.42	.30	.84	.44	1.18	.96	3.21	11.19			
1/22- 1/26	2.97	19.39	.16	1.00	.15	1.33	.16	3.37	13.69			
1/27- 2/10	1.09	20.48	.22	1.22	.14	1.47	.71	4.08	13.71			
2/11- 2/13	1.61	22.09	.16	1.38	.11	1.58	.13	4.21	14.92			
2/14- 2/25	14.52	36.61	3.51	4.89	.52	2.10	.47	4.68	24.94	2/19-24	9.37	18.6
2/26- 3/ 7	10.35	46.96	3.91	8.80	.40	2.50	.80	5.48	30.18	3/ 1- 7	6.50	22.5
3/ 8- 3/15	4.21	51.17	2.18	10.98	.18	2.68	.60	6.08	31.43			
3/16- 3/27	0	51.17	1.85	12.83	0	2.68	1.28	7.36	28.30			
3/28- 3/30	2.80	53.97	.49	13.32	.15	2.83	.16	7.52	30.30	3/28-29	2.80	4.6
3/31- 4/ 6	5.34	59.31	1.89	15.21	.28	3.11	.55	8.07	32.92	3/31-4/3	3.08	6.8
4/ 7- 4/12	3.05	62.36	1.54	16.75	.15	3.26	.57	8.64	4/33.71	4/4 -6	2.26	18.1
4/13- 4/29	.01	62.37	2.81	19.56	.01	3.27	5/1.91	10.55	28.99	4/10-13	3.04	3.9
4/30- 5/ 1	2.72	65.09	.38	19.94	.14	3.41	.25	10.80	30.94	4/30-5/1	2.72	6.0
5/ 2- 9/30	.16	65.25	5.19	25.13	.10	3.51	6/3.36	14.16	22.45			
Total as percentage of precipitation		100		38.5		5.4		21.7	34.4			

1/ Excludes ground-water depletion flow of preceding year. 2/ Includes riparian loss. 3/ Excludes ground water component of storm hydrograph. 4/ Maximum retention during year. Includes rainfall that may have drained from watershed as subsurface flow. 5/ All available water lost from Wilson granodiorite soils during this period. 6/ Average soil-rock storage capacity of water available to evapo-transpiration loss 2.75 inches, plus .55 inch summer riparian use.

Both type of vegetation and density of the cover were considered important factors in watershed performance. However, there proved to be a close correlation between type and density of the cover. Preliminary vegetation rating classes, therefore, were based solely on the mean areal density of the unburned watershed cover.

Precipitation classes were expressed in terms of the average annual rainfall, in inches depth, of the respective watersheds. Reasons for the use of the actual rainfall data are explained in the succeeding discussion of the watershed ratings.

WATERSHED RATINGS IN TERMS OF PEAK DISCHARGE

After the watershed rating factors for each storm zone were established and divided into standardized rating classes, the ratings for each unit were assigned and tabulated as illustrated for a sample watershed in table 2, columns 2(a) and 2(b). The numerical significance of each class rating was determined by comparing normal peak discharges of a watershed with other watersheds that were similar in all hydrologic characteristics except the one being evaluated. These numerical ratings were expressed as ratios to the corresponding peak discharge of the key watershed. The ratings thus determined indicated the effect of differences in each factor on peak discharge but did not constitute a measure of the total effect of all differences on peak discharge.

Variation in amounts of watershed precipitation was one of the more important factors contributing to differences in normal peak discharge. Because of this the precipitation ratings were the first to be determined. This was accomplished by segregating watersheds for which suitable stream flow records were available into three groups, (1) watersheds with topographic, soil, and geologic characteristics estimated to be similar to those of the key watershed except for differences in amounts of precipitation, (2) watersheds with topographic, soil, and geologic characteristics estimated to be favorable to slightly higher discharge peaks than from the key watershed, and (3) watersheds with topographic, soil, and geologic characteristics estimated to be favorable to slightly lower peaks than from the key watershed.

Ratios of both precipitation and peak discharge of the individual watersheds to corresponding precipitation and peak discharge of the key watershed were next computed. The ratios of peak discharge, as illustrated in figure 6, were then plotted over the corresponding ratios of precipitation. A curve drawn through the point of group 1, and along the mean boundary line between the points of groups 2 and 3 was considered to delimit the average effects of difference in watershed precipitation on peak discharge of watersheds within the storm zone. For example, figure 6 shows that a watershed having a mean precipitation equal to .75 that of the key watershed, will have an average peak discharge to about .79 that of the key watershed, other conditions being equal.

Table 2.--Use of watershed ratings in computing peak discharge

(1) Items	(2) Rating classes		(3) Ratings for sample watershed[1]			
	(a) Key watershed	(b) Sample watershed	(a) Very small discharge[2]	(b) Small discharge[3]	(c) Medium discharge[4]	(d) Large discharge[5]
1.- Topographic factors						
a. Size	[6]10.6	[6]26.7	.83	.88	.92	.94
b. Shape	I^{-}	IV^{-}	.56	.68	.78	.84
c. Density of surface water courses	II	II	1.00	1.00	1.00	1.00
d. Average gradient of side slopes	II	II	1.00	1.00	1.00	1.00
e. Flow characteristics of main channel	II^{-}	III^{-}	.90	.94	.97	.97
f. Average gradient of main channel	III^{+}	III^{-}	1.00	.99	.99	.99
2.- Soil-geologic factors						
a. Soil infiltration capacities	IV^{+}	IV	1.00	1.00	.98	.96
b. Soil water storage capacities	II	II^{-}	1.00	.99	.96	.94
c. Rock permeability	III^{+}	IV^{+}	1.00	.99	.94	.92
d. Rock water storage capacities	IV^{-}	V	1.00	.99	.96	.94
e. Rock outcrop	III	II	1.00	1.00	1.04	1.06
3.- Precipitation factor	[7]36.6	[7]32.6	.91	.91	.91	.91
4.- Integrated topographic, soil-geologic, and precipitation ratings			.20	.37	.45	.47
a. Peak discharge of key watersheds, c.s.m.			.81	33.5	152.0	389.0
b. Computed peak discharge of sample watershed, c.s.m.			.16	12.4	68.0	183.0

[1] Ratings expressed as ratios of peak discharge of sample watershed to corresponding discharges of key watershed.
[2] Peak discharge of size equaled or exceeded an average of ten times each year.
[3] Peak discharge of size equaled or exceeded an average of once each year.
[4] Peak discharge of size equaled or exceeded an average of once each 10 years.
[5] Peak discharge of size equaled or exceeded an average of once each 100 years.
[6] Area in square miles.
[7] Precipitation in inches depth.

In watersheds that are similar hydrologically the total amount of precipitation that goes to evaporation and transpiration losses, ground water storage, etc., rather than to runoff would be the same for each watershed. The amount of water available for storm runoff would then be dependent upon the amount of precipitation in excess of other losses. If the only variation among a group of watersheds is in precipitation amount then the ratios of peak discharge between the watersheds could be expected to be smaller and decrease more rapidly than the precipitation ratios. The failure of the curve in figure 6 to follow this expected trend thus reflected the influence of factors other than differences in precipitation.

The reason for the relatively high discharge ratios became apparent in the attempt to develop ratings of the effects of differences in vegetation upon peak discharge. Uncorrected for differences in rainfall, vegetation ratings proved to be about the same as precipitation ratings. Corrected for differences in rainfall, however, they became practically negligible. This indicated that under the semiarid conditions of southern California the amount of precipitation was the limiting factor in the character and development of vegetation and hence controlled indirectly the vegetation effect on peak discharge. The precipitation ratings thus reflected the effect of differences in normal vegetation on peak discharge as well as the effects of differences in precipitation. The only apparent exception to this occurred when differences in such factors as depths and water storage capacities of the soils had a material effect on the vegetation. These effects of soil on vegetation, however, appeared to be accounted for in the soil and geologic ratings. Vegetation effects were thus reflected in other ratings and a separate rating was not necessary.

The same procedure used in determining the precipitation ratings was followed for each of the topographic, soil, and geologic factors. As ratings were developed the available data were corrected for differences in the factors rated. Thus the peak discharges used in developing ratings for watershed shape (figure 7) were adjusted, if necessary, for differences in precipitation and watershed size. This procedure permitted the use of a larger sample for each succeeding ratings, and served as a progressive check of the applicability of each of the ratings as they were established.

After the numerical ratings were established for a storm zone they were used to compute normal peak discharges for the units with stream flow records. The computation method is described in the following discussion of peak discharge frequencies for watersheds not having stream flow records. The computed discharges were then compared with the normal peak discharges developed from the observed data. If this check indicated too great a variation (variations in moderate and large discharges in excess of 10 percent of the observed discharges) or consistent variation above or below the observed discharges, the ratings were re-evaluated in an attempt to attain better estimates.

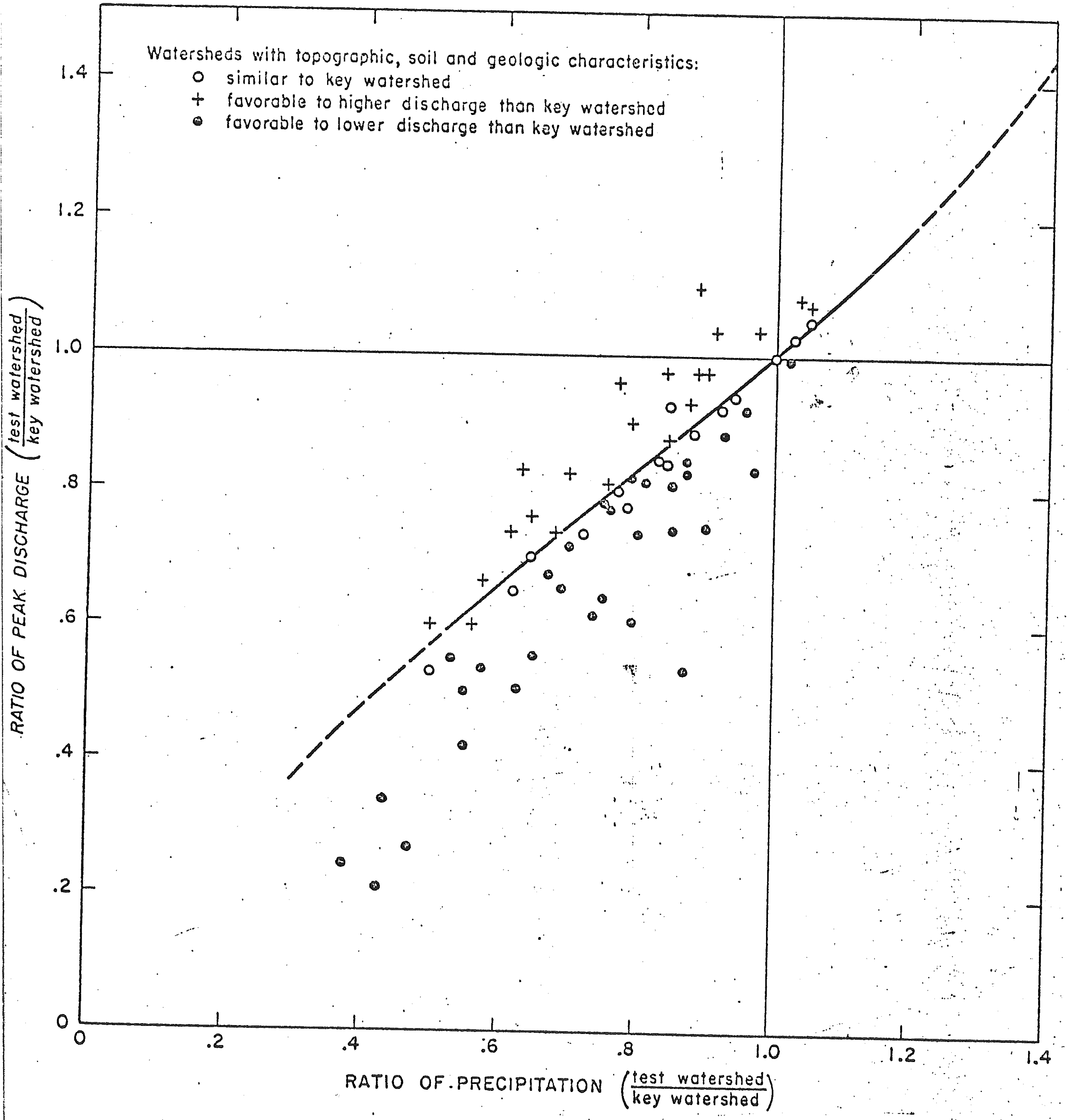

Figure 6.- Relation of peak discharge to rainfall--Angeles storm zone.

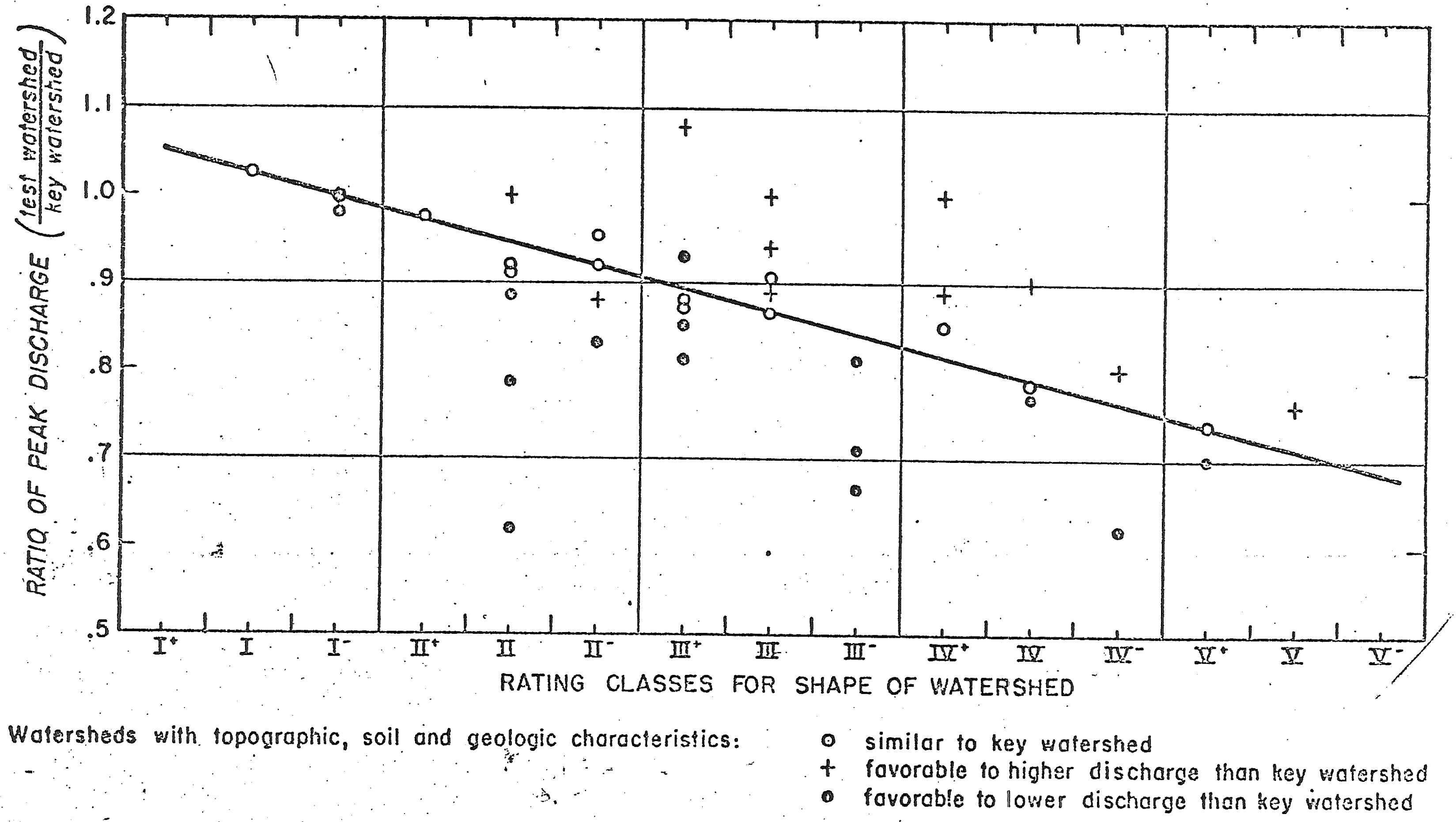

Figure 7.- Relation of peak discharge to watershed shape--Angeles storm zone.

PEAK DISCHARGE FREQUENCIES FOR WATERSHEDS NOT HAVING STREAM FLOW RECORDS

With the rating factors for the different watershed characteristics evaluated in terms of peak discharge the determination of normal peak discharges for the watersheds lacking measurements of stream flow was possible. Numerical ratings were determined and tabulated for each watershed by selected peak discharge classes, as illustrated for the sample watershed in table 2, columns 3(a), (b), (c), and (d). The numerical ratings expressed the effect of each factor on peak discharge when all of the other factors were similar to those of the key watershed. To get the total effect of all the factors that varied from those of the key watershed it was necessary to compute the algebraic sum of all the corrections. For the size discharge represented in column 3(a) of table 2, the effect of size of the sample watershed would be to reduce the peak discharge to .83 of the key watershed or a reduction of .17. Similarly, the reduction for watershed shape would be .44, for main channel flow characteristics .10, and for precipitation differences .09. This would give a total reduction of .80. The peak discharge per square mile of the sample watershed would thus be only .20 that of the key watershed.

This final figure may be more readily computed by finding the sum of the individual ratings of the discharge class and subtracting one less than the total number of ratings. For column 3(a) of table 2 this would be 11.20 - (12-1), or .20. This method was used to compute the "integrated" ratings for the selected discharge classes as shown in table 2.

The peak discharge for each of these selected discharge classes was then computed by multiplying the discharge of the key watershed by the integrated rating. These computed discharges were plotted on the same frequency scale as the key watershed (figure 8). A smooth curve drawn through the points then established the discharge-frequency curve for the watershed.

The integrated ratings do not allow for differences in inter-storm stream flow (based on ground water depletion flow). For units in which the base flow varied appreciably from that of the key watershed compensating corrections to the peak discharges were necessary, particularly for the smaller discharges. Many of the watershed units had fragmentary stream flow records from which estimates of the base flow could be made. In units without any records the estimates were based upon the senior author's or other hydrologist's knowledge of the stream and upon the similarity of the unit to other nearby watersheds with stream flow records. In the sample watershed of table 2 and figure 8, the base flow of the smaller discharges were estimated to average 0.2 c.s.m. higher than those of the key watershed. The computed peak discharges of the watershed were thus corrected by this amount.

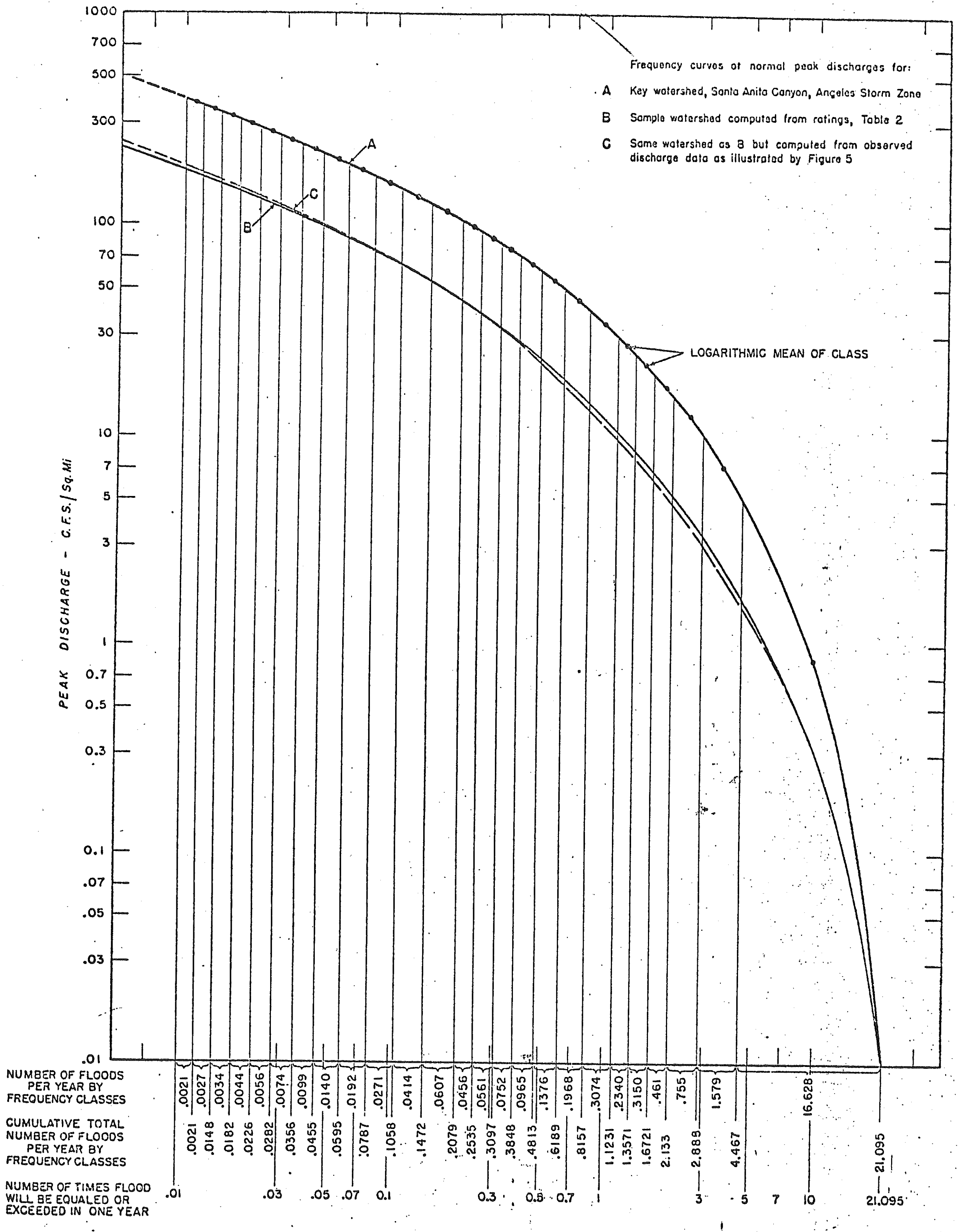

Figure 8.- Determination of peak discharge frequencies for watersheds not having streamflow records.

The establishment of a normal peak discharge frequency curve for each watershed unit completed the first objective of the hydrologic analysis. Using the discharge frequency curve and the damage-discharge relation for the watershed it was possible to construct a damage frequency curve for each unit. The damage frequency curve would show the most probable average annual damage and establish the rate as illustrated by curve A of figure 1.

DETERMINATION OF EFFECTS OF FIRE ON PEAK DISCHARGE

Determination of the effects of fire on peak discharge were made in order to predict the most probable peak discharges of individual watersheds by years, from time of burning until complete recovery of the watershed. Since burning has no effect on storm frequency the only difference in the discharge frequency curve for a unit before and after burning is in the size of the average discharge for each frequency class. The average discharge per class can be expected to change from year to year as the watershed recovers from the fire.

EFFECTS OF COMPLETE BURNING ON PEAK DISCHARGE

The effect of complete burning[6] of watershed cover was determined by (1) comparing peak discharge rates of burned watersheds with those of similar but unburned watersheds[7] for the same storm, and (2) comparing peak discharge rates from similar storms on the same watershed before and after burning. Watersheds used in these determinations were restricted to those in which the total watershed area had been burned over within a single year, in which measurements of streamflow were available for the burned and comparable unburned watersheds, and in which the normal vegetative cover consisted of chaparral associations of average density.

These comparisons were made storm by storm by years after the last fire. Similarity of watersheds was judged by comparison of normal discharge frequency curves and watershed ratings. Comparative watersheds were always close to or adjacent to the burned units.

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[6] Complete or partial burning, as used in this paper, refers to proportion of watershed area burned over by a fire, and not to the intensity of the burn nor to the degree to which the vegetation cover was consumed by it.

[7] Unburned watersheds were those in which the vegetation was unburned, or had recovered from past fires to the extent that present peak discharge and erosion rates were unaffected.

The most probable size of each peak discharge event of the burned watershed had the unit remained unburned was first determined. The frequency of each discharge peak from a burned watershed was assumed to be the same as the frequency of the corresponding peak from the key and other nearby unburned watersheds. Using this frequency an estimated peak for the burned unit in an unburned condition could be read directly from its normal frequency curve. The ratio of the observed peak of the burned unit to the computed peak for unburned conditions was then calculated to obtain the fire-effect ratio. This procedure of computing peak discharges following burning automatically corrects for differences in the physiographic characteristics of the watersheds for as previously shown these are reflected in the normal curves.

Similar fire-effect ratios were also developed by comparing peak discharges occurring from watersheds before complete burning with those occurring in the same watersheds after burning. The similarity of storms was established on the basis of uniformity in amounts of maximum 24-hour and total storm precipitation, occurrence of the storms in relation to antecedent precipitation and time of year, and similarity in size of storm peak discharges in the key and in adjacent unburned watersheds of the storm zone.

The fire-effect ratios were plotted over their corresponding frequencies on logarithmic paper for all years after burn for which data were adequate. Variation in the ratios within years were eliminated by fitting a smooth curve to the plotted points. Thus a series of curves giving average fire-effect ratios by discharge frequency classes and years after burn was developed.

To smooth out differences in rates of change in the ratios between years and to provide ratios for years for which data were inadequate, ratios for each frequency class were read from the curves and plotted over time in years. Smooth curves were then drawn through these data. Ratios read from these curves were then replotted in their original form and the recovery curves redrawn as illustrated in figure 9 for selected years following burning. The fire effect ratios as given by these final curves were used as the basis for computing the average, or most probable peak discharge, for all watersheds within the storm zone. To facilitate computations the mean ratio for each discharge class for selected years after burn were listed in tabular form as illustrated in table 3.

A period of 70 years was used as a standard recovery-from-fire period for all watersheds. This was done to simplify both the peak flow and damage rate computations. Although it was recognized that the recovery period would vary between units, the comparatively small fire effect after the first few years and greatly increased computational work did not appear to justify the refinement of using varying recovery periods.

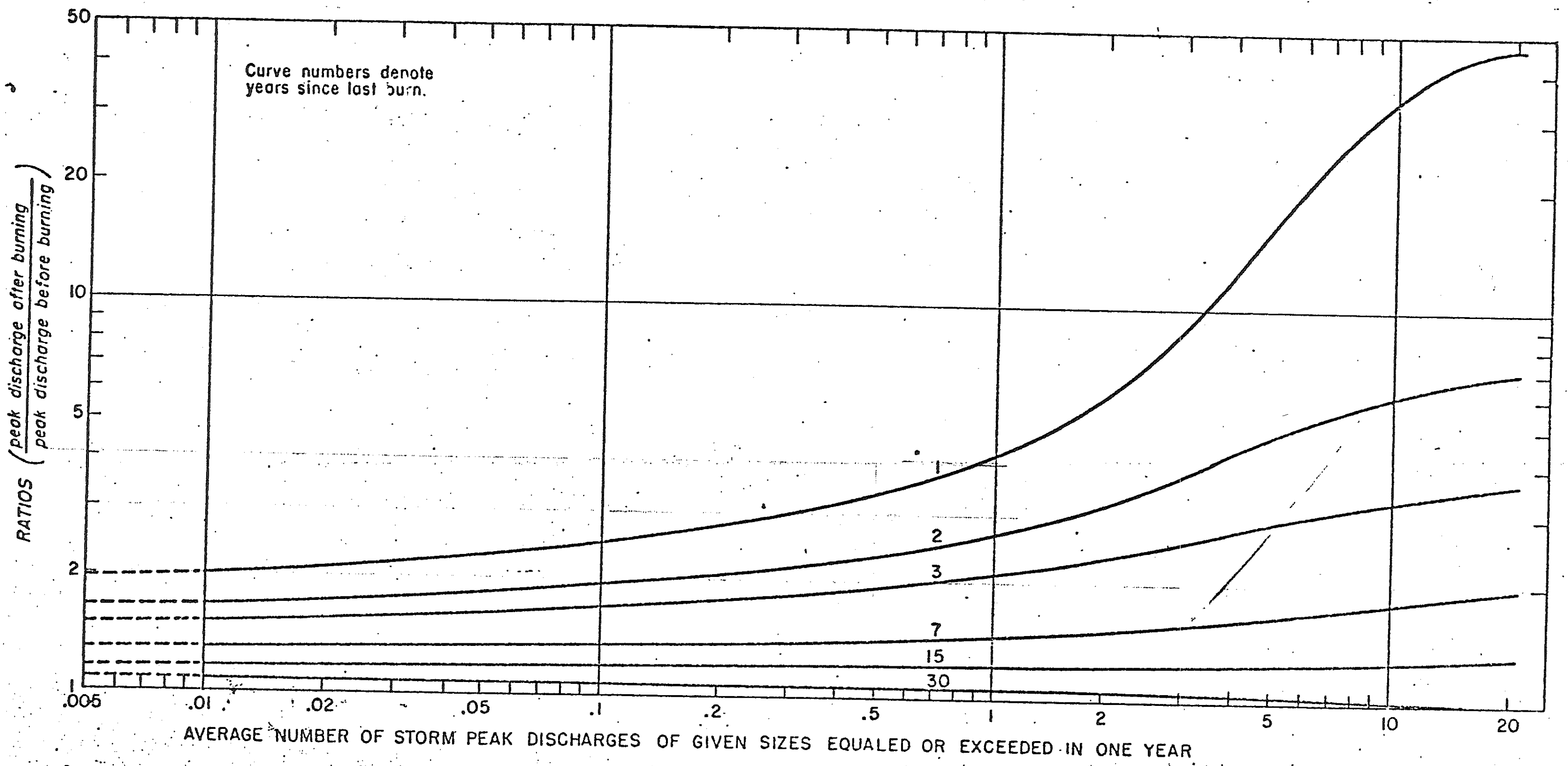

Figure 9.- Average effect of fire on peak discharge by frequency classes and years following burning--Angeles storm zone.

Table 3.-Ratios used in computing increases in peak discharge following burning.[1] Angeles storm zone

No. of events per discharge class per year:	Years after burning							
	1	2	3	7	15	30	50	(Normal) 70
16.628	34.0	6.00	3.30	1.80	1.28	1.01		
1.579	11.0	4.12	2.70	1.60	1.24	1.03		
.755	7.42	3.50	2.46	1.54	1.23	1.04		
.461	6.02	3.19	2.31	1.50	1.22	1.05		
.315	5.23	2.96	2.20	1.48	1.21	1.05		
.234	4.71	2.80	2.13	1.46	1.21	1.06		
.307 1.0	4.20	2.63	2.06	1.44	1.21	1.06		
.1968	3.73	2.46	1.98	1.42	1.20	1.06		
.1376 – 0.5	3.43	2.35	1.91	1.40	1.20	1.07		
.0965	3.20	2.25	1.86	1.38	1.20	1.07	1.00	
.0752	3.05	2.18	1.82	1.38	1.20	1.07	1.01	
.0561	2.92	2.12	1.79	1.37	1.19	1.07	1.01	
.0456	2.82	2.08	1.76	1.36	1.19	1.07	1.01	
.0607 – 0.2	2.70	2.02	1.72	1.35	1.19	1.07	1.01	
.0414	2.55	1.95	1.68	1.34	1.18	1.07	1.02	
.0271 – 0.1	2.44	1.90	1.65	1.34	1.18	1.07	1.02	
.0192	2.36	1.86	1.63	1.33	1.18	1.07	1.02	
.0140	2.29	1.82	1.60	1.32	1.18	1.07	1.02	
.0099	2.23	1.79	1.58	1.32	1.18	1.08	1.02	
.0074	2.18	1.77	1.75	1.31	1.18	1.08	1.02	
.0056	2.14	1.74	1.55	1.31	1.17	1.08	1.02	
.0044 – 0.05	2.10	1.72	1.53	1.30	1.17	1.08	1.03	
.0034	2.07	1.70	1.52	1.30	1.17	1.08	1.03	
.0027	2.04	1.69	1.51	1.30	1.17	1.08	1.03	
.0021	2.02	1.68	1.50	1.30	1.17	1.08	1.03	
.01	2.00	1.67	1.50	1.29	1.17	1.08	1.03	1.00

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[1] These ratios are the "R: values used in computing peak discharges following burning.

MOST PROBABLE PEAK DISCHARGES OF INDIVIDUAL WATERSHEDS FOLLOWING BURNING

The fire-effect ratios in table 3 were applicable directly only to those units having complete cover of average density or subject to "full fire effect." The most probable peak discharges following complete burning for these units were computed by discharge classes, using the equation

$$Q_b = RQ_n \qquad (1)$$

where

Q_b = Peak discharge in cubic feet per second per square mile for a given frequency class and year after burn.

R = Fire effect ratio for the frequency class and year after burn (from table 3).

Q_n = Normal peak discharge for the frequency class.

For example, using data from Santa Anita Canyon, it is found that the normal peak discharge for the frequency class with an average of 0.307 event per year is 34.5 c.s.m. Table 3 shows that the normal peak discharges of this class are increased an average of 4.2 times the first year after burning. Substituting in equation (1) the average peak discharge (Q_b) for this frequency class the first year after burning is equal to 4.2 x 34.5, or about 145 c.s.m. Peak discharges for each frequency class for each year after burning were computed in like manner, and tabulated as illustrated by table 6, page 45.

For watersheds not subject to the full fire effect it was necessary to adjust the average fire effect ratios for the proportion of the watershed not subject to burning or for deviations from the average effects of burning owing to sparseness of vegetation, or for both. These adjustments were expressed by a correction or "C" factor.

For watersheds in which only part of the area was burnable but in which the burnable area was of average cover density the effects of fire on the unit as a whole was assumed to be directly proportional to the area burnable. Thus a unit in which only 80 percent of the total area would burn, but in which the burnable area was subject to full fire effect, the C factor would be 0.80 and the average increases in peak discharge due to fire as shown in table 3 would be reduced by 20 percent.

The influence of cover density on effects of fire on peak discharge was determined by computing fire effect ratios for watersheds with different cover densities. In this the same general procedure was used as described for computing the fire effect ratios for average cover conditions. The relation between cover density and fire effect was expressed as a percentage of the average fire-effect ratios. When this was the only correction necessary this value became the C factor. Thus in a watershed unit completely burnable, but because of sparsity of cover the effects of burning are only 80 percent of average, the increases in peak discharge due to fire would be only .80 of those shown in table 3. When it was necessary to make adjustments for both cover density and burnable area the C factor became the product of the two corrections.

In some watersheds the effects of fire upon small peak discharge flows varied appreciably from the average for the storm zone. These variations were determined in developing the average fire effect curves and were due principally to such watershed factors as size and shape, high permeability of soil type and geologic formations, or high inter-storm ground-water flow. Corrections for these variations as in the case of those for differences in burnable area and vegetation density, were expressed as a ratio to the average increases in peak discharge due to fire, shown in table 3. The C factor was then adjusted by means of this ratio. These adjustments, when necessary, generally affected only the first few peak discharge classes.

The C factors were determined for all watersheds not subject to average effects of burning and a frequency table similar to part A of table 6, page 45 was computed for each watershed. Equation (1), modified as follows to include the C factor, was used in computing the peak discharges:

$$Q_b = \left[(R - 1.0)\ (C) + 1\right] Q_n \qquad (2)$$

The equation takes this form rather than $Q_b = RCQ_n$ because the C factor applies only to the <u>increase</u> in peak discharge and not to the total peak given by direct application of the fire-effect ratio.

The computation of peak discharge-frequency tables for each watershed unit from time of burning to watershed recovery completed the second objective of the hydrologic analysis. Using damage-discharge relations and the peak discharge tables total damage for each year from time of burn to watershed recovery can be computed for each watershed. From these computations curve B of figure 1 can be established.

RESIDUAL EFFECTS OF PAST FIRES ON PEAK DISCHARGE

At the time the fire damage appraisal study was started (1945) the peak discharges of many watershed units were above normal because of residual effects of past fires. For each of these watersheds it was necessary to develop peak discharge frequency tables by years from 1945 until the time of watershed recovery. Tables for watersheds that had been completely burned were computed in the same way as in the preceding discussion except that the discharges were computed only for years from 1945 to recovery.

Not all past fires, however, burned the entire burnable area of the watershed. When only part of the watershed was burned the equation for effect of fire on discharge was adjusted to allow for the proportion of the watershed burned. The equation then became:

$$Q_b = \left[(R - 1.0)\,(C)\,\left(\frac{A_b}{A_x}\right) + 1.0 \right] Q_n \qquad (3)$$

where A_b = the percent of total area burned.

A_x = the percent of total area burnable.

In watersheds in which more than one partial burn had occurred in different years, the $\left[(R - 1.0)\,\left(\frac{C A_b}{A_x}\right) \right]$ part of the burn effect-discharge equation was worked out for each fire. Peak discharges for the watershed were then calculated by determining the sums of this part of the equation for each frequency class and year after burn, inserting these sums into the equation and completing the remaining computations.

EFFECTS OF WATERSHED SIZE AND SHAPE ON PEAK DISCHARGE FROM PARTIALLY BURNED WATERSHEDS

To determine average effects of watershed size and shape upon peak discharge from part or small burns, the watersheds were segregated into three classes. Class I included the small, fan-shaped watersheds favorable to a rapid concentration of storm discharge and in which analysis of the data showed that small burns caused about the same relative increase in peak discharge per area burned as did large burns. Class III included the larger watersheds unfavorable to rapid concentration of storm discharge and in which the concentration time of peak discharge from small burns would have the maximum opportunity to vary from that of the watershed as a whole. Class II included watersheds intermediate in size and shape between Classes I and III. Average increases in peak discharge for each class of watershed were determined by comparing peak discharges on the basis of the proportion of the watershed burned, as illustrated in figure 10.

No adjustments for size and shape were necessary for Class I watersheds. For Class II and III watersheds, however, the area of burn (A_b) in equation (3) was adjusted to conform to values shown in figure 10. For example, if 30 percent of Class I watershed were burned, the A_b value of the equation would be 0.3, whereas the corresponding values for Class II and III watersheds would be 0.27 and 0.24, respectively.

The computation of the peak discharge-frequency tables for all watersheds with residual fire effects completed the third objective of the hydrologic analysis. Again using the damage-discharge relations and the present-to-recovery peak discharge tables the residual damage from past fires could be computed and curve C of figure 1 established.

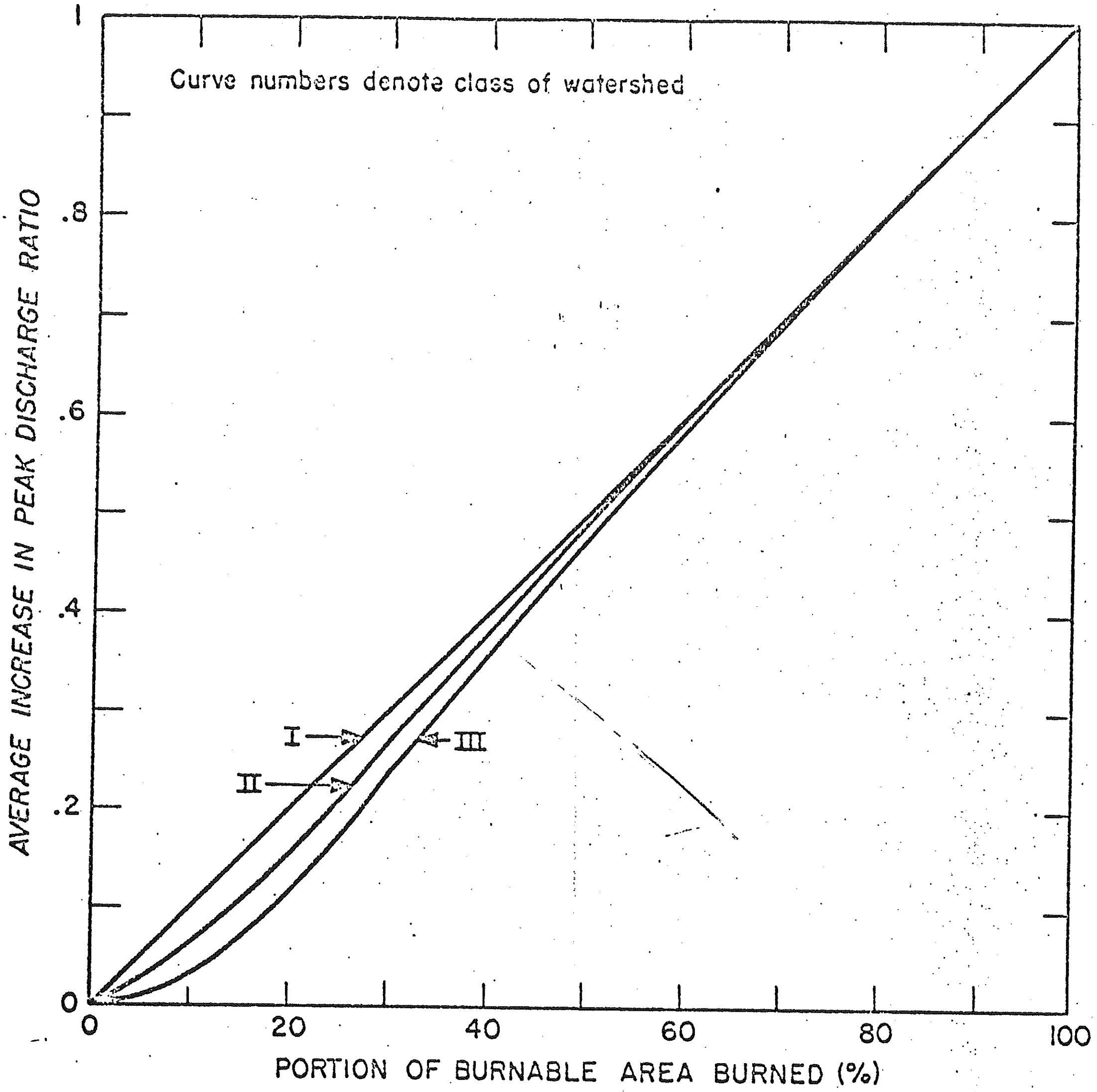

Figure 10. - Effects of watershed size and shape on peak discharge from partially burned watersheds.

DETERMINATION OF ANNUAL NORMAL EROSION RATES[8]

Data used in determining annual rates of normal erosion consisted of measurements of total siltation in reservoirs situated in watersheds with normal vegetation cover. Periods for which erosion records were available ranged from 1 to 15 years. Because of the short duration of the erosion records and because the siltation measurements were at irregular intervals including various numbers and types of storms, it was necessary to determine relations between the recorded peak discharges and corresponding erosion rates. These relations were then used to compute normal erosion rates of the individual watersheds on the basis of the normal peak discharge frequencies.

Details of this procedure are explained in the following discussion by use of data from the Santa Anita Canyon, and from certain other watersheds on the south slope of the San Gabriel Mountains in the Angeles storm zone.[9]

RELATION OF EROSION RATE TO NORMAL PEAK DISCHARGE

The first step in determining relations between erosion and normal peak discharge was to prorate measured erosion to the individual discharges that produced it. To accomplish this, a representative cross section of the stream channel just upstream from the reservoir was selected for determining velocities by peak discharge sizes. The shape, cross-sectional dimensions, and average slope of this section were determined and a roughness coefficient 0.05 was assumed. Using Scobey's graphical solution of Kutter's formula (2), a series of velocities were computed for various depths. A velocity-flow graph was then plotted showing velocity in feet per second over flow in cubic feet per second. Velocities for all discharge peaks during the period of siltation measurements were determined directly from this graph, and the total eroded material was distributed to individual peak discharges in proportion to the fifth power of the velocity (1), as illustrated in table 4.

This type of computation was repeated for each period of record. The erosion rates (column 6, table 4) were next plotted against the corresponding units peak discharges (column 7) on logarithmic paper as shown in figure 11. A smooth curve drawn through the mean of these data was taken as representing the average relation between peak discharge and erosion rates of the watershed.

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[8] Erosion rate as used in this paper is the volume of eroded material (soil and rock) discharged from a watershed by specified discharges or in given units of time. Normal erosion is that uninfluenced by past fire.

[9] The Los Angeles storm zone is divided naturally into two parts: (1) the generally south- or ocean-facing slope of the San Gabriel Mountains, and (2) the generally north- or desert-facing slope of the mountains. South slope and north slope as used in this discussion refer to this division and not necessarily to the aspect of the watershed units.

Peak discharge-erosion rate curves similar to that for Santa Anita were developed for four additional watersheds of the south slope storm zone for which these data were available. Although these curves represented a wide sample of south-slope watersheds, they showed very little variation when superimposed. The five curves were therefore used to develop a single mean curve to represent the average relations between normal peak discharge and erosion rates for all the south-slope watersheds of the zone. This mean curve varied only slightly from that shown for Santa Anita Canyon in figure 11.

INDIVIDUAL WATERSHED EROSION RATES

Using the peak discharge-erosion rate curve as a base, normal erosion for each individual watershed was computed from its normal peak discharge frequency curve. The procedure followed in these computations is illustrated in table 5. The data in columns 1 and 2 are taken directly from the Santa Anita normal peak discharge frequency curve. Erosion rates (column 4), corresponding to each discharge peak, were read from the peak discharge-erosion rate curve for the zone. The "weighted peak discharges" of column 3 are the products of columns 1 and 2, and the "weighted erosion rates" of column 5 are the products of columns 2 and 4. The sum of column 5 is the most probable or normal annual erosion rate of the watershed.

Annual rates of normal erosion were computed in this way for the five watersheds referred to earlier. When plotted on logarithmic paper over the sum of their corresponding weighted peak discharges, these normal rates formed a straight line, as illustrated by figure 12. The sums of the weighted peak discharges were then computed for each of the watershed units of the south slope of the zone. Based on this datum the annual rate of normal erosion for each unit was read directly from the erosion rate curve of figure 12, thus eliminating the need for computing the weighted erosion rates for individual watersheds.

Data were not available to permit determination of annual erosion rates for watersheds of other areas in the same detail as was done for the watersheds of the south slope of the Angeles storm zone. However, some data were available for each area. This data and the information developed for the south slope of the Angeles storm zone were used as the basis for estimates of normal erosion rates in these areas. The method employed in developing these estimates was the same as that described below for the north-slope watersheds of the Angeles storm zone.

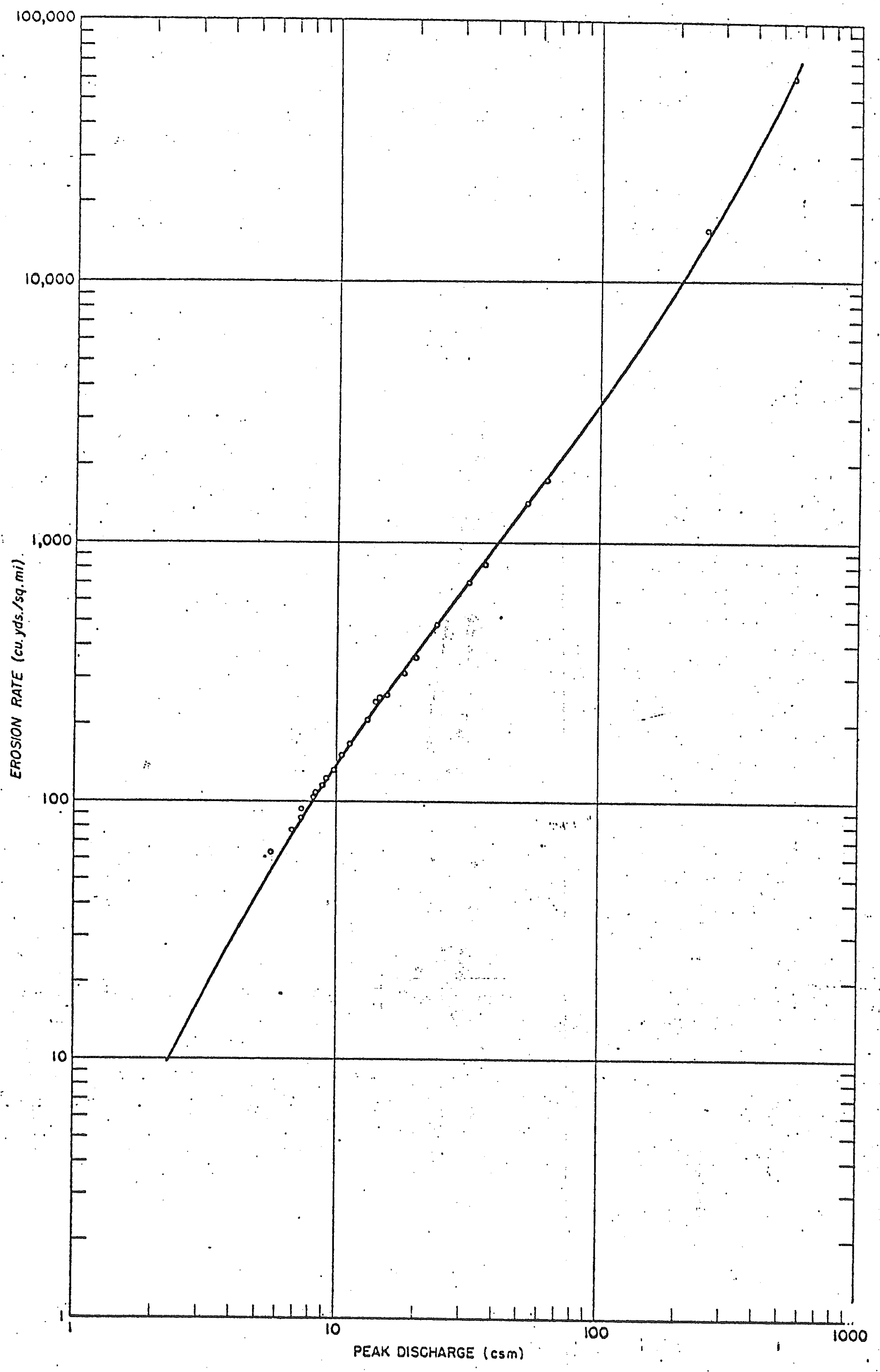

Figure 11.- Relation of erosion rates to normal peak discharges--Santa Anita Canyon, Angeles storm zone.

Table 4.- Computation of relations of erosion rates and normal peak discharge.
Santa Anita Canyon, Angeles storm zone

1940-41 rainy season — Total siltation for period, 31 acre-feet

(1) Peak Discharge	(2) V (Velocity)	(3) V^5 (Fifth power of velocity)	(4) V^5 Proportion of total	(5) Erosion	(6) Erosion rate	(7) Peak discharge
Cu.ft./sec.	Ft./sec.		Percent	Ac. ft.	Cu.yds./sq.mi.	C.s.m.
58	6.0	7,703	1.49	.46	68.7	5.5
121	7.3	21,000	3.90	1.21	180.7	11.5
63	6.1	8,521	1.67	.52	77.7	6.0
79	6.5	11,500	2.23	.69	103.0	7.5
266	9.1	62,900	11.71	3.63	542.1	25.3
80	6.5	11,500	2.23	.69	103.0	7.6
235	8.8	51,500	9.66	2.99	446.6	22.4
342	9.8	89,300	16.54	5.13	766.2	32.6
193	8.3	40,100	7.43	2.30	343.5	18.3
123	7.4	22,100	4.09	1.27	189.7	11.7
88	6.7	13,400	2.42	.75	112.0	8.4
465	10.6	134,000	24.91	7.72	1,153.0	44.3
153	7.8	28,300	5.20	1.61	240.4	14.6
175	8.1	34,600	6.51	2.02	301.7	16.7
Totals		536,424	99.99	30.99		

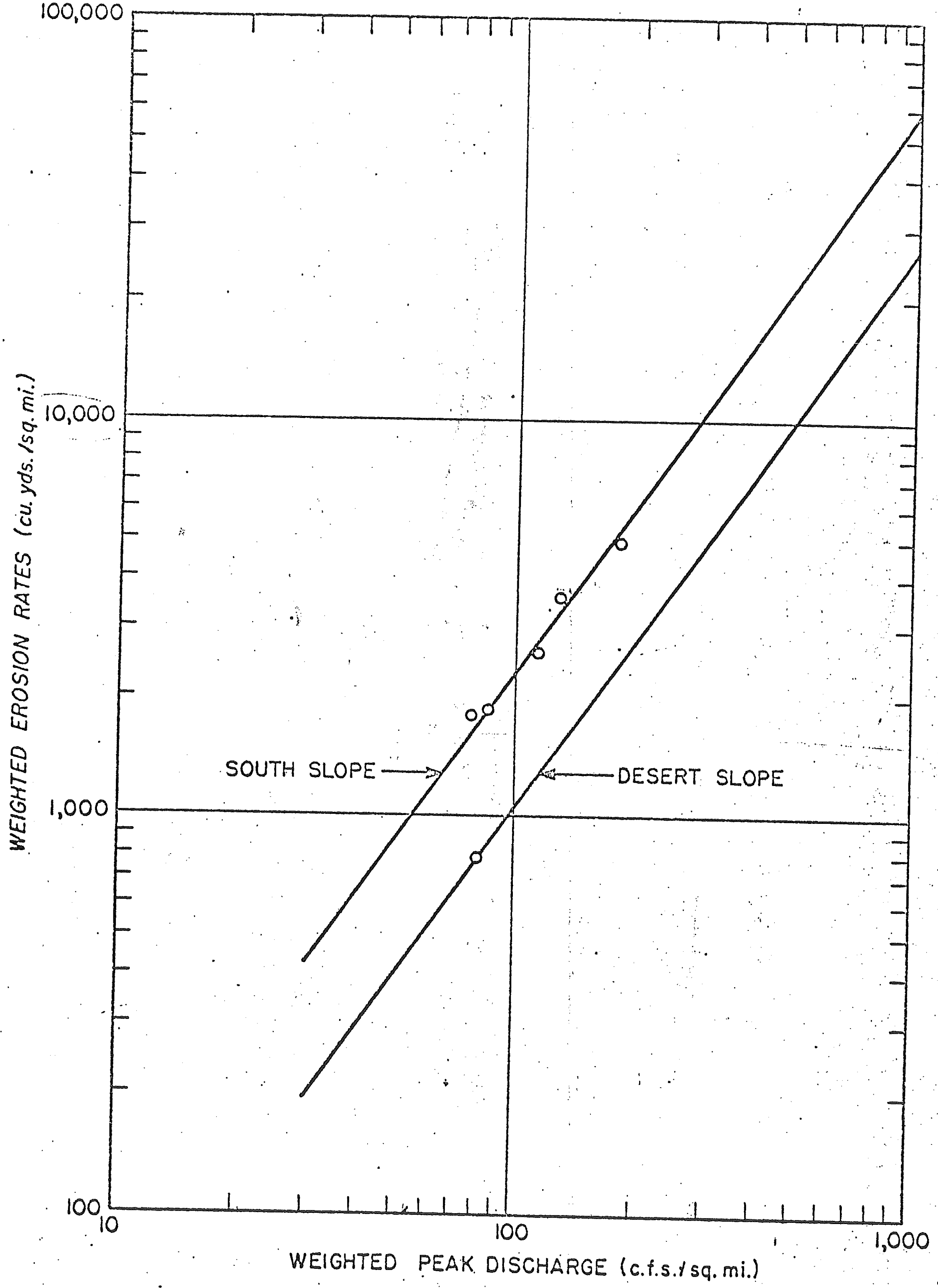

Figure 12.- Relation of annual erosion rates to weighted peak discharge--Angeles storm zone.

Table 5.-Computation of normal annual erosion rate--Santa Anita Canyon, Angeles storm zone

(1) Mean peak discharge	(2) No. of events/yr.	(3) Weighted peak discharges	(4) Erosion rates	(5) Weighted erosion rates
C.s.m.		C.s.m.	- - - Cu. yds./sq. mi. - - -	
.849	16.628	14.12	0	0
7.10	1.579	11.21	87	137
12.25	.755	9.25	189	143
17.30	.461	7.98	309	142
22.35	.315	7.36	460	145
27.40	.234	6.41	570	133
34.56	.3074	10.62	780	240
44.64	.1968	8.78	1,110	218
54.83	.1376	7.54	1,470	202
65.31	.0965	6.30	1,880	181
75.75	.0752	5.70	2,260	170
86.20	.0561	4.84	2,720	153
96.92	.0456	4.42	3,210	146
113.40	.0607	6.88	4,000	243
135.3	.0414	5.60	5,100	211
157.5	.0271	4.27	6,400	173
180.2	.0192	3.46	7,900	152
203.3	.0140	2.85	9,500	133
226.8	.0099	2.24	11,300	112
250.8	.0074	1.86	13,300	98
274.9	.0056	1.54	15,700	88
300.	.0044	1.32	18,400	81
325.	.0034	1.10	21,700	74
350.	.0027	.94	25,200	68
375.	.0021	.79	29,200	61
389.	.0100	3.89	32,000	320
Total	21.095	141.27		3,824

In the north slope of the Angeles zone siltation data were available for only the Little Rock Creek unit, a typical desert-slope watershed. A curve of peak discharge over erosion rate developed from these data, although showing lower erosion rates, was parallel to the mean curve of peak discharge over erosion rate for the south-slope watersheds (figure 11). Based on the similarity, a curve of average annual erosion rates for watersheds of the desert slope, was drawn parallel to that of the south-slope watersheds, as illustrated in figure 12. The limits of this curve were defined by the computed normal erosion rate of Little Rock Creek. Annual rates of normal erosion for the desert-slope watersheds were then determined directly from this curve following the same procedure as described for the south-slope drainages.

The establishment of normal average annual erosion rates completed the fourth objective of the hydrologic analysis. From the normal erosion rates it was possible to compute the normal annual erosion damage rate.

DETERMINATION OF EFFECTS OF FIRE ON ANNUAL EROSION RATES

Determination of the effects of fire upon erosion was based on comparison of erosion rates of completely burned watersheds with those of unburned watersheds. Details of the procedure are here illustrated by use of data from the Los Angeles storm zone.

EFFECTS OF COMPLETE BURNING ON ANNUAL EROSION RATES

Records of siltation from debris basins situated in watersheds completely burned over during the 1930's were used to establish average erosion rates by years from time of burning until return to normal. Siltation records from Santa Anita Canyon, the key watershed of the zone, were used to establish erosion rates for unburned conditions during the same time.

Streamflow records were not available for the burned watersheds. In order to establish the relation between erosion in these watersheds and peak discharge it was necessary to correlate the erosion with peak discharges of the unburned key watershed. This was accomplished by first computing ratios of erosion from the burned watersheds to erosion for corresponding periods from the key watershed. These ratios became practically constant in 9 to 10 years, indicating the establishment of relatively stable watershed conditions and normal erosion rates.

Using the ratios thus established, it was then possible to compute the most probable rates that would result if the key watershed were burned. This computation was made as follows: the first year after the fire in one of the completely burned watersheds, erosion totaled about 75,000 cubic yards per square mile. The ratios described above indicate that the key watershed, if burned at the same time, would have had an erosion rate for the same period of about 110,000 cubic yards per square mile. During this period of siltation six storms occurred with peak discharges that would produce erosion. The estimated erosion (110,000 cubic yards per square mile) was prorated to each of these peak discharges in the same manner as described for computing normal rates. The computed erosion rate allotted to each peak discharge was next plotted on logarithmic paper over the recorded peak discharge. Similar erosion rates computed by use of data from other burned watersheds was also used. A smooth curve was then fitted to these data. The same procedure was used for other years after burn and a series of curves showing the average relation between normal peak discharge and erosion by years after burn established. These curves are illustrated in figure 13.

MOST PROBABLE ANNUAL EROSION RATES OF INDIVIDUAL WATERSHEDS FOLLOWING BURNING

Probable average annual erosion rates were computed for the key watershed for each year following a complete burn, using the same method as described for computing the normal rate. These rates were then plotted over time in years since burning, and irregularities between years eliminated by drawing a smooth curve through the plotted points. The average annual rates were read from this curve and plotted over the weighted <u>normal</u> peak discharge of the key watershed. The relation between weighted normal peak discharge and annual erosion rate for individual watersheds was established by drawing a curve through the plotted point for each year after burn and parallel to the normal erosion rate curve for the south-slope watersheds from figure 12. This resulted in the series of curves shown in figure 14.

Estimates of the most probable annual erosion rates by years following fire (table 6, page 45) for watersheds of the Los Angeles storm zone were read directly from the curves of figure 14. Entry to these curves was made through either the normal weighted peak discharge or normal annual erosion rate of the individual watershed. The estimated watershed erosion rates following burning were thus related directly to frequencies of normal peak discharge. As indicated in previous discussions, frequencies of peak discharge varied with storm zones. However, the relations between normal erosion rates and erosion rates following fire were reasonably constant from storm zone to storm zone. Thus these relations developed for the Los Angeles storm zone, figure 14, were also used to estimate the effects of fire on erosion rates in all zones.

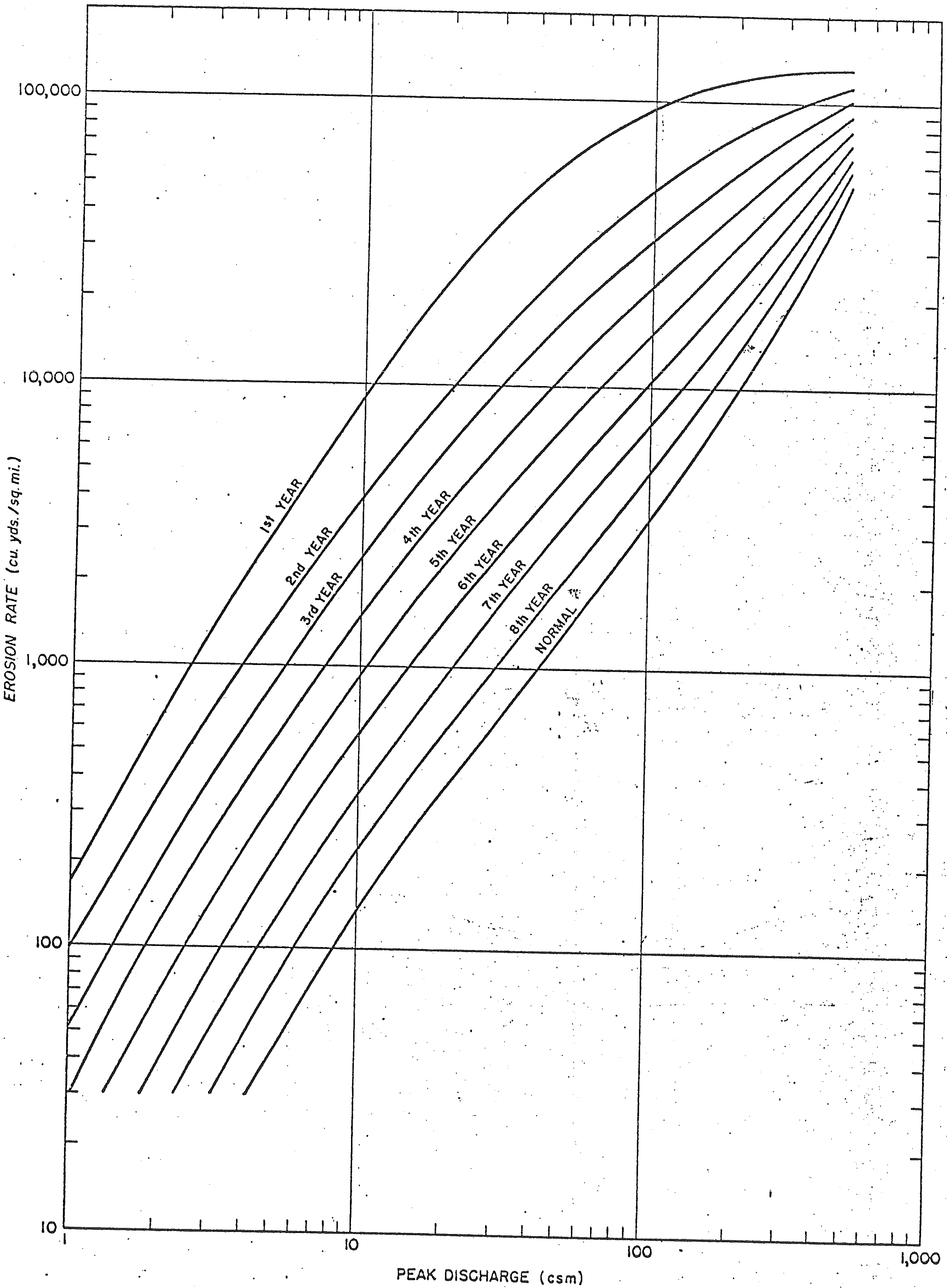

Figure 13.- Relation of erosion rates to storm peak discharge following burning--Angeles storm zone.

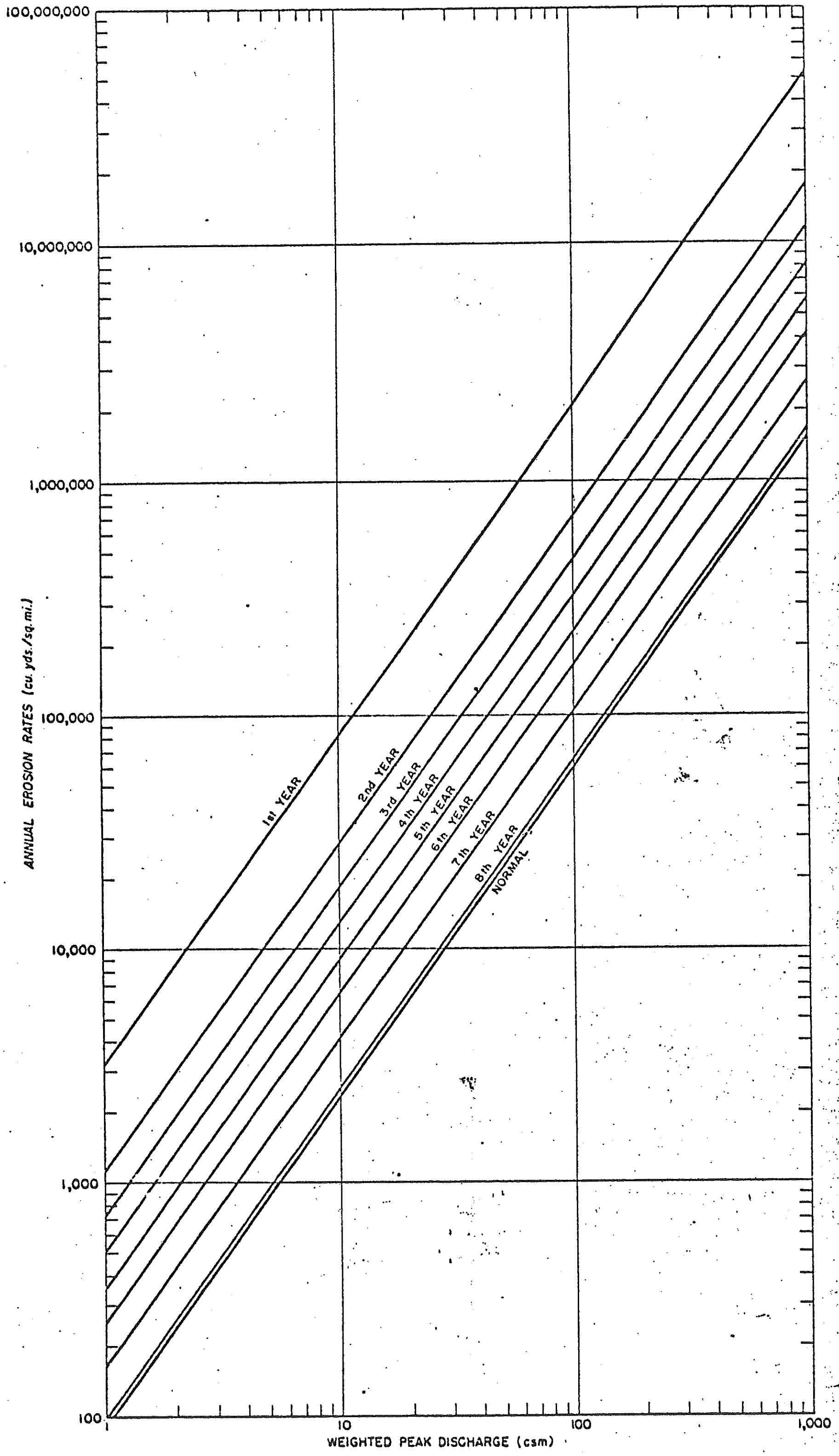

Figure 14.- Relation of annual erosion rates to weighted peak discharge following burning.

As for the estimates of peak discharge, it was necessary to estimate separately erosion following burning for those watersheds which were not subject to complete burning or were only sparsely covered with vegetation. For this purpose the burn factor (C factor), described in the discussion concerning determination of effects of burning on peak discharge, was used. For example, figure 15 shows that the average annual erosion rate of a watershed completely burned and subject to the full effects of burning (burn factor 100 percent) would be increased about 35 times the first year after the burn, about 12.2 the second year, and so on, returning to normal in about 9 years. However, if the burn factor for the watershed was only 50 percent, the average annual erosion rate the first year after the burn would be only 17.5 times the normal rate, and the second year only about 6.1 times the normal rate.

Computation of the watershed annual erosion rates from time of burning until recovery completed the fifth objective of the analysis. From these data total expected erosion damage following fire could be computed for all watersheds except those not fully recovered from past fires.

EFFECTS OF PAST BURNS ON ANNUAL EROSION RATES

Because of the effects of past fires erosion rates of many watersheds were in excess of normal when this study was started in 1945. For each of these watershed units it was necessary to develop estimates of annual erosion rates from 1945 until the time of watershed recovery from past fires.

For those watersheds completely burned over by the last fire, estimates of annual erosion rates for present conditions were taken directly from the computed rates described in the preceding section. Thus the 1945 rate for a watershed burned in 1940 would be the same as the rate previously computed for the unit the fifth year following a complete burn, and the 1946 rate the same as that computed for the sixth year following a burn, and so on until the watershed had recovered.

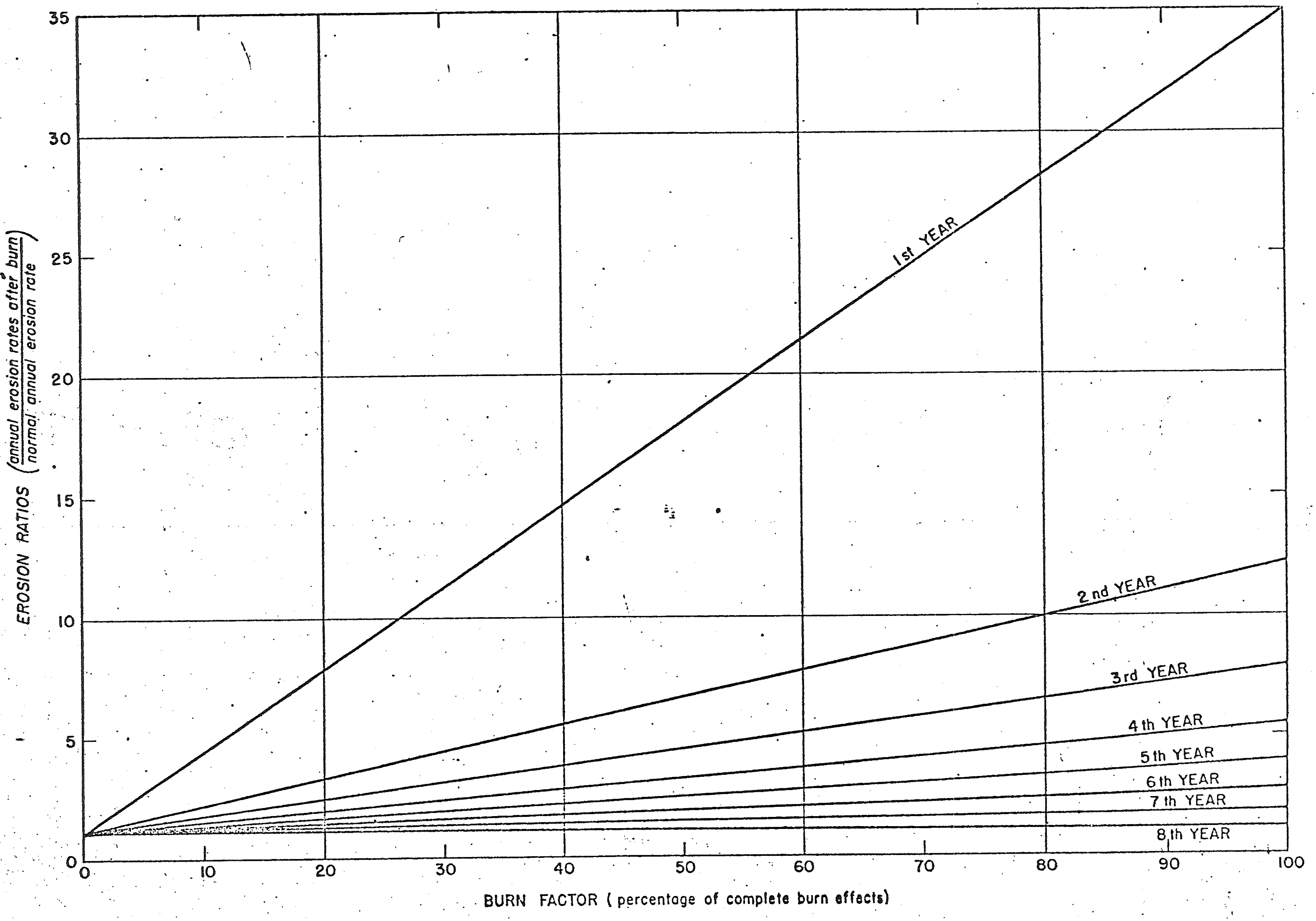

Figure 15.- Effect of partial burns on annual erosion rate.

For watersheds only partly burned, it was assumed that the burned part would erode at the same rate as if the entire watershed had been burned, and that the unburned part would erode at the normal rate. Increases in the erosion following past burns, then, were computed on the basis of the percentage of the watershed that had been burned, using the equation:

$$E_x = (E_b - E_n) \frac{A_x}{A_b} + E_n \qquad (4)$$

where

E_x = Erosion rate at a given year after a partial burn.

E_b = Estimated erosion rate for complete burn at a given year.

E_n = Normal erosion rate.

A_x = Percent total area burned.

A_b = Percent total area burnable.

When the watershed was recovering from more than one partial burn, the $(E_b - E_n) \frac{A_x}{A_b}$ part of the equation was computed for each burn and the sum used in computing the average rate.

The computation of the effect of past fires on erosion completed the sixth and last objective of the hydrologic analysis. Burn-to-recovery, normal, and present-to-recovery damages could be computed from the erosion rates established in this analysis and the damages due to fire determined.

THE PEAK DISCHARGE AND EROSION TABLES

As indicated at the beginning of this paper the requirements of the economic analysis of flood and erosion damage dictated the form in which the peak discharge and erosion estimates appear. This is illustrated by table 6 which gives the estimates of peak discharge and erosion rates for the Santa Anita watershed of the Los Angeles storm zone from time of complete burning until watershed recovery. Similar tables were prepared for the 256 watersheds in the national forests of southern California[10].

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[10] Because of the cost these tables were not reproduced, but copies are available for reference use at the following locations: California Forest and Range Experiment Station, 347 Forestry Building, Berkeley, California; U. S. Forest Service, 630 Sansome Street, San Francisco, California; and San Dimas Experimental Forest, 110 North Wabash Avenue, Glendora, California.

Table 6.-Peak discharges and annual erosion rates following burning--Santa Anita Canyon, Angeles storm zone

Watershed area 10.65 sq.mi. Discharge point Lat. 32° 11'6"; Long. 118° 1'14"

Watershed type I. Percent burnable 100. Mean annual precipitation 36.6 in.

A. Peak discharge rates following burning

Number of events per year	Years after burning							
	1	2	3	7	15	30	50	(Normal) 70
	Cubic feet per second per sq. mi.							
16.628	28.9	5.09	2.80	1.53	1.09	0.86	0.85	0.85
1.579	78.1	29.2	19.2	11.4	8.8	7.31	7.1	7.1
.755	90.9	42.9	30.1	18.9	15.1	12.7	12.2	12.2
.461	104.	55.2	40.0	26.0	21.1	18.2	17.3	17.3
.315	117.	66.2	49.2	33.1	27.3	23.5	22.4	22.4
.234	129.	76.7	58.4	40.0	33.2	29.0	27.4	27.4
.307	145.	90.9	71.2	49.8	41.8	36.6	34.5	34.5
.1968	166.	110.	88.4	63.4	53.6	47.3	44.6	44.6
.1376	188.	129.	105.	76.8	65.8	58.7	54.8	54.8
.0965	209.	147.	122.	90.1	78.4	69.9	65.3	65.3
.0752	231.	165.	138.	104.	90.9	81.1	76.6	75.8
.0561	252.	183.	154.	118.	103.	92.2	87.1	86.2
.0456	273.	202.	171.	132.	115.	104.	97.8	96.9
.0607	306.	230.	195.	153.	135.	121.	114.	113.
.0414	345.	264.	227.	181.	161.	145.	138.	135.
.0271	384.	299.	260.	211.	186.	168.	161.	158.
.0192	425.	335.	294.	240.	213.	193.	184.	180.
.0140	466.	370.	325.	268.	240.	218.	207.	203.
.0099	506.	406.	358.	299.	268.	245.	232.	227.
.0074	547.	444.	394.	329.	296.	271.	256.	251.
.0056	588.	478.	426.	360.	322.	297.	280.	275.
.0044	630.	516.	462.	390.	351.	324.	309.	300.
.0034	673.	553.	494.	423.	380.	351.	335.	325.
.0027	714.	592.	529.	452.	410.	378.	360.	350.
.0021	758.	630.	563.	484.	439.	405.	386.	375.
.01[1]	778.	650.	583.	502.	455.	420.	401.	389.

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[1] Peak discharges of this frequency class are those expected to be equaled or exceeded an average of once in 100 years. All others in table are means of their respective frequency class.

Table 6.- (Continued)

B. Annual erosion rates following burning

Years after burning								
1	2	3	4	5	6	7	8	(Normal) 10
Cubic yards per square mile								
133,000	46,360	30,020	29,900	14,820	10,260	6,840	4,070	3,800

Peak discharges are given as the mean discharge of relatively small discharge classes. Frequency of discharges is shown as the average number of events per year within the discharge class. Thus in the Santa Anita unit the first discharge class has an average of 16.628 storms per year. The average normal peak discharge for these storms is 0.85 c.s.m. The first year after burn the 16.628 storms will produce an average peak of 28.9 c.s.m., the second year 5.09 c.s.m., the third year 2.80 c.s.m., etc. Likewise, the second discharge class has an average storm frequency of 1.579 storms per year producing an average normal peak of 7.10 c.s.m. The first year after burn this peak discharge becomes 78.1 c.s.m., the second year 29.2 c.s.m., the third year 19.2 c.s.m., etc.

Frequencies of peak discharge of a size equaled or exceeded less frequently than once in one hundred years were not determined. Thus the figures shown in the last line of Section A of the tables are not the mean of the discharge class as are the preceding data, but rather indicate the peak discharge that will be equaled or exceeded on the average once in one hundred years.

The sum of the number-of-events-per-year column, 21.095 for Santa Anita, indicates the average total number of storms per year for the storm zone. The number of storms in each discharge class then does not represent any possible actual distribution of storms in a given year or following a given burn, but only the average of the storms that will occur over a long period of time. Thus in a 100-year period a total of 2,110 (100 x 21.095) storms may be expected to occur in Los Angeles storm zone. Of this number 1,663 will cause an average normal peak discharge of 0.85 c.s.m. in the Santa Anita unit, 158 will cause an average peak of 7.10 c.s.m., 75.5 will cause an average peak of 17.3 c.s.m., etc. The last class in section A of the table would indicate that one storm in the one-hundred-year period would equal or exceed 389 c.s.m.

The erosion rates in section B of the table were based on the hypothetical distribution of storms given in section A. Thus these rates are also estimates of long-time averages and agreement with actual rates for a given year or following given burns can happen only by chance. However, applied to a large number of watersheds over a long period of time the estimates of peak discharge and erosion provide a sound basis for estimating future damages.

ACKNOWLEDGMENT

The analysis described in this paper was used in one phase of a fire damage appraisal study undertaken by the Forest Fire Research and Forest Influences Division of the California Forest and Range Experiment Station in cooperation with the California Region of the Forest Service and the four national forests of southern California.

A major portion of the basic data used in the analysis were obtained from information published by or made available through the courtesy of the Los Angeles office of the U. S. Geological Survey, Los Angeles County Flood Control District, Los Angeles office of U. S. Engineers, Los Angeles and San Francisco offices of U. S. Weather Bureau, and many water districts, city water departments, and water companies within the area of the study.

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