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PAPERS

THE UNIT HYDROGRAPH PRINCIPLE APPLIED TO SMALL WATER-SHEDS

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Synopsis

The unit hydrograph principle was first presented in 1932 by Leroy K. Sherman,[2] M. Am. Soc. C. E. Since then it has been developed into a usable method for surface run-off analysis. The most notable advance was the introduction of the distribution graph and pluviagraph in 1934 by Merrill M. Bernard,[3] M. Am. Soc. C. E.

Although the method has become quite generally accepted, the engineers and hydrologists who have made special studies in this field have suggested that further research be conducted to determine, more definitely, the limitations in the application of the unit hydrograph. One of the unsettled issues is the question of its usefulness on small streams.

It is hoped that the present investigation will provide a better understanding of the natural phenomena involved in the production of a unit hydrograph. The paper demonstrates that the unit hydrograph principle may be applied to small water-sheds, and that the distribution graphs and pluviagraphs are valuable tools for the analysis of surface run-off. The study further indicates that the unit hydrograph method is one of the best practical devices for predicting flood flows.

Introduction

[illegible] investigation described in this paper was conducted to determine [illegible] the unit hydrograph principle is applicable to small streams and, if so, [illegible] usefulness as a tool in the analysis of surface run-off.

[illegible] are invited for immediate publication; to insure publication, the last [illegible] 1940.

[1] [illegible] Ann Arbor, Mich. (The study was undertaken while the [illegible] Forest Experiment Station.)

[2] [illegible] the Unit Hydrograph Method," by L. K. Sherman, *Engineering* [illegible]

[3] [illegible] Flow," by Merrill M. Bernard, *Proceedings*, Am. Soc. C. E. [illegible]

The study is based on continuous records of run-off and rainfall taken from twenty-two small water-sheds by the Appalachian Forest Experiment Station.[4] The water-sheds lie in the high rainfall belt of the Southern Appalachians. They vary in area from 4.24 acres to 1 876.7 acres, and in cover type, from old-growth forest to complete denudation.

The first part of the investigation was devoted to the selection of unit hydrographs and the preparation of distribution graphs on the twenty-two streams. The method of selecting the unit hydrographs from the discharge records of the water-sheds is presented, with a general consideration of the principles involved in the selection. The various factors to be considered in the separation of surface run-off from ground-water flow are discussed, and a method of procedure for making this separation on hydrographs from small streams is suggested. Distribution graphs were derived from each of the unit hydrographs, and the graphs from each stream were superimposed upon one another to permit the selection of a composite distribution graph for the stream. A detailed study was made of the rainfall that produced the unit hydrographs for the purpose of determining more definitely the conditions that govern the formation of such graphs.

The second part of the work consists of some applications of the distribution graphs for the purpose of further testing the adequacy of the theory, and to indicate the value of the unit hydrograph as a tool in the analysis of run-off phenomena. The composite distribution graphs were analyzed for the purpose of disclosing any correlations between the shapes of the distribution graphs, especially the peak percentages and the widths of bases, with the physical characteristics of the water-sheds. The distribution graphs of three of the streams were then utilized in the construction of pluviagraphs for comparison with actual hydrographs of run-off. The pluviagraph studies led logically to a consideration of surface run-off coefficients. Finally, a method is submitted for the use of the unit hydrograph principle as a practical method of predicting surface run-off.

Basic Data

The investigation is based on rainfall and discharge records collected continuously for periods varying from two to three years. Fifteen of the twenty-two water-sheds are forested, two are void of all vegetation, and the remainder have varying types of vegetative cover. They are situated in three separate experimental areas, the streams of each group being designated by the name of the experimental area together with their number within the area.

Locations of the Installations.—The first group of seven installations is in or near the Bent Creek Experimental Forest which is about 11 miles south of Asheville, N. C. Four of these are forested, and one is a mixture of forest and adjoining agricultural land, whereas the other two are over-grazed pasture and abandoned farm land. The location of Bent Creek and the other two experimental areas is shown in Fig. 1. Descriptive data concerning all individual water-sheds are given in Table 1, the vegetal cover in each case being as follows:

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[4] Appalachian Forest Experiment Station, U. S. Forest Service, Department of Agriculture, Asheville, N. C. (see "Engineering Aspects of the Influence of Forests on Mountain Streams," by Richard A. [illegible], Assoc. M. Am. Soc. C. E., *Civil Engineering*, August, 1939, p. 487).

Stream No.	Description
Bent Creek 1	Forest; oak-chestnut type; a high percentage of old-growth timber; the forested areas were heavily settled and farmed prior to 1900; no large-scale lumbering operations have been undertaken on this area except for cutting and clearing on the individual farms. Scattered areas were burned from time to time, prior to 1926.
Bent Creek 2	Forest; two-thirds of the standing trees, including all non-commercial trees, were cut in the winter of 1930–1931; heavy skidding operations at that time greatly depleted the litter layer.
Bent Creek 3	Over-grazed pasture and abandoned old fields; sheet erosion well advanced.
Bent Creek 4	Approximately 50% forested, and 50% cultivated land and abandoned old fields.
Bent Creek 5 and 6	Forest; second growth of the oak-chestnut type.
Bent Creek 8	Abandoned old fields; eroded.
Copper Basin 1 and 2	Forest of the oak-chestnut type; this region has a relatively thin layer of soil, underlain by shales and sandstone.
Copper Basin 3 and 4	Grass-land; sheet erosion and some gullying in progress.
Copper Basin 5 and 6	No cover; top-soil completely removed and terrain deeply gullied.
Coweeta 1 to 9	The primary vegetation of all the Coweeta watersheds is second-growth forest of the oak-chestnut type, with scattered areas (less than 25% of the whole) of old-growth timber. The entire area was lumbered commercially as long ago as 1919.

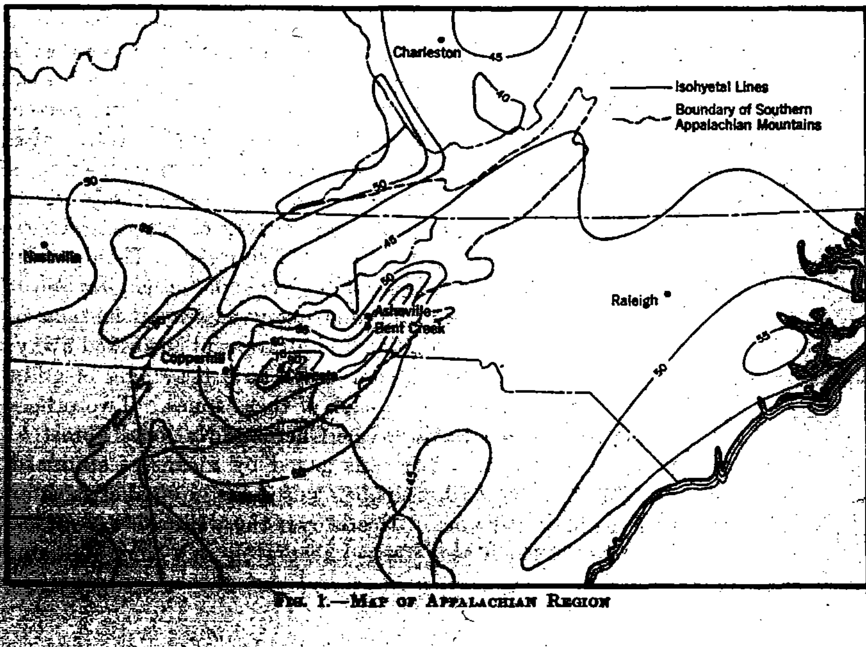

FIG. 1.—MAP OF APPALACHIAN REGION

TABLE 1.—DESCRIPTION OF WATER-SHEDS IN THE APPALACHIAN REGION (FIGURE 1)

Stream No.	Area, in acres	Discharge, in Cubic Feet per Second per Square Mile		Elevation above Sea Level (Atlantic Datum), in Feet	
		Maximum	Minimum	Weir	Maximum of water-shed
	(1)	(2)	(3)	(4)	(5)
(a) Bent Creek Water-Sheds					
1	48.6	41.5	0.075	2 080*	2 450
2	17.3	84.3	0.055	2 020*	2 680
3	10.78	335.0	0.125	2 050*	2 150
4	773.95	38.2	0.189	....†	....
5	90.4	61.1	0.06	2 350*	3 100
6	71.5	68.3	0.23	2 400*	3 100
8	16.25	188.3	....	2 160*	2 220
(b) Coweeta Water-Sheds					
1	38.77	41.60	0.35	2 300*	3 250
2	30.78	55.55	0.11	2 350*	3 314
4	10.18	83.03	0.29	2 750*	3 000
5	4.24	88.99	0.81	2 300*	2 500
(b) Coweeta Water-Sheds (*continued*)					
6	21.88	66.28	0.25	2 300*	2 650
7	145.45	37.12	0.71	2 400*	3 491
8	1 876.7	57.76	0.75	2 300‡	5 097
9	1 787.9	67.58	0.72	2 250‡	4 887
10	212.3	36.57	0.87	2 450§	3 600
(c) Copper Basin Water-Sheds					
1	19.0	144.4	0.005	1 632*	1 947
2	88.7	164.0	0.14	1 635*	2 492
3	6.0	832.0	0.00	1 528*	1 645
4	6.7	1 094.7	0.16	1 554*	1 698
5	15.6	1 263.2	0.04	1 695‖	1 821
6	4.7	1 433.9	0.00	1 719*	1 817

* Right-angle, V-notch. † 5-ft trapezoid. ‡ 12-ft trapezoid. § 120° V-notch. ‖ 3.5-ft trapezoid.

Coweeta Experimental Forest (see Table 1(*b*)) is about 15 miles south of Franklin, N. C., and 6 miles north of the Georgia State line. The two larger water-sheds of this group (Stream No. 8 and Stream No. 9) include the entire experimental area. All of the others lie within the boundaries of these two. The entire area is covered with second-growth forest.

The remaining six water-sheds are in the southeast corner of Tennessee, within or near the area known as the Copper Basin (see Table 1(*c*)). This region derives its name from the copper-mining and smelting activities in Copperhill and Ducktown, Tenn., about which the area centers. The Copper Basin consists of approximately 8 sq miles of completely denuded land surrounded by a zone of grass-land the area of which is 22 sq miles. The denudation was started by cutting the larger trees, but the principal damaging factor was the sulfur fumes resulting from the original open roast-heap method of smelting. The denuded area is deeply gullied and all top-soil is washed away. The grass-land has suffered from sheet erosion and is in early stages of gully formation. Two water-sheds were gaged in each of these zones. Two others are located just west of the Copper Basin in the Cherokee National Forest.

Methods of Measurement.—Stream flow was gaged by means of standard sharp-crested weirs, right-angle V-notch weirs being used on the smaller streams and trapezoidal weirs on the larger ones. Heads over the weirs were recorded continuously by float gages. Each weir was set accurately in a concrete dam, which was extended to rock bottom in all cases. Stilling basins behind all the weirs were more than adequate to satisfy requirements for proper contraction of the jet and for reducing the velocity of approach to a negligible quantity. The type of weir used in each case is indicated by footnotes in Table 1.

Rainfall was measured by means of standard Weather Bureau rain gages, with a smaller number of recording gages. There were twenty-seven standard rain gages and five recording gages on the Bent Creek water-sheds, twenty-three standard and six recording gages on the Copper Basin water-sheds, and sixty-three standard and six recording gages on the Coweeta water-sheds. Considering the total area of all the water-sheds, the average area per rain gage was thirty-seven acres. The gages were arranged to give the best possible sample, taking into account aerial distribution, elevation, and aspect. The average precipitation was computed by the Thiessen method.[5]

The Preparation of Unit Hydrographs and Distribution Graphs

The principle underlying the unit hydrograph method may be stated briefly as follows:[6] For any water-shed, the surface run-off resulting from a unit storm is distributed, according to time, in a characteristic manner, and this distribution is independent of the intensity of the rainfall.

A unit storm is a rain of an intensity sufficient to produce surface run-off which occurs within the period of rise of the hydrograph. The period of rise is the time from the beginning of surface run-off to the occurrence of peak discharge.

Definitions.—Since the terminology that is applied to this phase of hydrology is not entirely uniform, the following terms are defined according to their usage in this paper.

Surface Run-Off.—That portion of the precipitation which reaches the stream by means of overland flow.

Period of Surface Run-Off.—The time intervening between the appearance of surface run-off at the gaging station and the time when all surface run-off has passed the station. The period of surface run-off is equal to the period of overland flow plus the time required for the remaining channel storage, derived from overland flow, to pass the gaging station.

Period of Rise.—The time intervening between the beginning of surface run-off and the occurrence of the peak discharge.

Infiltration Capacity.—The maximum rate at which a given soil, when in a given condition, can absorb falling rain.[7]

Surface Run-Off Coefficient.—The percentage of the total rainfall on a water-shed that appears at the gaging station as surface run-off.

Unit Storm.—Isolated rainfall falling at an intensity greater than the infiltration capacity and having a duration equal to or less than the period of rise.

Unit Hydrograph.—A hydrograph of surface run-off resulting from a unit storm. [illegible]

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[5] [illegible] New England Water Works Assoc., March, 1924, p. 26.

[6] [illegible] Water-Supply Paper 772.

[7] [illegible] Part I—Analysis of the Hydrograph," by Robert E. Horton, *Publication* [illegible] Lab., Voorheesville, N. Y.

Distribution Graph.—A graph having a time base equal to that of the unit hydrograph from which it was derived and having ordinates that represent the percentage of total surface run-off that occurs in certain selected equal time intervals. It provides a graphical representation of the characteristic distribution of surface run-off from a water-shed.

Selection of the Unit Hydrographs.—The first step in the preparation of the distribution graphs was the selection of unit hydrographs from the continuous run-off records. The method was to select isolated, clean-cut surface run-off

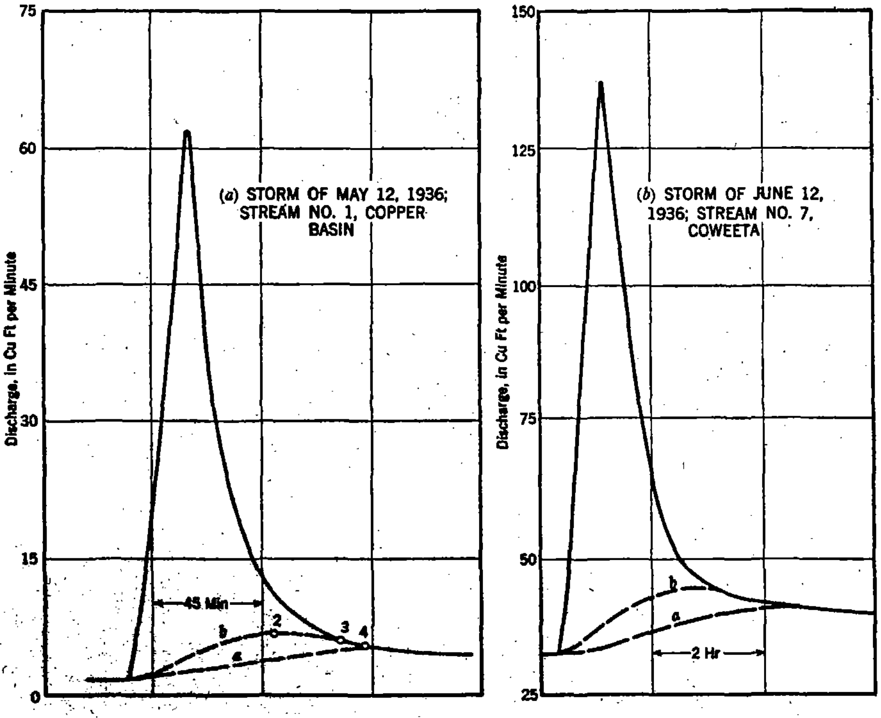


FIG. 2.—TYPICAL HYDROGRAPHS

graphs that occurred at a time of low flow (see Fig. 2). If insufficient graphs of this nature were available, those which were affected by small rains before or after the main one were used. In such a case the main graph was separated from its "parasite" after a careful study of the normal rising or receding sides of other surface run-off hydrographs from the same stream.

This procedure was necessitated by a lack of knowledge of the type of rains that would produce unit hydrographs. In the light of the knowledge gained from the work, it is possible to select the unit storms from the rainfall records by selecting intense isolated rains, the duration of which was less than the period of ... fixed by the area and nature of the water-shed. The only advantage of selecting the unit storms from the rainfall records rather than from stream-flow records occurs when continuous stream-flow records in the form of hydrographs are not available.

The Separation of Surface Run-Off from Ground-Water.—The second step in the preparation of the unit hydrographs was the separation of surface run-off from ground-water contribution. Under these ideal conditions (isolated storms occurring at times of low flow) this procedure became relatively simple. The separation was made first as indicated by Base Line *a*, Fig. 2(*a*). A study of the ground-water build-up during rainfall later indicated that for most streams a base, such as Base Line *b*, was more nearly correct. In the case of Stream No. 1, Copper Basin, distribution graphs were prepared for both sets of base lines and it was found that the difference was small. An investigation of the hydrographs produced by rains of such intensities that no appreciable surface run-off occurred has also indicated that the general shape of the line separating ground-water from surface run-off is in the nature of Base Line *b*. The following two considerations lend weight in favor of the accuracy of this observation.

First, the rate of ground-water contribution depends upon the average slope of the water-table at the shores of the stream. Obviously, the ground-water elevations adjacent to the stream must rise more rapidly than the stream elevations to cause the rate of ground-water inflow to increase during the course of surface run-off. This is true in the case of the small water-sheds under consideration, where the rainfall nearly always covers the entire water-shed. It seems logical to assume that the maximum rate of ground-water contribution (Point 2, Fig. 2(*a*)) will occur at a time after the elevation of the water in the stream has finished its rapid decline, while the adjacent ground-water is still nearly at a maximum elevation. This point occurs near the time when overland flow ends, and during that time when the surface run-off at the gaging stations consists only of channel storage.

Second, it is inconceivable that the ground-water discharge could vary in an erratic or jerky manner. Similarly, the effect of channel storage cannot be thought of as ending abruptly. It follows, therefore, that the line of separation must be a smooth curve tangent to the actual hydrograph both where it leaves and where it rejoins it.

If continuous records of ground-water elevations were taken in conjunction with records of water elevation in the stream, it would be possible to determine the exact nature of this line of separation with considerable accuracy.

Although the preceding comment concerns especially the conditions on small water-sheds, the same general line of reasoning may be applied to larger water-sheds. However, in the latter case, unusual conditions may arise which require special consideration. For instance, it frequently happens that rain occurs only in the upper reaches of a water-shed and misses entirely the region where the gaging station is situated. When the stream rises at such a station, there must be a temporary reversal in the ground-water gradient and the ground-water contribution could conceivably be negative for a short interval. Even in this case the volume of water required in most water-sheds to build up the [illegible] to the level of the stream would be quite small. Further-more, a portion of the water flowing in the stream is ground-water contribution from the region in which the rain occurred, and it would be a very extreme case if this volume were not more than sufficient to supply the deficiency in the lower reaches. It can safely be assumed that, in all cases, the line of separation will have a minimum slope of zero and generally will slope upward during the period of overland flow.

On the basis of tests by the Appalachian Forest Experiment Station, thus far, it may be stated with considerable assurance that the line of separation for small water-sheds is a reverse curve of the nature of Base Line *b*, Fig. 2(*a*). The line is quite definitely fixed by the two points of tangency (Points 1 and 3) and by the maximum ordinate (Point 2).

Generally, even in the case of storms producing overlapping unit hydrographs, the point where surface run-off begins (such as Point 1, Fig. 2) is quite definite.

In the case of the hydrograph shown, the point where surface run-off ends (namely, Point 3) was selected because at this point the graph flattens out rather suddenly. Such a point is not always evident and its selection requires considerable judgment. Although this point cannot be chosen definitely, the maximum time that surface run-off continued after the rainfall ended usually may be selected with assurance, as for instance the time from the peak to Point 4, Fig. 2. This information becomes extremely important when applied to complicated hydrographs resulting from a series of rains, in which instance the selection of this point becomes much more difficult. In cases of this nature, studied by the writer, the lengths of base lines determined by different persons have varied by as much as 100 per cent. By utilizing the knowledge gained from the unit hydrograph, this difference would be more of the order of 5 per cent.

The high point (such as Point 2, Fig. 2(*a*)) probably occurs near the end of overland flow, or about half-way between the peak of the hydrograph and the end of surface run-off. Until more quantitative results are available, the height of this point must be a matter of judgment based on a study of the flow characteristics of the particular stream.

The Construction of the Distribution Graphs.—Having separated ground-water from surface run-off, the unit hydrographs are represented by the ordinates between the line of separation and the actual hydrograph. The unit hydrographs thus determined were then divided arbitrarily into time intervals, and the average rate of surface run-off was determined for each interval. These values were totaled and the percentage of the total occurring during each of the periods was computed. The resulting percentages are a numerical representation of the distribution graphs. Time intervals varying from 2.5 min to 30 min were used, the object being to represent the shape of the graph faithfully with a minimum of labor.

It should be noted that the magnitude of the percentages making up a distribution graph depends on the time interval selected. If 7.5-min intervals instead of [illegible] intervals were chosen in a given case, it is evident that the [illegible] would be half as great. Therefore, for the purpose of comparison, [illegible] graphs were converted to a common time interval. For

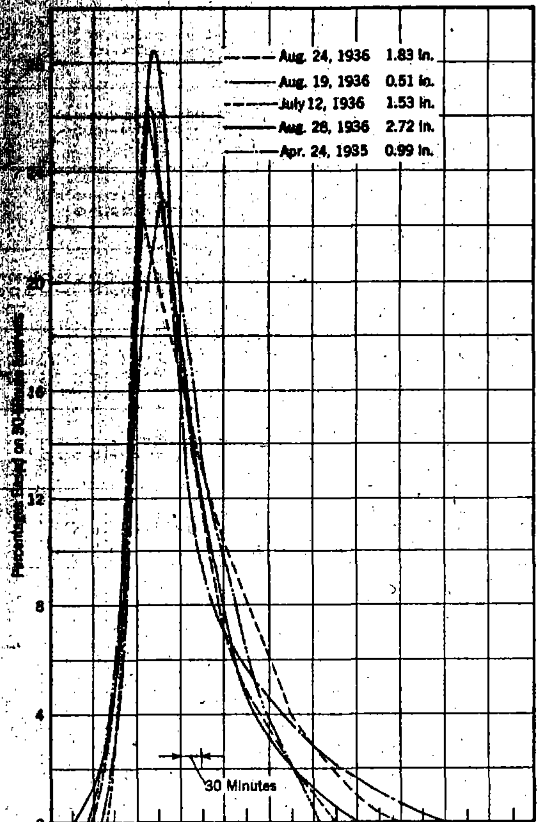


FIG. 3.—DISTRIBUTION GRAPH; STREAM NO. 9, COWEETA WATER-SHED; 1 788 ACRES; FORESTED

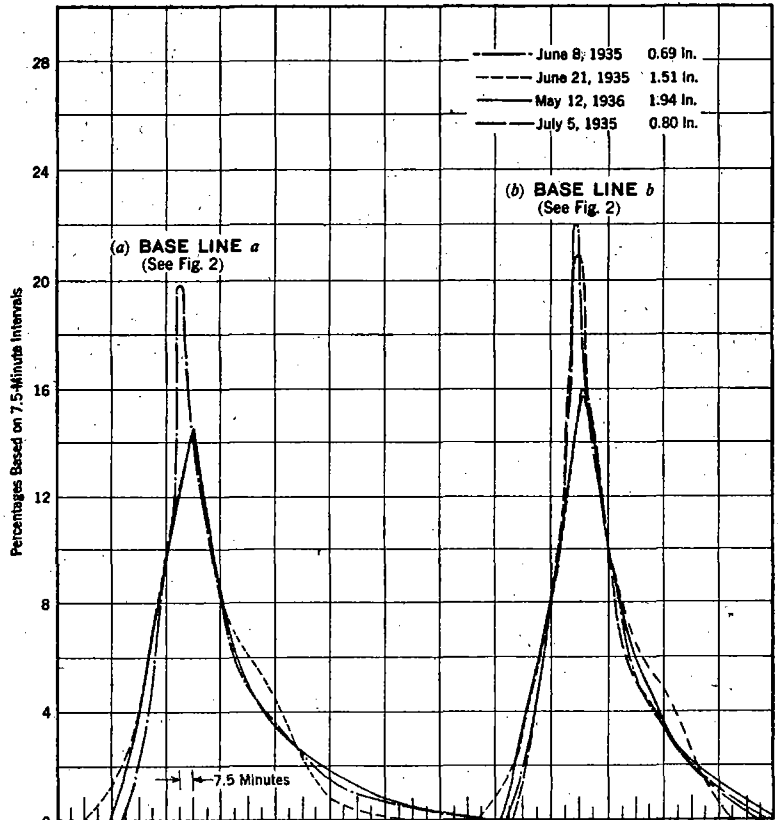


FIG. 4.—DISTRIBUTION GRAPH; STREAM NO. 1, COPPER BASIN WATER-SHED; 19.0 ACRES; FORESTED

example, percentages based on 15-min periods were divided by 6 to reduce the data to a 2.5-min basis. If these results are plotted, they must be spaced at 15-min intervals, since they represent the average 2.5-min interval for a period of 15 min.

The final step was to superimpose all the distribution graphs for each stream as nearly as possible on one another. Figs. 3 and 4 show the resulting clusters of characteristic graphs for two of the streams. A composite distri-

TABLE 2.—DATA FOR DISTRIBUTION GRAPHS

Interval No.	Stream Numbers:									
	1	2	3	4	5	6	7	8	9	10
	(a) BENT CREEK WATER-SHEDS									
T* =	7.5	7.5	5.0	7.5	15.0	7.5	....	5.0	....	....
1	1.6	2.0	2.5	1.4	0.4	3.0	....	10.0	....	....
2	6.0	19.0	14.0	3.2	7.4	14.0	....	19.0	....	....
....	....	(52.0)†	....	....	....	(20.0)†	....	....	....	....
3	12.8	33.0	41.0	5.2	21.6	17.0	....	48.0	....	....
....	(20.4)†	....	(52.5)†	....	(34.0)†	....	....	(80.0)†	....	....
4	18.4	16.0	15.0	8.0	25.4	13.0	....	7.0	....	....
5	13.0	8.0	9.0	12.0	14.0	10.0	....	5.0	....	....
6	10.6	6.5	6.0	17.4	7.0	8.0	....	3.5	....	....
....	....	....	....	(18.7)†	....	....	....	....	....	....
7	9.6	4.5	4.5	15.2	4.6	6.0	....	2.5	....	....
8	6.8	3.5	3.0	9.0	3.6	5.0	....	2.0	....	....
9	4.4	2.5	2.0	6.2	2.8	4.0	....	1.5	....	....
10	3.6	2.0	1.5	5.4	2.8	3.6	....	1.0	....	....
11	2.8	1.5	1.0	4.5	2.4	3.1	....	0.5	....	....
12	2.4	1.0	0.5	3.7	2.0	2.7	....	....	....	....
13	2.0	0.5	....	2.8	1.6	2.4	....	....	....	....
14	1.6	....	....	2.0	1.6	2.0	....	....	....	....
15	1.3	....	....	1.4	1.2	1.6	....	....	....	....
16	1.1	....	....	1.0	0.8	1.3	....	....	....	....
17	0.8	....	....	0.7	0.4	1.0	....	....	....	....
18	0.6	....	....	0.5	0.4	0.8	....	....	....	....
19	0.4	....	....	0.3	....	0.6	....	....	....	....
20	0.2	....	....	0.1	....	0.5	....	....	....	....
21	....	....	....	....	....	0.3	....	....	....	....
22	....	....	....	....	....	0.1	....	....	....	....
	(b) COWEETA WATER-SHEDS									
T* =	15.0	15.0	....	15.0	7.5	15.0	15.0	30.0	30.0§	15.0
1	2.6	1.2	....	0.9	1.1	8.0	0.6	0.5	0.6	1.8
2	10.9	4.8	....	9.3	6.9	27.6	3.4	5.7	2.4	6.4
....	....	....	....	....	....	(42.5)†	....	....	....	....
3	21.7	12.2	....	31.6	18.5	28.7	6.4	13.4	9.0	12.2
....	(29.1)†	....	....	(46.8)†	(34.2)†	....	....	....	....	....
4	23.9	24.0	....	33.4	30.0	14.4	20.8	20.9	25.4	17.8
....	....	....	....	....	....	....	(21.5)†	(22.1)†	(28.6)†	....
5	16.1	30.4	....	10.5	16.5	9.0	19.6	17.7	23.3	20.0
....	....	(35.2)†	....	....	....	....	....	....	....	(21.0)†
6	9.6	15.7	....	6.2	8.9	5.9	14.2	13.4	14.5	15.2
7	6.4	6.8	....	4.1	6.0	3.7	10.0	9.7	9.7	11.3
8	4.3	3.1	....	2.3	4.3	2.0	6.8	7.2	5.9	7.0
9	2.7	1.4	....	1.2	2.9	0.7	4.6	4.7	3.9	3.8
10	1.3	0.4	....	0.5	1.7	....	3.5	3.2	2.6	2.5
11	0.5	....	....	....	1.1	....	2.5	2.0	1.6	1.5
12	....	....	....	....	0.9	....	2.0	1.1	0.8	0.5
13	....	....	....	....	0.6	....	1.6	0.6	0.3	....
14	....	....	....	....	0.5	....	1.2	....	....	....
15	....	....	....	....	0.2	....	1.0	....	....	....
16	....	....	....	....	....	....	0.7	....	....	....
17	....	....	....	....	....	....	0.5	....	....	....
18	....	....	....	....	....	....	0.3	....	....	....
19	....	....	....	....	....	....	0.2	....	....	....
20	....	....	....	....	....	....	0.1	....	....	....

TABLE 2.—(*Continued*)

Interval No.	Stream Numbers: 1	2	3	4	5	6	7	8	9	10
(c) Copper Basin Water-Sheds										
T* =	7.5‡	15.0	2.5	2.5	2.5	2.5	....	....	....	....
1	0.7	0.6	0.1	1.5	0.3	0.8	....	....	....	....
2	1.9	3.4	0.2	4.6	1.0	3.5	....	....	....	....
3	5.6	7.8	0.6	27.4	2.6	16.5	....	....	....	....
....	....	....	....	(37.5)†	....	....	....	....	....	....
4	9.4	14.0	8.0	12.9	4.1	40.0	....	....	....	....
....	....	....	....	....	....	(56.0)†	....	....	....	....
5	15.6	19.2	24.0	10.0	6.3	19.8	....	....	....	....
....	....	(20.2)†	(34.8)†	....	....	....	....	....	....	....
6	20.3	16.0	24.0	8.7	8.9	13.7	....	....	....	....
....	(21.0)†	....	....	....	....	....	....	....	....	....
7	14.0	11.6	10.1	7.4	11.75	3.8	....	....	....	....
8	8.7	8.2	7.4	6.1	15.25	1.1	....	....	....	....
9	5.7	6.2	6.2	4.8	18.6	0.5	....	....	....	....
....	....	....	....	....	(20.0)†	....	....	....	....	....
10	4.4	4.4	5.2	3.6	16.1	0.2	....	....	....	....
11	3.7	3.2	4.0	2.8	11.55	0.1	....	....	....	....
12	3.0	2.2	3.1	2.5	2.8	....	....	....	....	....
13	2.3	1.4	2.5	1.7	0.5	....	....	....	....	....
14	1.7	1.0	1.5	1.2	0.2	....	....	....	....	....
15	1.4	0.6	0.9	1.0	0.1	....	....	....	....	....
16	0.9	0.2	0.5	0.9	0.05	....	....	....	....	....
17	0.5	....	0.4	0.8	....	....	....	....	....	....
18	0.2	....	0.35	0.7	....	....	....	....	....	....
19	....	....	0.3	0.6	....	....	....	....	....	....
20	....	....	0.25	0.4	....	....	....	....	....	....
21	....	....	0.2	0.2	....	....	....	....	....	....
22	....	....	0.1	....	....	....	....	....	....	....
23	....	....	0.05	....	....	....	....	....	....	....

* T = time interval, in minutes. † Peak percentages are shown in parentheses.
‡ See Fig. 4. § See Fig. 3.

bution graph was then chosen for each case. This was done either by selecting one of the individual graphs as representing an average, or by drawing an average graph through the cluster and taking the percentages from it. The latter process involves a trial-and-error procedure in order to produce a total of 100 per cent. Numerical values of the composite distribution graphs are listed in Table 2.

Characteristics of the Distribution Graphs.—An examination of the twenty-two sets of distribution graphs similar to Figs. 3 and 4 showed that there was a close agreement among the graphs in each group. Furthermore, for any stream, the shapes of the graphs were singularly individualistic. The adherence to the characteristic shape for each of the streams appears to be much closer than in the case of streams draining larger water-sheds.

The rainfall varied considerably within the individual clusters of graphs. For example (see Table 3), unit hydrographs selected for Coweeta 9 were produced by rains varying from 0.51 in. to 2.72 in., those of Coweeta 5 by rains varying from 0.35 in. to 1.69 in., and those of Bent Creek 1 varied from 0.51 in. to 1.44 in.

The actual peaks of the unit hydrographs also varied widely within the individual cluster. For instance, the peak discharges varied from 9 to 95 cu ft per sec in the unit hydrographs used for Coweeta 9 and, in the case of Bent Creek 3, the peak discharge varied from 1.9 to 13.0 cu ft per sec.

The duration of each of the rains used in preparing the distribution graphs and the period of rise for each stream are given in Table 3. The period of rise corresponds approximately to the time of concentration in the so-called rational formula. The latter is usually defined as the time required after the beginning of rainfall for run-off to reach the point of concentration from the most distant point on the water-shed. These studies indicate that a somewhat different conception must be given to this time interval.

A careful study of Table 3 in conjunction with the corresponding distribution graphs will show that the peak discharge appears at approximately the same time after surface run-off starts, regardless of the duration or magnitude of the rainfall. Nearly every set of graphs provides illustrations of this. For

TABLE 3.—Description of the Rains that Produced Distribution Graphs Similar to Figures 3 and 4

Date of storm* (1)	Total rainfall, in inches (2)	Duration of rain-fall, in minutes (3)	Date of storm* (1)	Total rainfall, in inches (2)	Duration of rain-fall, in minutes (3)
(a) Bent Creek Water-Shed					
Stream No. 1; P = 22 min:			Stream No. 4; P = 45 min:		
August 22, 1935	1.22	....	August 29, 1936	0.71	25
July 1, 1936	0.75	20	September 20, 1936	0.44	15
July 2, 1936	1.44	30	September 29, 1936	0.69	30
July 20, 1936	0.51	20			
September 20, 1936	0.95	20	Stream No. 5; P = 30 min:		
			July 2, 1936	2.04	30
Stream No. 2; P = 15 min:			September 20, 1936	1.02	70
July 20, 1936	0.50	20			
August 6, 1936	0.58	20	Stream No. 6; P = 12 min:		
August 27, 1936	0.81	20	August 23, 1935	1.38	50
September 20, 1936	0.37	15	July 2, 1936	2.22	30
September 29, 1936	0.66	30	September 20, 1936	0.85	70
Stream No. 3; P = 12 min:			Stream No. 8; P = 20 min:		
July 2, 1936	1.03	20	June 7, 1936	0.74	20
July 6, 1936	0.64	15	July 1, 1936	0.53	20
July 23, 1936	0.41	30	July 6, 1936	0.64	15
August 10, 1936	1.13	20	July 20, 1936	0.63	20
(b) Copper Basin Water-Shed					
Stream No. 1; P = 38 min:			Stream No. 4; P = 8 min:		
June 8, 1935	0.69	25	March 25, 1935	0.77	8
June 21, 1935	1.51	55	July 27, 1935	0.35	10
July 5, 1935	0.80	30	August 17, 1935	0.63	8
May 12, 1936	1.94	60	August 23, 1935	1.41	40
			October 28, 1935	1.10	12
Stream No. 2; P = 60 min:			Stream No. 5; P = 20 min:		
June 8, 1935	0.73	25	April 2, 1935	0.29	8
June 21, 1936	1.48	55	April 3, 1935	0.73	15
July 20, 1936	0.67	25	July 29, 1935	0.67	8
August 10, 1936	0.72	35	August 4, 1935	0.28	14
Stream No. 3; P = 10 min:			Stream No. 6; P = 10 min:		
April 2, 1935	0.35	8	July 13, 1935	0.25	10
July 2, 1935	0.90	7	July 29, 1935	0.67	10
March 24, 1936	0.74	8	August 3, 1935	0.28	14
June 10, 1936	0.89	12	August 17, 1935	0.50	12
August 10, 1936	0.70	16			

TABLE 3.—(*Continued*)

Date of storm* (1)	Total rainfall, in inches (2)	Duration of rainfall, in minutes (3)	Date of storm* (1)	Total rainfall, in inches (2)	Duration of rainfall, in minutes (3)
(c) COWEETA WATER-SHED					
Stream No. 1; P = 45 min:			Stream No. 7; P = 60 min:		
August 22, 1935	1.43	30	May 11, 1936	1.51	60
August 23, 1935	0.33	35	June 10, 1936	0.79	30
July 12, 1936	1.74	40	June 12, 1936	0.92	22
July 17, 1936	0.68	20	July 22, 1936	1.18	65
August 19, 1936	0.97	20			
			Stream No. 8; P = 70 min:		
Stream No. 2; P = 60 min:			May 11, 1935	1.36	120
July 12, 1936	1.94	40	July 25, 1935	1.15	65
August 19, 1936	1.02	20	July 26, 1935	1.37	35
August 24, 1936	0.99	20	August 22, 1935	1.49	30
Stream No. 4; P = 25 min:			Stream No. 9; P = 75 min:		
August 11, 1934	1.40	.....	April 24, 1935	0.99	42
May 11, 1935	1.38	60	July 12, 1936	1.53	35
August 19, 1936	0.72	20	August 19, 1936	0.51	25
August 24, 1936	1.91	20	August 24, 1936	1.83	20
			August 28, 1936	2.72	75
Stream No. 5; P = 15 min:					
July 12, 1936	1.69	35	Stream No. 10; P = 60 min:		
July 13, 1936	0.35	16	June 4, 1936	1.13	15
August 19, 1936	1.09	25	June 12, 1936	1.06	22
August 24, 1936	1.60	42	August 24, 1936	1.17	20
Stream No. 6; P = 30 min:					
August 11, 1934	....	....	....	....	....
July 12, 1936	1.66	35	....	....	....
August 19, 1936	1.02	25	....	....	....
August 24, 1936	1.46	42	....	....	....

* P = Period of rise.

instance, the period of rise for Stream 9, Coweeta (see Fig. 3), is 75 min. Four of the distribution graphs were produced by rains lasting only from 20 to 42 min. These graphs fall very well in line with the one produced by a much heavier rain which fell during the entire 75 min. On Coweeta 7, rains lasting 30 and 22 min, respectively, produced distribution graphs which coincide with those produced by rains of 60- and 65-min duration. In contrast to these shorter rains, about ten of the rains used were of a longer duration than the period of rise, although, in most cases, the major portion of the rain fell within this period. However, even in the case of the rain of August 23, 1935, on Copper Basin 4 (which lasted five times as long as the period of rise) a definite peak occurred at the same time as those of the other distribution graphs. This evidence may be summarized as follows:

(1) Any rain occurring in a time equal to or less than the period of rise will produce a unit hydrograph;

(2) A rain that lasts somewhat longer than the period of rise but with decreasing intensity also produces a unit hydrograph; and,

(3) There is a tendency for the period of rise to be unaffected even if the rain continues longer at a high intensity.

The foregoing considerations help to trace the sequence of events that constitute the process of surface run-off. This process is believed to be as follows: The first rainfall that occurs at a rate in excess of the infiltration capacity produces surface storage. As rainfall continues the surface water begins to move down the slopes in thin films and tiny streams. Surface tension and friction play an important part at this stage. As these minute rivulets increase in volume, their velocity becomes greater; but their path is tortuous and every small obstruction causes a delay until sufficient head is built up to overcome it. Upon its release, the stream is suddenly speeded on its way again. Each time that two or more of these little streams combine, the water is further accelerated in its down-hill path. It is the culmination of all these small contributions into a final combined accretion to the main stream which produces the ultimate hydrograph. It appears, therefore, that the period of rise has no particular relation to the time required for water to reach the gaging station from the most remote part of the water-shed, since the peak is merely the result of the simultaneous release of the accumulated rainfall from the major portion of the water-shed. The rain that falls near the end of the period begins its overland flow much more readily than that falling earlier, since it falls at a time when all the surface depressions have been filled and into water which is flowing with a relatively high velocity. An increase in the intensity of the rainfall over the minimum required to produce surface run-off increases the total surface run-off but does not materially change the time required to complete the foregoing process.

Applications of the Distribution Graph

It has been shown that unit hydrographs exist in, and may be isolated from, the discharge records of small streams. A study of the natural phenomena involved in the formation of a unit hydrograph has thrown light on some phases of the process of surface run-off. In the following studies, the distribution graphs are utilized to test the value of the unit hydrograph principle in surface run-off analysis.

Correlation of the Distribution Graph with Water-Shed Characteristics.—The variety of types and sizes of water-sheds upon which the investigation is based offers an opportunity to relate the characteristics of the distribution graphs with those of the water-sheds. The writer is aware that the exact dimensions of the distribution graphs are partly a matter of personal judgment, especially the widths of bases and the peak percentages. A change in the method of separating base flow from storm flow might change, considerably, the total length of base of the distribution graphs, although it would not materially affect their general shape. Furthermore, in some of the streams, the records may not have been long enough to produce a true unit hydrograph; however, as demonstrated later by the construction of pluviagraphs, the evidence is in favor of their adequacy. In view of the foregoing consideration, the correlations were made to include as much information as possible. None of the graphs contained "average curves." The only averages used were the composite distribution graphs for each stream.

For a comparison of peak discharge, the twenty-two composite distribution graphs were reduced to a 2.5-min basis. The peaks were then plotted in order of magnitude as shown in Fig. 5.

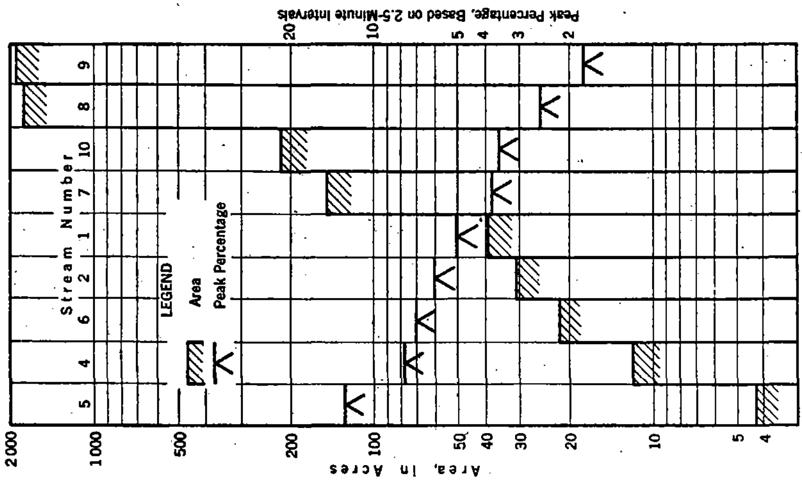


FIG. 6.—RELATION BETWEEN PEAKS OF DISTRIBUTION GRAPHS AND AREAS; COWEETA WATER-SHEDS

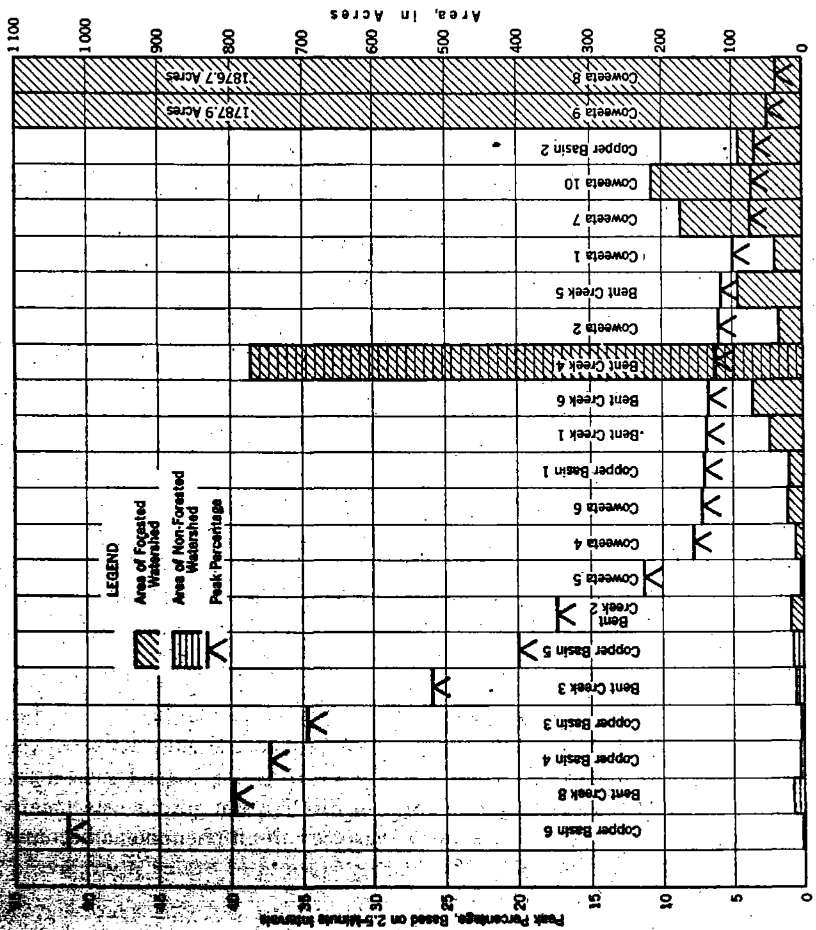


FIG. 5.—RELATION BETWEEN PEAKS OF DISTRIBUTION GRAPHS AND AREAS OF WATER-SHEDS

That the peak percentage varies according to the area of the water-shed is quite obvious. However, it is the manner in which the variation occurs that is especially interesting. For instance, if the forested water-sheds of the Bent Creek, Coweeta, and Copper Basin areas are considered separately, the agreement between peak percentage and area becomes consistent. That is, from left to right on the graph the areas are constantly increasing. This may be noted by a careful study of Fig. 5; but it is more clearly indicated in Fig. 6, in which only the Coweeta streams are plotted. The greatest peaks for a given area are found at Bent Creek—the smallest at Copper Basin and Coweeta. It is significant that the denuded and grassed areas have peaks much higher than would be indicated by the general trend of the forested areas.

It is interesting to consider, specifically, some of the individual variations from the general trend. For instance, Bent Creek 8 is considerably out of its place, considering merely area and peak. It has the largest area of any of the unforested water-sheds, but has the second highest peak. It is possible that this is due to the fact that this water-shed has nearly a semi-circular shape, with its outlet at the center of the circle, thus permitting all sectors of the water-shed to contribute their run-off simultaneously with practically no delay due to channel storage.

Water-shed 4 on Bent Creek has approximately the position in the graph that one would expect, being about 50% forested and 50% cultivated farmland, abandoned farmland, and cut-over land.

The peak percentage of Stream No. 2, Bent Creek, is considerably above the trend of the other forested water-sheds. Two-thirds of the standing trees were cut from this water-shed in 1930 and 1931, and skidding operations at that time were exceptionally heavy. Furthermore, drainage from approximately 100 yd of roadway discharged into the water-shed. Although the quantity of water entering from this source was not great, it entered in the form of a small stream and followed a fairly narrow and well-defined course to the main stream, discharging into it at a point about 100 ft from the weir. This latter difficulty was eliminated in subsequent records to determine whether the high peak was due to the scarcity of vegetative cover or to the unnatural drainage.

Fig. 7 was prepared to show the variation in the duration of run-off for a unit storm, as indicated by the lengths of bases of the distribution graphs. The bases are plotted using the area, in acres, as the zero ordinate for each graph. The types of water-sheds are indicated by the legend. As is to be expected, the length increases with the area. The sharp difference between the forested and unforested areas is apparent.

Although the individual variations from the general trend (with possible causes as stated previously) are interesting and perhaps significant, the important feature is that there appears to be a general relationship between the dimensions of the distribution graph and the area, and a logical reason for all the deviations. If this is true, the value of distribution graphs as a means of isolating the area factor in the analysis of surface run-off phenomena becomes apparent.

Instead of using a uniform interval of 2.5 min as a percentage basis in the foregoing analysis, it would have been possible, and might at first appear logical, to base the percentage upon a constant portion, say 10%, of the base of the distribution graphs. The effect of selecting the proper length of base lines becomes much more pronounced when this method is used. For instance, the peak percentages based on 2.5-min intervals are 4.0% for Base Line *a* and

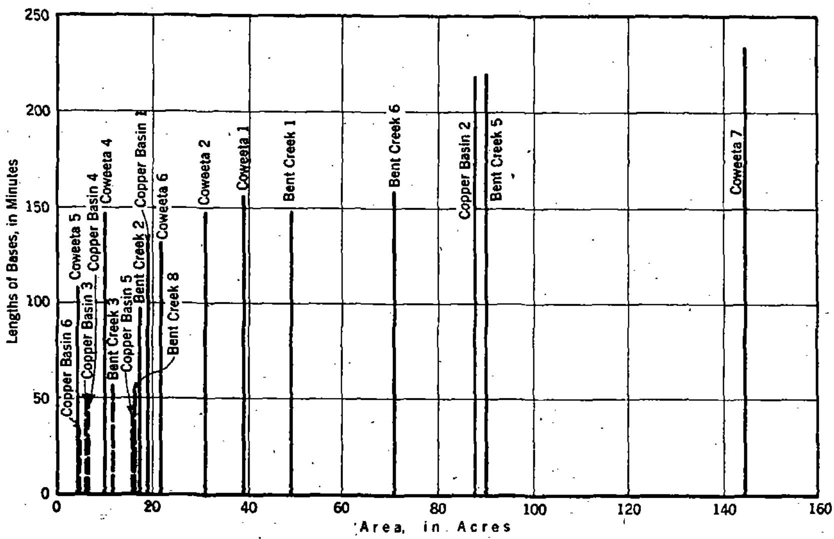


FIG. 7.—RELATION OF WATER-SHED AREAS TO BASES OF DISTRIBUTION GRAPHS

4.4% for Base Line *b*, Fig. 2(a). Based on an interval equal to 10% of the length of bases, the peak percentages are, respectively, 43.6% and 31.9 per cent. The difference in the first case is 10% and in the latter case about 35% showing that personal judgment in selecting the base line would play a much more important part if the latter method were adopted.

For this reason, and because the peak percentage based on a definite time interval may be translated into rate of surface run-off and therefore has a real practical value, the comparisons were all based on such intervals.

Application of the Pluviagraph.—The pluviagraph is a hydrograph of 100% surface run-off prepared by distributing a rain or a series of rains according to the ordinates of the distribution graphs. It is assumed that each unit storm produces a unit hydrograph, although other subsequent or succeeding rains may produce overlapping graphs. Then, since a distribution graph shows the successive periodic surface run-off contribution of a unit hydrograph, each unit storm must contribute to each time interval, after the beginning of rainfall, a portion determined by the successive percentages of the distribution graph. Only that rainfall which falls at a rate greater than the infiltration capacity becomes surface run-off. Therefore, a coefficient must be applied to the pluviagraph values to produce an actual hydrograph of surface run-off.

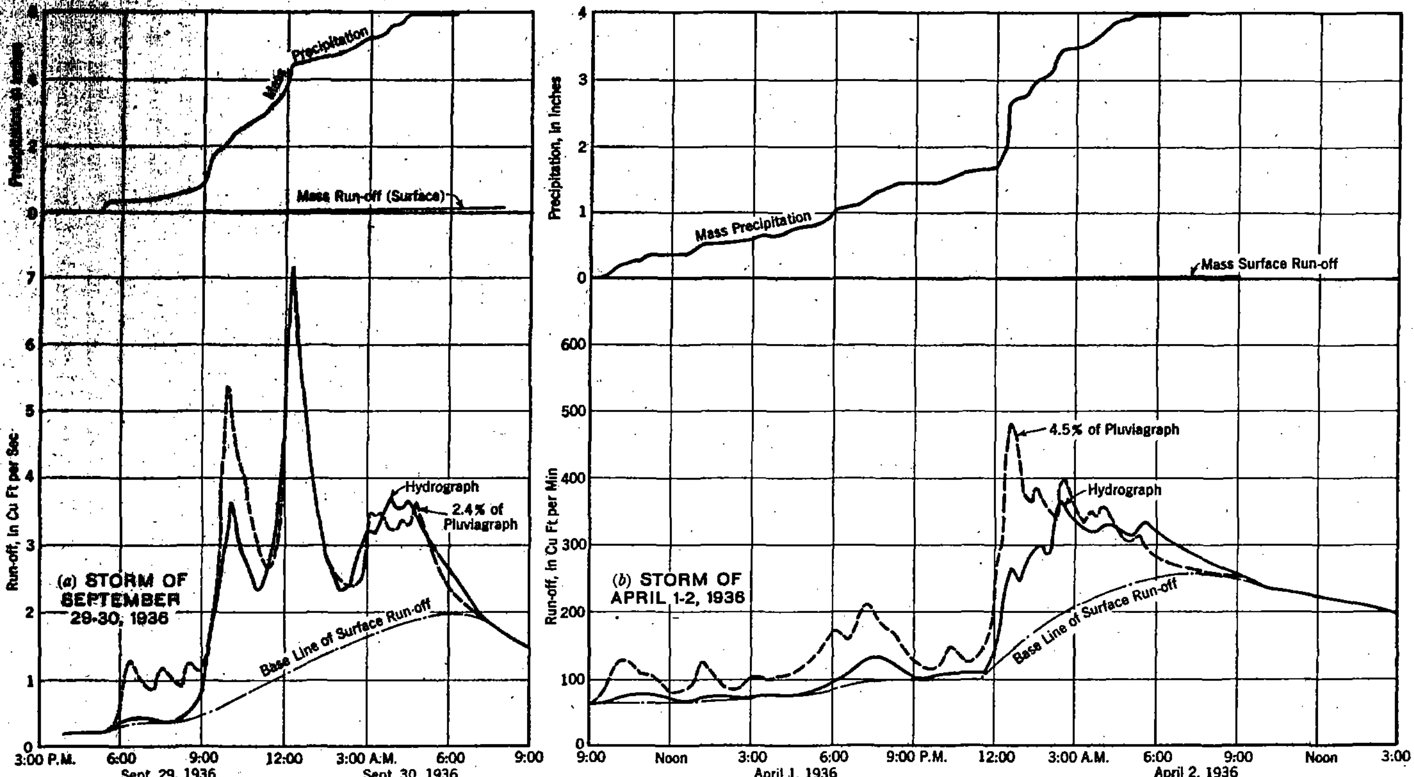


FIG. 8.—PLUVIAGRAPHS FOR TWO STORMS; STREAM NO. 7, COWEETA

The preparation of pluviagraphs has been adequately described elsewhere.[6] The selection of the time interval into which the distribution graphs are divided must be made arbitrarily. Lengthening the interval shortens the labor involved in computing the pluviagraph. The length is limited, however, to such a unit of time as will give a smooth and correct curve. For example, it was found that a 30-min interval was too long to be applied to Stream No. 2, Copper Basin, with a water-shed area of 89 acres, whereas a 15-min interval produced satisfactory results; 15-min intervals were also used for Stream No. 7, Coweeta, which has a water-shed area of 145 acres. In the case of Stream No. 3, Bent Creek, which drains an area of 10.8 acres, 5-min intervals were used.

The division of the continuous precipitation into individual rains or unit storms requires considerable care and usually some experimentation. In general, the rain was divided according to changes in intensity. However, if any rate of rainfall continued for too great a time, it was found necessary to break it up arbitrarily into parts, especially if the rain was of low intensity. In the case of Copper Basin 2, and Coweeta 7, a half-hour was found to be an adequate unit of time into which to break these rains. However, on Stream No. 3, Bent Creek, much of the rain was broken down into 5-min intervals. It was found that the procedure became clarified after several trials on each stream. The rainfall records must be of such a type that the rain can be broken down, easily and accurately, into less than 5-min periods in order to apply this method successfully to very small water-sheds.

Fig. 8 shows two pluviagraphs prepared for Stream No. 7, Coweeta, from which it may be seen that the actual hydrograph is quite faithfully reproduced. These pluviagraphs would seem to be conclusive evidence that the unit hydrograph principle may be applied to small water-sheds.

Run-Off Coefficients and Infiltration Capacity.—In every case where a pluviagraph was prepared for a relatively intense series of rains, during which surface run-off was continuous, it was found that the percentage of the rainfall discharged as surface run-off became progressively greater during the course of the rain. This may be observed in Fig. 8. The values plotted are the pluviagraph data reduced by some constant percentage. The percentage chosen for each graph was such as to bring the pluviagraph into the region of the actual hydrograph. The percentage value used is always too great at the beginning; it becomes correct sometime during the course of the storm; and the value is too small near the end of the storm. It is indicated, therefore, that the infiltration capacity decreased during the course of the rain. Graphs such as these suggest that the pluviagraph provides a means of tracing the quantitative changes in infiltration capacity, or run-off coefficient, during continuous rainfall, thus permitting a correlation of these quantities with rainfall characteristics.

The correlations attempted in the following pages are based on quantity of rainfall and do not specifically take rainfall intensity into account. Although it is recognized that intensity of rainfall has an important bearing on the percentage that becomes surface run-off, the intense rains are usually large ones, and therefore, if the run-off coefficient or the infiltration capacity is correlated with quantity of rainfall, the intensity will be taken into account somewhat. There are several reasons for leaving intensity "out of the picture." In the first place, the determination of mean rainfall intensity for a given series of rains often leads to a distorted result, dependent upon how much of the rain is taken into account. Furthermore, it is difficult to include antecedent rainfall in a correlation involving intensity rather than quantity of rainfall.

In order to determine, quantitatively, the variations in percentage run-off, the percentage which brought the pluviagraph into practical coincidence with the actual hydrograph was determined for each significant peak during the course of surface run-off. This was then related to the quantity of rainfall, which, according to the pluviagraph, had had an opportunity to be converted to run-off at the time when that coefficient was applicable. In Fig. 9, each group of connected points represents such a series of consecutive rains during which surface run-off was continuous.

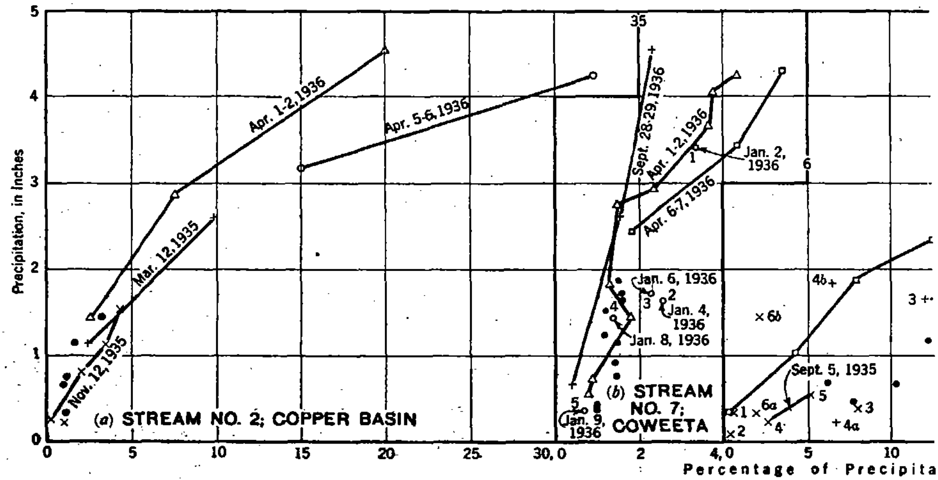
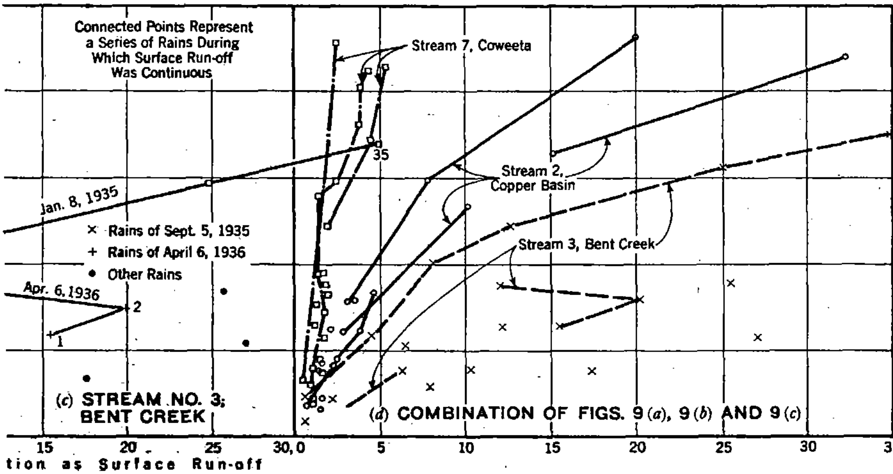


FIG. 9.—RELATION BETWEEN ACCUMULATED

Four of such series are plotted for Stream No. 2, Copper Basin, in Fig. 9(*a*), together with a number of points from individual rains. It will be seen that there is a definite relationship between accumulated rainfall and percentage of surface run-off, despite the fact that rain intensity and previous saturation are not considered. It will be noted that points plotted for the storm of April 5 and 6, 1936, have higher percentages than for the preceding storm of April 1 and 2, 1936. Undoubtedly, the first storm had an appreciable effect on the second one, and, if this could be taken into account, the two curves would probably come near to coinciding. As the study of soil moisture and its effect upon surface run-off is advanced, this may become possible, but for the present it is more important to know the range within which the coefficients will vary.

Fig. 9(*b*) is a similar graph for Stream No. 7, Coweeta. It will be seen that the trend is noticeably different in this case. The effect of previous saturation noted for the two April storms may be seen again for the same storms on this stream.

Three sets of coefficients in series, and a number of single ones, are plotted for Bent Creek 3, in Fig. 9(*c*). The series of storms occurring on January 7, 1935, is a good example of the rising percentage of surface run-off. At the time Rain No. 1 occurred, 1.72 in. of rainfall had fallen. Since surface run-off was intermittent to this point, the previous rainfall was not considered in plotting the points. The intensity of rainfall was relatively low throughout this rain. The fact that these points lie in a lower percentage range than the main trend would indicate that intensities of rainfall have an important effect in water-sheds of this nature. More evidence of this is found in the series of rains occurring on April 6, 1936. Rain No. 3 of this series was a much less intense shower than Nos. 1 and 2. It may be seen from the graphs that the percentage of surface run-off has dropped back for this rain.



RAINFALL AND PERCENTAGE RUN-OFF

Thus far, no mention has been made of the length of time in which a build-up in the coefficient is sustained after the end of surface run-off. In this connection it is interesting to consider Rain No. 4 of the series just mentioned. In Fig. 9(*c*), Point 4*b* is plotted according to accumulated rainfall, whereas Point 4*a* is plotted according to the rainfall that produced its run-off. A value lying between these two would fall in line with the general trend. A break in the continuity of surface run-off of 1 hr occurred between this rain and Rain No. 3. Although Rain No. 4 was nearly equal in amount and intensity to Rain No. 3, the percentage of surface run-off is much smaller. Surface detention may account for some of this difference, but the following considerations indicate that its effect could not have been great: (1) The slope is relatively great and erosion has advanced to such a stage on this water-shed that actual detention in the form of puddles on the ground must be very slight; and (2) in the several hours intervening between the rains, the relative humidity remained at nearly 100%, so that practically no evaporation occurred. Therefore, the quantity of rainfall previously intercepted and held by the vegetation had not been depleted, and detention from this source may be practically eliminated. The conclusion may be drawn, then, that the infiltration capacity increased considerably in the space of 1 hr despite the 1.60 in. of rainfall immediately preceding.

Another illustration is furnished by the rains of September 5, 1936. Surface run-off resulting from these rains was interrupted for periods varying from a half to 1.5 hr between all of the rains except Nos. 4 and 5. For illustration, Point 6*b* was plotted according to accumulated rainfall whereas Point 6*a* was plotted according to the actual rainfall. Since Point 6*a* falls into line with the other points, it appears that the effect upon infiltration capacity of the previous 1.10 in. of rainfall is completely gone in 1.5 hr.

Five heavy rains occurring in the period from April 2 to April 9, 1936, on Coweeta 7 are plotted individually in Fig. 9(*b*). Breaks in the occurrence of surface run-off between the successive storms were 29, 28, 32, and 13 hr in duration, respectively. The amount of each rain is shown by the graph. It may be seen that the points plotted individually fall quite well in line with the general trend, which indicates that these rather heavy rains had little or no effect on the surface run-off coefficient of those following.

The points plotted for each stream in Figs. 9(*a*), 9(*b*), and 9(*c*) are all combined in Fig. 9(*d*). The definitely distinct trends of the points for the three streams are evident, despite the limitations in allowing for intensity of rainfall and previous saturation. If such a series were prepared for a sufficient number of streams, covering a wide enough range in area, cover type, slope, etc., the resulting information would be of value to the practicing engineer, as well as being an important step in the accumulation of a basic knowledge of surface run-off phenomena. It would give the engineer definite limits between which the coefficient could be expected to vary for a given type of water-shed. If he were then able to choose a representative distribution graph, he could predict, far more accurately than he could by the use of any empirical formula, the run-off to be expected from a given quantity of rainfall.

It will be noted that no attempt was made to separate winter and summer rains in the foregoing correlations. A similar study on northern streams would undoubtedly require such a separation. Furthermore, although the indications are that the effect of previous saturation on infiltration capacity is negligible on these water-sheds, it is likely that in other locations this effect may be extremely important.

The value of a series of investigations to determine run-off coefficients under varying conditions cannot be over-estimated. It is extremely desirable that data collected from different sections of the United States be gathered and analyzed to show the effect of soil structure, topography, vegetative cover, temperature, and other water-shed and rainfall factors on the surface run-off coefficient or infiltration capacity.

The Use of the Unit Hydrograph in Estimating Flood Flows

The design of so many structures depends upon a knowledge of the maximum rate of run-off to be expected from a water-shed that any method that will give a more dependable determination of this quantity must be of inestimable value to the engineering profession. The unit hydrograph method possesses several advantages over other methods usually employed for this purpose. First, this method permits the engineer to estimate not merely the peak discharge, but the entire hydrograph of run-off. Second, the peak may be determined for any desired time interval. It thus provides a flexibility that is not provided by any empirical formula. Third, the quantities involved in computation by this method have physical conceptions which are familiar to the engineer. No empirical formulas with vaguely defined constants are involved; the physical characteristics of the water-shed have a straight-forward bearing on the computations. Finally, the method lends itself easily to the experimental determination of the quantities involved—namely, percentage of rainfall appearing as surface run-off and the shape of the distribution graph.

An outline of the procedure that can be followed in estimating the flood flow from a water-shed for which no records are available follows:

(1) A complete knowledge of the physical properties of the water-shed must be secured. Specifically, the size, shape, topography, soil type, and nature of the vegetative cover must be determined. In areas where the underlying geologic structure may vary radically from place to place, it is important to determine the depth and orientation of impervious strata.

(2) Collect all the available stream-flow, rainfall, and water-shed data from similar drainage basins, preferably from the same region.

(*a*) Study the physical characteristics of these water-sheds in relation to the shapes of their distribution graphs. Correlations in the nature of those illustrated in Figs. 5, 6, and 7 would reveal the desired information. Determine the position of the water-shed in question with respect to those used in the correlation as defined by the physical properties of the water-shed. The shape of its distribution graph is thus also defined within reasonable limits.

(*b*) Determine the range of variation of run-off coefficients. The accumulation of all the available data in graphical form as illustrated in Fig. 9(*d*) would show the variations of this coefficient with rainfall and would permit the selection of a maximum value.

(3) Determine the maximum storm that has occurred in the region which might reasonably be expected to occur on the water-shed being studied. Transpose this rainfall upon the water-shed and compute the volume of water applied to the water-shed.

(4) The portion of this volume that will appear as surface run-off may be computed by applying the coefficient determined in Item (2*b*). The hydrograph of surface run-off may now be constructed by apportioning this quantity according to the figures of the distribution graph selected in Item (2*a*).

Where flood estimates are to be made on a water-shed for which some records are available, the results may be obtained in a similar manner except that the records on the water-shed itself would be utilized to the fullest extent in the foregoing procedure.

It is evident that the determination of the maximum flood becomes more dependable as the number of available stream-flow and rainfall records increases. A great mass of such data has been collected in the United States, but its usefulness is limited until it is brought together and analyzed in a systematic manner. Furthermore, for very small water-sheds, average daily discharge records of a stream are of little value for any type of stream-flow analysis. It is necessary that records on such streams (and likewise the rainfall records) be continuous, and that they be available as such to permit their utilization in the advancement of the knowledge of stream behavior.

Summary

The preparation of unit hydrographs and distribution graphs for twenty-two small streams and a study of their relation to the corresponding rainfall and water-shed characteristics have served to reveal some of the natural phenomena involved in the process of surface run-off as well as to point out the usefulness of the unit hydrograph principle in flood-flow prediction. The results are summarized as follows:

(1) Unit hydrographs are produced on small streams and may be readily selected from continuous run-off records;

(2) The ground-water contribution may be separated from the surface run-off with considerable assurance in the case of hydrographs resulting from isolated rains;

(3) The unit hydrograph is an important aid in the separation of ground-water contribution from surface run-off in the case of a complex hydrograph produced by a series of rains;

(4) Any rain that is sufficiently intense to produce surface run-off will produce a unit hydrograph if its duration is equal to, or less than, the period of rise;

(5) The period of rise is a function of the water-shed characteristics and is the time required for the major portion of the water-shed to release its accumulated rainfall load;

(6) There is a definite correlation between the shape of the distribution graphs and the water-shed characteristics;

(7) The reproduction of known flood hydrographs by the use of the pluviagraph provides a method of determining the variation of run-off coefficient or infiltration capacity on a water-shed throughout the period of surface run-off; and,

(8) The unit hydrograph principle provides a fundamentally sound method of predicting surface run-off.

The study has indicated certain lines of investigation that should be conducted to strengthen some features of the unit hydrograph principle and to provide a background of experimental data upon which to base its application in flood-flow prediction. The studies which it is believed would be most fruitful are:

(*a*) An intensive examination of the variations in stream levels and adjacent water-table levels during the course of surface run-off to provide a dependable basis for separating ground-water flow from surface run-off. An exhaustive study on only a few water-sheds would provide data upon which to base the separation in other cases.

(*b*) A study to determine whether a composite or average depletion curve may be used to estimate a hydrograph of run-off during intervals between rains.

(*c*) An investigation to determine the influence of rainfall and water-shed characteristics upon surface run-off coefficients. (Such a study should attempt to isolate and show the effect of various factors such as size, shape, and slope of the water-shed, vegetative cover, cultivation, air temperature, duration and intensity of rainfall, antecedent rainfall, etc. The results would provide a basis for estimating the coefficients in cases where no discharge or rainfall records are available, and would indicate how changes on the surface of the water-shed would influence run-off.)

(*d*) The preparation and systematic analysis of distribution graphs from a large number of streams showing variations in the shapes of the graphs with relation to water-shed characteristics. The knowledge provided by such an investigation in conjunction with a known surface run-off coefficient would permit the construction of flood hydrographs on streams where no discharge records are available.

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