SURFACE RUNOFF FROM AGRICULTURAL WATERSHEDS

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SYNOPSIS

The hydrologic behavior of small watersheds is materially different from that of large watersheds Because of these differences, many analytical procedures and empirical formulae used successfully in estimating runoff from large watersheds have been found to be unsatisfactory when applied to the small watershed.

Attempts to supplement short-time runoff records with long-time rainfall records by use of: (1) direct relationships between rainfall intensity and rates of runoff; (2) rational method; (3) unit hydrograph; and (4) infiltration theory have not proved satisfactory when applied to the small watershed.

Probability studies integrate the frequency of occurrence of various watershed conditions with the frequency of occurrence of various rainfall intensities and patterns and are, therefore, especially useful in estimating peak rates of runoff from small watersheds that may be expected for various recurrence intervals.

The theory of extreme values, developed by Dr. E. J. Gumbel assumes a distribution of peak rates such that the coefficient of skew does not have to be calculated as is the case with the Hazen and Foster probability curves. For this reason the Gumbel curve is very well suited for use in probability studies of skewed distributions as those of rainfall and runoff data.

Probability studies based on short-term runoff records are reliable only if the rainfall for the short period is a good sample of a much longer period. Three normalcy tests should be applied to the rainfall and probability curves should be corrected when rainfall for the period of runoff record is found to be abnormal.

Probability studies have been completed for seven physiographic areas and the recommended peak rates of runoff for use in the design of conservation structures have been published in Technical Publications of the Soil Conservation Service. These recommended peak rates are summarized for five of the seven areas.

There is no fixed limit that can be ascribed to the maximum size of a small watershed, but it is probably safe to say that most areas smaller than 20 sq. mi. will have the characteristics of the small watershed while those larger than 100 sq. mi. can be classed as large watersheds. The area between these limits may be thought of as a transition zone.

Small agricultural watersheds present a special field for the hydrologist. Such factors as soil type, soil depth, size of watershed, shape of watershed, topography, vegetal cover, and antecedent soil moisture, have marked effects on amounts and peak rates of surface runoff from small watersheds that are discernible only to a much lesser degree on large watersheds. This is because the range of differences in any of these factors on a small watershed at the beginning of any storm is usually small. The large watershed, however, is composed of many small watersheds that may differ materially with each other in any or all of the above factors. Since the runoff from the large watershed is dependent on the runoffs from the smaller tributary watersheds the net effect of any factor on amounts and rates is comparatively small. For example, the high rates and amounts of runoff from one tributary row-crop area could be offset by the much lower values from another tributary where the vegetal cover was woods or grass.

Two other factors contribute to differences in runoff characteristics between large and small watersheds.

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In large watersheds, drainage channels are usually well defined and channel storage is appreciable, whereas in small watersheds this is seldom the case. Channel storage acts as a detention reservoir, tending to flatten the peaks of tributary stream flow and to increase the uniformity of the main-stream hydrograph. The other factor, closely allied to channel storage, is the increased time of concentration of the large watershed. Because of this, peak rates of runoff from large watersheds are not likely to be affected by short intense rainfall or by the time of occurrence of such intense rainfall with respect to the beginning of the storm period (storm pattern), both of which materially affect runoff from small watersheds.

As a consequence of these differences in runoff, many procedures and empirical formulae used successfully in estimating runoff from large watersheds have been found to be unsatisfactory when applied to the small agricultural watershed.

Prior to 1931, data on runoff from small agricultural watersheds were practically nonexistent. During the period, 1931-34, the Soil Conservation Service established eight conservation experiment stations where measurements were begun of the runoff from watersheds ranging in size from 1 to 35 acres. During the period, 1937-39, runoff measurements were started at three experimental watersheds located at Coshocton, Ohio, Hastings, Nebraska, and Waco, Texas. The watersheds at each of these locations ranged in size from one to approximately 5,000 acres and were representative of various types of vegetal cover and tillage practices. Since 1939, runoff measurements from additional watersheds have been made for various periods of time, for the most part from watersheds of from 1 to 300 acres.

PROCEDURES BASED ON RAINFALL VERSUS RUNOFF RELATIONSHIPS

Since all hydraulic structures to control surface runoff are so designed that their capacities may be expected to be exceeded once in some specified period, analysis of hydrologic data to be of maximum use should be expressed in terms of recurrence intervals. Because of the short periods of runoff records, early analysis of these data attempted to establish relationships between rainfall and runoff. This relationship would then have been applied to long-time Weather Bureau records to supplement the short runoff records. These attempts can be grouped under four headings; (1) direct relationship between amounts and intensity of rainfall with corresponding amounts and intensity of rainfall with corresponding amounts and rates of runoff; (2) rational method; (3) unit hydrograph, and (4) infiltration theory.

Direct Relationships - Maximum average rainfall intensities for the estimated time of concentration of a watershed are determined for each storm and plotted against the corresponding peak rates of runoff. This procedure results in a wide spread of the plotted points as is shown in Figure 1. Here, the peak rates of runoff from a 2,000-acre mixed cover watershed were plotted against 90-min. rainfall intensity for the 8-yr. period, 1939 to 1946. It will be noted that there were 11 occurrences of rainfall intensity between 0.70 and 0.90 in. per hr. with resulting peak rates of runoff varying from a few thousandths of an inch an hour to 0.18 in. per hr.

The reason for this wide variation in the value of peak rates for a given rainfall intensity is that factors affecting runoff, such as type and density of vegetal cover, initial soil moisture, and storm pattern differ materially from storm to storm. Figure 1 shows how this variation could be reduced by considering three runoff conditions. The maximum condition curve would indicate the relationship between rainfall intensity and peak rates of runoff at times when the moisture content of the soil at the time of the beginning of the storm was high; when the vegetal cover was poor or nonexistent, as after harvest or seeding; and when the storm pattern was such that the maximum intensity occurred near the end of the storm. Likewise, the minimum condition curve would represent the relationship when soil moisture was low; when the crop was making most rapid growth and of a type that afforded good cover; and when the high intensity rainfall occurred near the beginning of the storm.

For these reasons, it was found that estimates of runoff conditions for storms that had occurred prior to the period of runoff record could not be made with any degree of accuracy. Since the same difficulties were experienced when attempts were made to establish relationships between amounts of rainfall and amounts of resultant runoff, this method of analysis was found to be unsatisfactory.

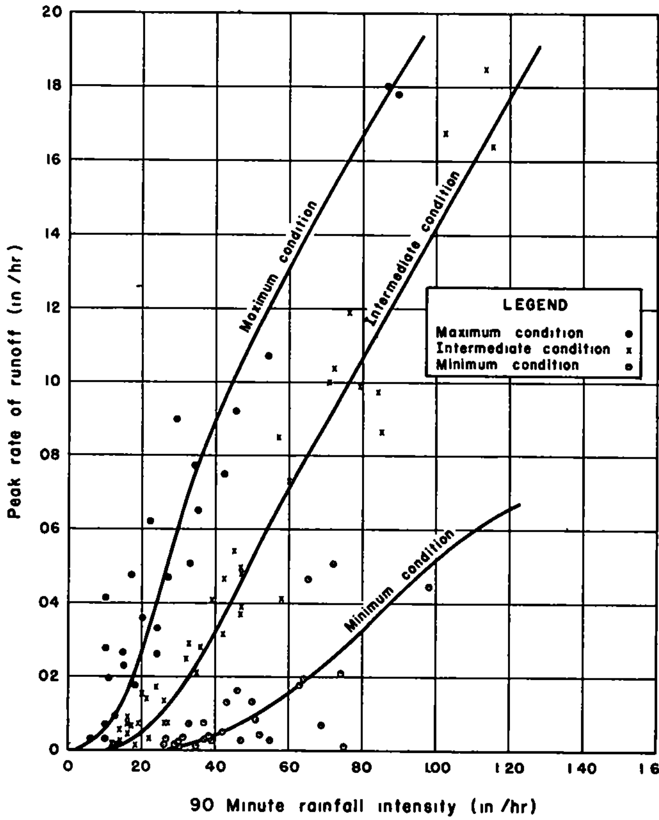


Figure 1. Preliminary Curves Showing Relationship Between Rainfall Intensity and Peak Rates of Runoff for W8

Soil moisture varies not only from day to day but also, for any one day, from one location in a watershed to another and vertically throughout the depth of the soil profile. Likewise, crops are rotated from year to year and from field to field and vary greatly as to times of planting, cultivating, and harvesting as well as to density of foliage and area protection afforded.

The Rational Method -The rational method assumes that the difference between maximum rainfall intensity for the time of concentration of a watershed and the resultant peak rate of runoff can be expressed as a constant. An examination of Figure 1, shows how far this comes from being true (14)[2]. For intensities of from 0.80 to 1.00 in. per hr. the values of C vary as much as 470 percent. If the values of C are limited to maximum runoff conditions, it then becomes necessary to determine the proportion of storms of given intensity that would occur when runoff conditions were maximum. Referring again to Figure 1, it will be noted that five storms occurred with maximum 90-min. intensities between 0.80 and 1.00 in. per hr., yet, only two of these occurred when runoff conditions were maximum. The difficulties in determining the proportion of storms that might be expected to result in maximum runoff have already been discussed in the preceding paragraph.

If the frequency of peak rates of runoff determined by using C for maximum runoff conditions is taken to be the same as that of the maximum rainfall intensity, then for any frequency the peak rates of runoff will be too high. For small structures, such as terrace outlets, culverts, and spillways for farm ponds where the design frequency is usually from 10 to 50 yr., the use of these high values of peak rates may result in structures that are greatly overdesigned. Suppose, for example, that it was desired to build a highway culvert that could be expected to be overtopped on an average of once in 10 yr. Suppose that the culvert was designed for a peak rate determined by substituting the once in 10-yr. rainfall intensity and C for maximum runoff conditions in the rational formula Q = CIA. If the rainfall intensity that occurred once in 10 years resulted in maximum runoff only once in 10 occurrences, then the culvert would have been overdesigned and could be expected to be overtopped on an average of only once in 100 years. If the structure had been the spillway for a large flood-control dam and due to an error in frequency it had been built for a capacity that could be expected to be exceeded once every 1,000 years instead of once in 500 years, the percent difference in Q would have been small in comparison with the difference between the once in 10-yr. and the once in 100-yr. values of our example. This is because in a frequency curve the rate of change in Q decreases rapidly as the recurrence interval increases. This is illustrated in Figure 2, which shows a typical frequency curve for a 176-acre cultivated watershed. In our culvert ex-

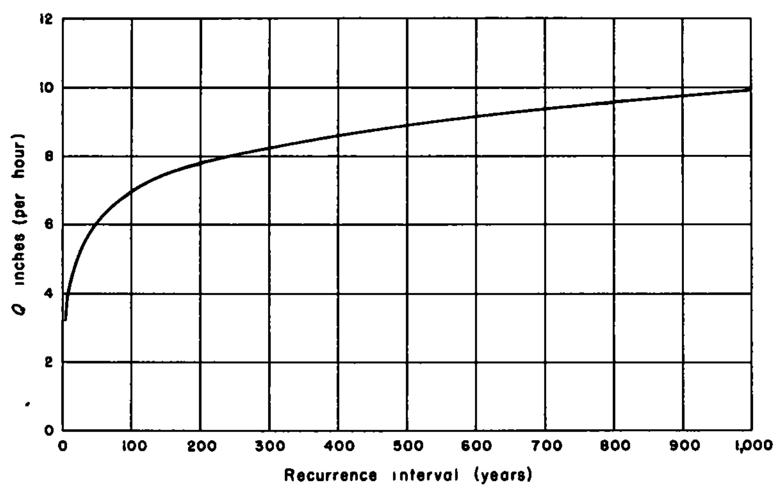


Figure 2. Frequency Curve for Watershed W-1 (1938-1948), Soil Conservation Service Blacklands Experimental Watershed, Waco, Texas

[2]Figures in parentheses refer to references listed at the end of the paper.

ample, the precent error introduced by the use of the once in 100-yr. Q instead of the one to be expected once in 10-yr. would have been

$$\frac{7.0 - 4.1}{4.1}$$

or approximately 71 percent. In the case of the flood-control spillway, the error would have been

$$\frac{9.9 - 8.9}{8.9}$$

or only 11 percent.

From the foregoing discussion, it should be concluded that the rational method will give accurate results only if the values of C are taken for maximum runoff conditions and modified to compensate for the difference between rainfall and runoff frequencies. It provides a logical framework upon which to base estimates of Q in areas where no runoff measurements are available but its use should be restricted to those who are thoroughly familiar with rainfall and runoff relationships within the physiographic region in which it is to be applied.

The Unit Hydrograph -The same difficulties that have been discussed in connection with the two preceding analytical procedures were encountered when attempts were made to apply the unit hydrograph in the analysis of runoff data from small agricultural watersheds.

For a given storm pattern of unit duration, the unit hydrograph theory assumes that the runoff characteristics of a watershed are constant and may be expressed in the form of a hydrograph of 1 in. of runoff. The following discussion will show that this assumption is not satisfactory when applied to a small watershed.

For the same unit storm, the excess rainfall or runoff can vary considerably (Fig. 1), depending on runoff conditions. When runoff conditions are maximum, the rainfall excess will also be maximum as will the depth and hence the velocity of both overland and channel[3] flow. When runoff conditions are minimum, the velocity of runoff will also be minimum. Other factors being equal, the time lag or time between the occurrence of the center of the unit storm period and the peak rate of runoff will be dependent on the velocity of the surface runoff. It would be expected, therefore, that the unit hydrograph for a storm occurring when runoff conditions were maximum would have a short time lag and a sharp peak. Conversely, the same storm occurring when runoff conditions were minimum would have a longer time lag and a flatter peak.

For runoff conditions other than maximum, the effect of vegetal cover is to decrease rainfall excess and hence reduce the velocity of both overland and channel flow. For any watershed condition, vegetal cover reduces the velocity of overland flow, due to the impediment offered by its stems. In small watersheds, the ratio of length of overland flow to the length of channel flow is large. A reduction in the velocity of overland flow, therefore, materially increases the total travel time of runoff and has an appreciable effect on the shape of the unit hydrograph. Since the ratio of overland flow to channel flow becomes smaller as the length of channel flow increases, the effect of a reduction in the velocity of overland flow on total travel time is probably negligible on a large watershed.

Because vegetal cover reduces the velocity of overland flow, watersheds that are planted to row crops in some years have different unit hydrographs than in other years when the crop may have been changed to close-growing vegetation, such as grass. Also, watersheds in which meadows are rotated from field to field have different unit hydrographs, depending on the position of the meadow fields with respect to the watershed boundaries.

If it were assumed that peak rates

[3]Channel flow for the purposes of this paper is defined as flow in that portion of a channel that is not cultivated.

of runoff were determined by developing a unit hydrograph for a storm period in which the intensity distribution was such as to produce maximum runoff and that cover, location of grassland, and soil moisture on the watershed were also optimum for maximum runoff, then it would still be necessary to determine the frequency of occurrence of such a set of conditions. As pointed out in the discussion of the rational method, the assumption that the frequency of the unit storms are the same as the frequency of maximum runoff results in considerable error when used in connection with hydraulic structures designed for a failure of once in 10 to 50 years.

Infiltration Theory - The infiltration theory assumes that the runoff from a watershed can be determined by the establishment of relationships between such factors as rainfall rate, transmission velocity, infiltration rate, percolation rate, and soil moisture. It is not the purpose of this paper to review the procedures that have been developed by various engineers and hydrologists but to point out that the application of the theory has been tested on only a few very small single-cover watersheds. It may well be that future development of this theory will produce a simple and useful tool for the analysis of runoff data. Much work, however, remains to be done before this can be accomplished, not only in testing the application of the theory to a much wider range of field conditions, but also in unifying and simplifying the present procedures.

PROBABILITY STUDIES

The use of probability studies to determine peak rates of runoff was explored because it was felt that this type of analysis should integrate the frequency of occurrence of various watershed conditions with the frequency of occurrence of various rainfall intensities and patterns.

Classes of Probability Curves - In general, probability curves used in connection with hydrologic data may be divided into two classes. The first class considers all occurrences above a predetermined base. The probable frequency of occurrence is computed in terms of the average number of times that a given value will be equaled or exceeded in some interval of time. Thus, a frequency of occurrence of once in 5 years would mean that a designated value could be expected to be equaled or exceeded by an average of one occurrence every 5 years.

In the second class, only the maximum value per unit of time is considered. The frequency of occurrence is computed in terms of the average number of time units during which a given value may be expected to be equaled or exceeded in some time period. Thus, when one year is taken as the time unit, a frequency of occurrence of once in five years would mean that there would be an average of one year every five years during which a designated value could be expected to be equaled or exceeded.

It has been found that peak rates of runoff determined by the two classes of probability curves are practically identical for recurrence intervals of 10 years or more (2). Since hydraulic structures to control runoff from small agricultural watersheds are designed for frequencies of failure of not more than once in 10 years, and since the work involved in computing the probability curve is much less for the second class curve, probability studies of peak rates of runoff have been limited for the most part to maximum annual values. Probability curves as used in the balance of this paper refer, therefore, to curves of this class.

Hazen and Foster Probability Curves - Foster's Types I and III probability curves developed by H. A. Foster (4) in 1924 and the Hazen curve developed by Allen Hazen (12) were probably the best known and most widely used probability curves prior to 1941. These curves are similar in that they are all fitted curves based on a normal distribution of peak rates. Since rainfall and runoff phenomena do not occur as normal distributions but are considerably skewed, these curves are then corrected in accordance with coefficients of skew computed from the original data.

In 1936, J. J. Slade, Jr. (23), tested the significance of these skew coefficients and showed conclusively "that skewness is never a truly significant characteristic when the sample from which it is computed has less than about 140 items . . . and that it is quite meaningless to use this measure when there are 50 or fewer items." Since the length of record for most small agricultural watersheds is 10 years or less, it is obvious that the Foster or Hazen curves could be of little use in making probability studies of the peak rates of runoff that might be expected from these areas.

Gumbel Probability Curves-During the period 1941-45, E. J. Gumbel (5 to 10) published several papers in the various technical journals in which he developed a new concept of probability as applied to rainfall and runoff data. He computed the frequency for the highest and lowest peak rates in a sample of N years as those of the modal or most frequent values of an infinite number of samples of N years. These frequencies of the highest and lowest values he expressed in terms of N. Frequencies of intermediate peak rates could then be obtained by prorating the difference between the frequencies of the highest and lowest values.

In 1943, R. W. Powell (21) developed

TABLE 1

DEPARTURE FROM MEAN *Q* FOR MIXED COVER WATERSHEDS

Watershed Area in Acres	Mean *Q* in Cubic Feet per Second[a]	Area of Application: Upper Miss Valley Loessial Areas	Central Great Plains of Kansas and Nebraska[b]	North Appalachian Region	High Plains of Colorado and New Mexico[c]	Coastal Plains of N.J., Del and Md.[d]
		Percent of Area in Grass				
		50	20	50-75	50	25-50
		Departure from Mean *Q* in Percent of Mean				
10	37	- 16	+ 8	- 40	+ 14	+ 35
20	61	- 15	+ 3	- 31	+ 16	+ 30
30	83	- 16	- 1	- 25	+ 16	+ 25
40	102	- 16	- 3	- 21	+ 16	+ 24
50	121	- 16	- 6	- 17	+ 16	+ 22
100	198	- 14	-10	- 14	+ 17	+ 21
500	586	- 10	-14	- 25	+ 26	+ 23
1,000	926	- 8	-15	- 31	+ 28	+ 26
1,500	1,136	- 1	- 8	- 29	+ 38	
2,000	1,370	- 1	- 7	- 31	+ 39	
2,500	1,566	+ 1	- 8	- 33	+ 40	
3,000	1,750	+ 3	- 9	- 35	+ 41	
3,500	1,918	+ 3	- 8	- 36	+ 41	
4,000	2,088	+ 3	- 8	- 37	+ 41	
4,500	2,255	+ 4	- 8	- 37	+ 41	
5,000	2,390	+ 5	-10	- 37	+ 42	

[a]All values are for a recurrence interval of 10 years.

[b]For watersheds with a meander factor of 1 00

[c]Average of recommended values for 4 soil and slope conditions

[d]Average of recommended values for 3 soil and slope conditions

a special graph paper on which peak rates of runoff plotted in accordance with Gumbel's frequencies would approach a straight line.

The form of distribution of peak rates assumed by Gumbel is such that the coefficient of skew does not have to be calculated, as is the case with the Hazen and Foster curves, but is implied as a constant of 1.139. For this reason, his probability curve is very well suited for use in probability studies of skewed distributions as those of rainfall and runoff data.

To compute a probability curve of peak rates of runoff by the Gumbel method, maximum annual peak rates are arranged in ascending order of magnitude. Frequencies of the highest and lowest values are determined from Tables 1 and 2 (9, 10, 18) and the frequencies of intermediate peaks by prorating between these extreme values. Peak rates are then plotted against corresponding frequencies on special probability paper. For each plotted point a corresponding value is determined on the linear or "reduced variate" scale. Using these values as X and the peak rates as Y, a least squares straight line is then computed. Figure 3 shows an example of such a curve.

A simplification of this procedure was developed by the author (18) that involves only the calculation of mean Y, ($\bar{Y}$), and the coefficient of variation, (C_v). A series of curves was developed to express the relationship between $Y/\bar{Y}$ and C_v for various values of N and for various recurrence intervals. Knowing N and C_v, values of $Y/\bar{Y}$ may be selected from these curves for desired recurrence intervals. These values multiplied by $\bar{Y}$ give the peak rate that may be expected to be équaled or exceeded for each recurrence interval.

USE OF GUMBEL PROBABILITY CURVE IN ANALYSIS OF RUNOFF DATA

A probability curve is reliable only insofar as it is a representative sample of what has taken place in the past and of what may be expected to take place in the future. If we were dealing with a long runoff record of say 50 or 75 years from a watershed in which the physiographic features, land use, and tillage practices had been fairly constant, it would probably be safe to say that our sample was representative of past runoff conditions. And, if there was no reason to suspect that any of these factors would be materially changed, it would be reasonable to assume that the sample also was representative of future runoff conditions. If, however, our runoff record was for only 8 or 10 years, it is obvious that no such assumptions could be made with any degree of safety. Since most of the records of runoff from small agricultural watersheds are included in this latter range, it is evident that some test of their normalcy must be made before they can be used to estimate future runoff values.

In formulating a test of normalcy for short runoff records, two assumptions were made: (1) that if the rainfall for the period of runoff record is representative of that for a much longer period, then the runoff sample is also representative of that period; (2) that if there is no reason to suspect that the physiographic features, land use, or tillage practices of the watershed will be materially changed, then the runoff record is also a representative sample of what might be expected in the future.

The three tests of rainfall selected were: (1) comparisons of monthly and annual amounts of rainfall; (2) comparisons of maximum average rainfall intensities for various time intervals; and (3) comparisons of monthly and annual number of excessive storms. These rainfall factors were selected for test because they not only have a material effect on peak runoff rates but also are readily available from long-term Weather Bureau records. It is recognized that other factors, such as rainfall pattern, soil moisture, and infiltration rate, also affect runoff. However, until such time as long-term records of these additional factors become available, normalcy tests must necessarily be limited to the three tests more fully described as follows:

Rainfall Amounts - (19) Comparisons of monthly and annual rainfall can be made by computing probability curves for these values for the period of runoff record and comparing values for like recurrence intervals with those derived from long-term Weather Bureau records. Records of monthly and annual record may be compared to similar curves computed from long-term Weather Bureau records.

Prior to 1935, rainfall intensity data from first-order Weather Bureau Stations were included in the Annual Report of the Weather Bureau and beginning in 1935 in the Meteorological Yearbook. Prior to 1935, these data were published as accumulative amounts for each

TABLE 2

RECOMMENDED Q FOR CULTIVATED AND PASTURE AREAS EXPRESSED AS A PERCENT OF Q FOR MIXED COVER

	Area of Application				
	Upper Miss Valley Loessial Areas	Central Great Plains of Kansas and Nebraska	North Appalachian Region	High Plains of Colorado and New Mexico[a]	Coastal Plains of N J , Del. and Md [b]
Q(Cultivated Area) / Q(Mixed Cover Area)[c] Percent	130	116	170	113	
Range in Watershed Size, Acres[d]	2-100	2-400	5-10,000	2-250	
Q(Pasture Area) / Q(Mixed Cover Area)[c] Percent	65	72	60	82	51
Range in Watershed Size, Acres[d]	2-100	2-200	5-10,000	2-5,000	10-200

[a]Average of recommended values for 4 soil and slope conditions

[b]Average of recommended values for 3 soil and slope conditions

[c]All values are for a recurrence interval of 10 years

[d]Above ratios applicable only for indicated range in watershed size

rainfall from the beginning of record to 1930 may be found for all stations in "Summary of the Climatological Data for the United States, by Sections," United States Weather Bureau, Bulletin W. Similar data for the period subsequent to 1930 are published in the current year books of "Climatological Data."

Rainfall Intensity -(19) A comparison of maximum rainfall intensities for various time intervals can be made in a manner similar to that described for rainfall amounts. Probability curves based on highest average intensities for each time period for each year of runoff 5 min. of excessive rainfall. Since changes in rainfall intensity did not necessarily coincide with these 5-min. division points, maximum intensities computed for various time intervals from Weather Bureau tabulations for this period are usually less than the true maximum. Yarnell (24) found this difference to be 8 to 10 percent of the computed figure for 5-min. periods and 4 to 5 percent for periods of one hour.

Number of Excessive Storms - (19) As originally defined by the Weather Bureau, an excessive storm is one in which the amount of rain that fell during any 5-min. period was equal to or greater than 0.25 in. or in which the amount that fell during any period in excess of 5 min. was equal to or greater than 0.25 in. plus 0.01 in. for each minute in excess of 5. In 1935, the amounts defined by this definition were increased for the Southern States, including North Carolina, South Carolina, Georgia, Florida, Alabama, Mississippi, Tennessee, Arkansas, Louisiana, Texas, and Oklahoma, and San Juan, Puerto Rico. Under the new definition a storm was not considered excessive unless the amount of rain in inches that fell during any time period of five or more minutes was

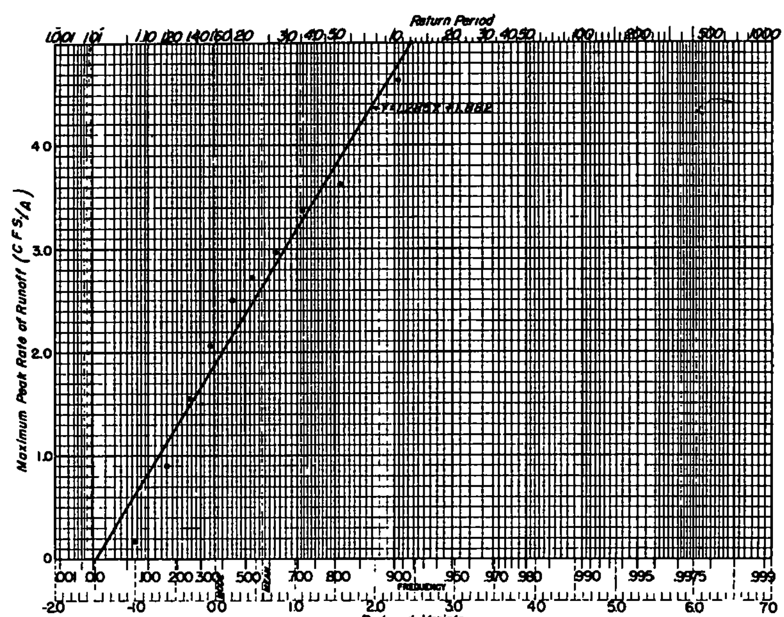


Figure 3. Frequency of Maximum Peak Rates of Runoff from Watershed D-3 at Conservation Experiment Station, Bethany, Mo., 1933-1942

equal to or greater than twice the time period in minutes expressed in hundredths of an inch plus 0.30 in. Care must, therefore, be exercised in making comparisons of excessive rainfall in these States to be sure that all storms are classified in accordance with the same definition.

Average monthly and annual numbers of excessive storms can be obtained from Yarnell's (24) 30-yr. totals and compared with similar averages for the period of runoff record. Since Yarnell's totals were based on Weather Bureau intensities published prior to 1935, and since these intensities were less than the true maximums, it follows that the number of excessive storms based on these lesser values must also be less than the actual number. As a result of comparisons made from experiment station records at eight different locations (19), it was concluded that Yarnell's 30-yr. totals must be increased by 16 percent to approximate the actual total.

Correction for Abnormal Rainfall.-If the rainfall for the period of runoff record is found to be materially different from that for a long-time period, then the peak rates computed from a probability curve should be adjusted to what they would have been had the runoff record been a good sample of past conditions (20). A methodology for making such a correction was developed by the author for an 8-yr. period of record on two watersheds located at the Central Great Plains Experimental Watershed near Hastings, Nebraska. A relationship was established between the three rainfall factors tested and the peak rates as computed by a probability curve. It was found that the amount of annual rainfall multiplied by the annual number of excessive storms determined the frequency of maximum runoff conditions, whereas the intensity of the rainfall determined the magnitude of the runoff peak for any runoff condition. Although much work remains to be done in testing this method for other physiographic and meteorologic conditions, it is felt that this method or some modification can be perfected for adjusting probability curves for abnormal rainfall.

The runoff records of small experiment station watersheds can usually be supplemented by U. S. Geological Survey records of larger watersheds with physiographic features and land use similar to those at the experiment station. To eliminate, insofar as possible, all factors other than size of watershed that might account for differences in peak rates of runoff, probability curves for these larger watersheds should be computed for the same period of record as that of the experiment station. These probability curves should then be corrected to compensate for differences between rainfall factors that existed at the large watersheds during the period of record and those previously determined for the experiment station from long-time Weather

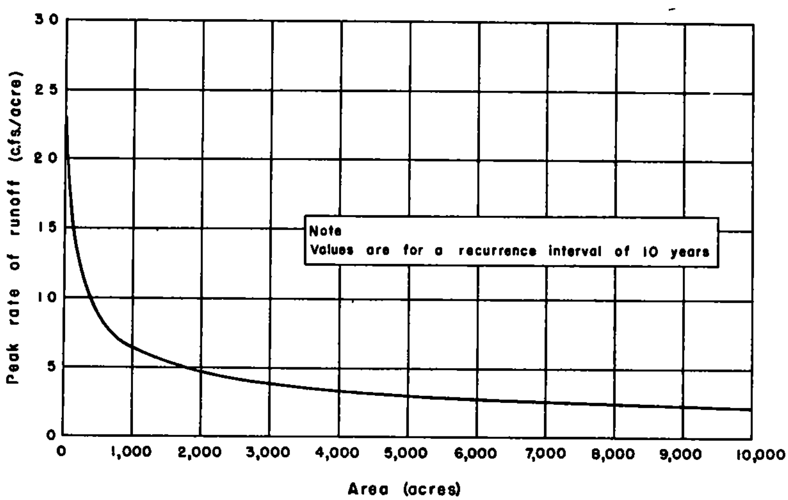


Figure 4. Relationship Between Peak Rates of Runoff and Area for Mixed Cover Watersheds in the North Appalachian Region

Area of Watershed Versus Peak Rate of Runoff - For the same recurrence interval, the peak rate of runoff per unit area decreases as the area of the watershed increases. Figure 4 shows that this decrease is very rapid for watersheds of less than 2,000 acres. The next step then in the analysis of the runoff data from the watersheds at any experiment station is to determine the relationship between the peak rates for any recurrence interval and the size of watershed.

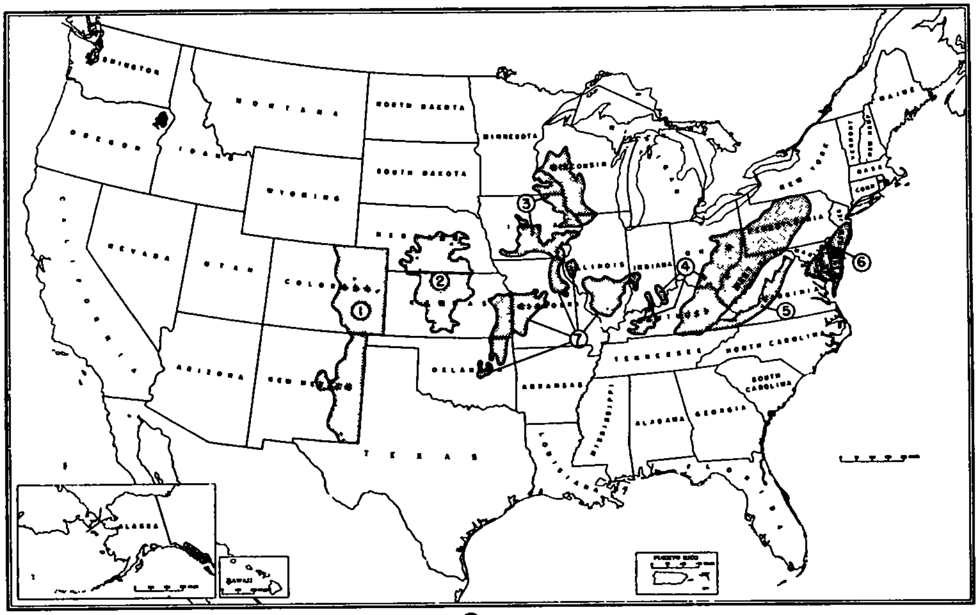
Bureau records. In making these corrections the same procedures may be followed as those developed for correcting the probability curves of small experiment station watersheds.

The corrected peak rates for a once-in-10-yr. recurrence interval can now be plotted against the corresponding size of watershed on log-log paper. As the corrected probability curves for all watersheds are now representative of runoff as it would have occurred if each watershed had been subjected to the same rainfall (that determined for the experiment station from long-term Weather Bureau records) and as the physiographic features and land use for all watersheds are similar, any difference in peak rates can be ascribed to the effect of watershed size. The relationship between peak rates and watershed size can, therefore, be expressed by computing a statistical curve from the coordinates of the plotted points. This relationship is assumed constant for all recurrence intervals and when applied to the probability curves of the experiment station watersheds gives the peak rate that may be expected from any size watershed for any desired recurrence interval.

Area of Application -One other step remains to be taken in our analysis; namely, that of determining the area of application for the computed peak rates of runoff. This involves the outlining of the area or areas in which physiographic features such as parent geologic formation, principal soil types, topography, and land use are similar to those of the experimental watersheds.

This last step was made possible when the Soil Conservation Service in 1943 printed a map of the United States showing "Basic Land Resource Areas." This map was developed primarily on physiographic features determined by conservation surveys and divides the country into nine physiographic regions, 68 major subdivisions, and numerous minor subdivisions. Revisions are made from time to time as additional surveys are completed. Detailed descriptions of each subdivision have been prepared and may be used in conjuction with the map to select areas where physiographic features, insofar as they affect runoff, are similar to those of the experimental watersheds.

Although physiographic and cultural features of the area selected generally will be similar to those of the experimental watersheds, small local areas can usually be found within the area of application where these features are materially different. No attempt



(1) High Plains, (2) Central Great Plains, (3) Upper Mississippi Valley Loessial Areas, (4) North Appalachian Region, (5) Ridges and Valleys of Virginia, (6) Coastal Plains (7) Claypan Prairies

Figure 5. Areas of Application for Recommended Peak Rates of Runoff

was made to delineate all of these local exceptions and it is left to the judgment of the field technician as to whether or not recommended peak rates should be increased or decreased because of these differences.

SUMMARY OF RUNOFF STUDIES COMPLETED TO DATE

Analysis of runoff data has been completed for seven physiographic areas and the recommended peak rates of runoff for use in the design of conservation structures have been published in Technical Publications of the Soil Conservation Service (Fig. 5), (1, 3, 11, 13, 16, 17, and 22). The procedures used in these analyses in general followed those outlined in the preceding pages of this paper (15). In all cases, it was found that the three rainfall factors experienced during the period of runoff record was equal to or greater than those determined from long-term Weather Bureau records. No corrections were applied to compensate for rainfall differences as the methodology for accomplishing this had not yet been developed. It is hoped that later reports will include such corrections.

It should be pointed out that all of these publications are preliminary reports that will be revised as more data become available. Also, that all of the reports are not based on the same completeness of data. The peak rates for the High Plains of Colorado and New Mexico; the Coastal Plains of New Jersey, Delaware, and Maryland; the Ridges and Valleys of Virginia, and the Claypan Prairies were determined primarily from small watersheds of from 2 to 300 acres. Additional data on peak rates from watersheds having a greater range in size are needed in these areas to more accurately establish the peak rate versus area relationship.

In the Ridges and Valleys of Virginia, the small experimental watersheds are underlain by shattered limestone and result in extremely low rates of runoff. It is felt that a large proportion of the water absorbed by the limestone on these small watersheds may appear as base flow runoff on larger areas. To test this possibility and to establish a more reliable peak rate versus area relationship, three additional watersheds ranging in size from 500 to 6,000 acres have been located on Bell Creek near Staunton, Va. Data from these watersheds are being collected as a cooperative project of the Soil Conservation Service and the U. S. Geological Survey.

In Table 1, the peak rates for a mixed-cover watershed and a recurrence interval of 10 years are expressed as percent departures from the mean for all physiographic areas shown on Figure 5 with the exception of the Ridges and Valleys of Virginia and the Claypan Prairies. The Ridges and Valleys of Virginia was not included because it was felt that insufficient data existed to determine accurately the effect of the underlying limestone on runoff peaks. Peak rates for the Claypan Prairies were determined only for recurrence intervals of 25 and 50 years. As the land use for the watershed is essentially the same for each area (mixed cover), the departures from the mean shown in the table can be ascribed to differences in rainfall and physiographic factors.

For the same five years, Table 2 shows the peak rate for a cultivated and pasture watershed for a 10-yr. recurrence interval expressed as a percentage of that for a mixed-cover watershed. Since rainfall and physiographic factors were the same for all three types of land use at any one area, the indicated increase or decrease in peak rates for that area can be ascribed to the effect of land use. The reduction in peak rates that may be affected by a change in land use is dependent to some extent on existing rainfall and physiographic factors. This is evidenced by the difference in the percentages shown in Table 2 for different areas.

CONCLUSIONS

It is hoped that this paper will help direct the attention of the engineer and hydrologist to the differences in the hydrologic behavior of large watersheds as compared to that of the small agricultural watershed.

It is felt that a recognition of these differences will lead to the development and increased use of such analytical procedures as the probability study, as a means of more accurately integrating the effects of the many factors that affect surface runoff.

It is felt that the use of such improved analytical procedures will make possible more accurate and economical designs of small hydraulic structures.

And, finally, it is hoped that greater cooperative efforts among interested Federal and State agencies will relieve the present sparsity of runoff data from small agricultural watersheds.

REFERENCES

1. Allis, John A., "Rates of Runoff for the Design of Conservation Structures in the Central Great Plains of Nebraska and Kansas," Technical Publication 69, Soil Conservation Service, Aug. 1948.
2. Cross, William P., "Floods in Ohio, Magnitude and Frequency," Bulletin No. 7, Ohio Water Resources Board, Columbus, Ohio, October 1946.
3. Edminster, T. W., and Lillard, J. H., "Rates of Runoff in the Ridges and Valleys of Virginia," Technical Publication 67, Soil Conservation Service, May 1948.
4. Foster, H. A., "Theoretical Frequency Curves," *Transactions*, American Society of Civil Engineers, Vol. 87, pp. 142-203, 1924.
5. Gumbel, E. J., "The Return of Flood Flows," *Annals of Mathematical Statistics*, Vol. 12, Baltimore, 1941.
6. Gumbel, E. J., "Probability Interpretation of the Observed Return Periods of Floods," *Transactions*, American Geophysical Union, Part 3, pp. 836-849, 1941.
7. Gumbel, E. J., "Statistical Control Curves for Flood Discharges," *Transactions*, American Geophysical Union, Part 2, pp. 489-500, 1942.
8. Gumbel, E. J., "On the Plotting of Flood Discharges," *Transactions*, American Geophysical Union, pp. 699-716, 1943.
9. Gumbel, E. J., "Floods Estimated by Probability Methods," *Engineering News Record*, Vol. 134, pp. 833-837, June 14, 1945.
10. Gumbel, E. J., "Simplified Plotting of Statistical Observations," *Transactions*, American Geophysical Union, Part 1, Vol. 26, pp. 69-82, August 1945.
11. Harrold, L. L., "Hydrologic Design of Farm Ponds and Rates of Runoff for Design of Conservation Structures in the North Appalachian Region," Technical Publication 64, Soil Conservation Service, December 1947.
12. Hazen, Allen, "Flood Flows," John Wiley and Sons, Inc., New York, 1930.
13. Hobbs, Harold W., "Rates of Runoff in the Coastal Plains of New Jersey, Delaware, and Maryland," Technical Publication 60, July 1946, Soil Conservation Service.
14. Krimgold, D. B., "On the Hydrology of Culverts," *Proceedings*, Highway Research Board, Vol. 26, pp. 214-226, 1946.
15. Krimgold, D. B., "Rates of Runoff from Small Drainage Basins," *Agricultural Engineering*, pp. 25-28, Jaunary 1947.
16. Krimgold, D. B., and Minshall, "Hydrologic Design of Farm Ponds and Rates of Runoff for Design of Conservation Structures in the Claypan Prairies, "Technical Publication 56, Soil Conservation Service, May 1945.
17. Minshall, N. E., "Rates of Runoff for the Design of Conservation Structures in the Upper Mississippi Valley Upland Loessial Areas," Technical Publication 73, Soil Conservation Service, January 1949.

18. Potter, W. D., "Simplification of the Gumbel Method for Computing Probability Curves," Technical Publication 78, Soil Conservation Service, May 1949.
19. Potter, W. D., "Normalcy Tests of Precipitation and Frequency Studies of Runoff on Small Watersheds," Technical Bulletin No. 985, Soil Conservation Service, June 1949.
20. Potter, W. D., "Effect of Rainfall Factors on Magnitude and Frequency of Peak Rates of Surface Runoff," *Transactions*, American Geophysical Union, Vol. 30, No. 5, pp. 735-751, October 1949.
21. Powell, Ralph W., "A Simple Method of Estimating Flood Frequencies," *Civil Engineering*, pp. 105-6, February 1943.
22. Rouse, Hayden K., "Rates of Runoff for the Design of Conservation Structures in the High Plains of Colorado and New Mexico," Technical Publication 66, Soil Conservation Service, April 1948.
23. Slade, J. J., Jr., "The Reliability of Statistical Methods in the Determination of Flood Frequencies," Floods in the United States, Magnitude and Frequency, Water-Supply Paper 771, U. S. Geological Survey, pp. 421-432, 1936.
24. Yarnell, David L., "Rainfall Intensity-Frequency Data," Miscellaneous Publication No. 204, U. S. Department of Agriculture, August 1935.