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Hydrograph Synthesis for Small Arid-Land Watersheds

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A method of estimating hydrograph characteristics from physiographic features of a watershed under study

FOR many hydrologic design problems it is necessary not only to estimate the expected peak rate of runoff, but for flood-routing purposes to synthesize the entire inflow hydrograph. In areas where few runoff data are available, the designer must resort to some method of estimating hydrograph characteristics from physiographic features of the watershed. This is particularly true in the southwestern area of the United States where such data are extremely scarce. This paper presents a method of hydrograph synthesis developed especially for small arid land watersheds.

The method involves *(a)* estimation of a characteristic lag time from readily determined watershed parameters, *(b)* use of the watershed lag time to predict the hydrograph peak rate for an assumed total volume of runoff, *(c)* synthesizing the entire hydrograph using the lag time, the estimated peak rate, and a standard dimensionless hydrograph.

Development of the method is based on the analysis of rainfall and runoff records for 14 experimental watersheds in Arizona, New Mexico and Colorado (Fig. 1). The watersheds were established in 1938-39 by the Soil Conservation Service (USDA), and the studies have been continued since 1954 by the Agricultural Research Service in cooperation with the Soil Conservation Service and the agricultural experiment stations of Arizona, New Mexico, and Colorado.

The Experimental Watersheds

The 14 watersheds range in size from 11 to 790 acres. They are in four locational groups near Albuquerque and Sante Fe, N. M.; Safford, Ariz.; and Colorado Springs, Colo. All of the watersheds, except Colorado Springs W-I which has been cultivated for more than 50 years, are on arid or semiarid range lands at intermediate elevations (3500 to 7000 msl). Mean annual precipitation is about 8 in. for the Albuquerque and Safford watersheds, and 14 in. for Sante Fe and Colorado Springs watersheds. Over one-half of the precipitation and nearly all of the runoff results from intense convectional thunderstorms in the June to September period.

Runoff from each watershed is measured by a precalibrated triangular weir equipped with a water-level recorder giving continuous records of stage to 0.01 ft and time to 1 min. Each watershed has one or more 12-hr recording rain gages and standard gages, and each watershed or group of watersheds has a weekly recording gage. The periods of record are from 9 to 16 years. Detailed watershed characteristics are given in Table 1.

Determination of Watershed Lag Time

The term "lag time" has been used in the literature to denote various time relationships between rainfall excess and runoff characteristics. It was found in this study that the least variable and most readily determined time parameter was the time from the center of mass of a limited block of intense rainfall to the resulting peak of the hydrograph. For the convectional thunderstorms causing flood

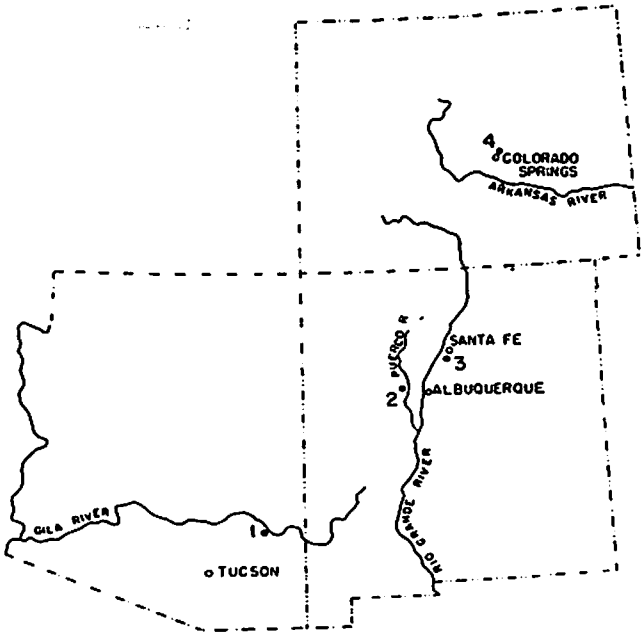

Fig. 1 Location map of experimental watersheds: (1) Safford, Ariz.; (2) Albuquerque, N. M.; (3) Santa Fe, N. M., and (4) Colorado Springs, Colo.

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TABLE 1. WATERSHED CHARACTERISTICS

Watershed	A Size, acres	S Avg. slope, percent	S_{sa} Avg. slope of source area, percent	DD Drainage density, ft per acre	T_L Lag time, min	W_{sa} Width of source area, ft	L_{sa} Length to source area, ft	Cover	Soils
				Safford, Arizona					
W-I	519	8.5	9.4	43	35	1690	9200	Shrubs-grass, 10-20%	Stony-sandy loam, moderate depth
W-II	682	12.4	19.7	70	19	1160	12300	Shrubs-grass, 10-35%	Stony-sandy loam, moderate depth
W-IV	764	2.6	2.6	106	46	1640	4800	Shrubs, 15-25%	Sandy loam, moderate depth
W-V	723	14.7	17.7	55	19	1500	12300	Grass, 10-35%	Stony-clay loam, moderate depth
				Albuquerque, New Mexico					
W-I	97.2	16.5	17.2	100	9	1420	720	Brush-grass, 10-25%	Sandy-clay loam, shallow rock outcrops
W-II	40.5	14.3	16.4	86	12	615	1790	Grass, 5-30%	Fine-sandy loam, shallow crusted
W-III	183.0	6.9	9.7	75	19	1210	1350	Grass-shrubs, 5-35%	Fine-sandy loam, shallow crusted
				Sante Fe, New Mexico					
W-I	50.0	9.9	10.4	89	16	680	2440	Grass-shrubs, 25-35%	Loam, shallow to moderate depth
W-II	790.0	4.3	5.4	42	41	1820	9180	Grass, 20-30%	Clay loam, moderate depth
W-III	51.6	18.9	19.4	143	7	880	620	Brush-grass, 10-35%	Sandy-clay loam, moderate depth
				Colorado Springs, Colorado					
W-I	10.6	4.2	4.7	Cultivated	6	290	810	Cultivated	Clay loam, deep
W-II	39.7	6.0	6.8	57	20	540	1720	Grass	Clay loam, deep
W-III	35.4	5.6	5.9	100	20	520	1810	Grass	Loam, deep
W-IV	35.6	8.4	9.1	180	12	720	1720	Grass	Sandy loam to gravelly-clay loam, moderate depth

runoff from the watersheds, there was little difficulty in selecting the intense rainfall block responsible for the runoff peak. The minimum duration of the block causing the peak varied, of course, with watershed size. Fig. 2 shows a typical rainfall intensity-hydrograph plotting from which lag time was measured. About 130 such plottings (consisting of several of the largest peak flows from each watershed) were made for determination of characteristic watershed lag time.

Correlation of Lag Time with Watershed Characteristics

Snyder (1)*, using data from the Appalachian Mountain area, has related basin lag time (which he defined as the time from center of mass of rainfall excess to peak of the unit hydrograph) to watershed length parameters. Linsley (2) modified Snyder's equation and applied it to watersheds on the western slope of the Sierra Nevada. The U.S. Bureau of Reclamation (3) has used channel slope in addition to length parameters in estimating lag time. None of these combinations of watershed characteristics correlated very well with lag time for the 14 watersheds in this study. Therefore, multiple correlations of lag time with various combinations of watershed and channel slopes and lengths, drainage density, shape, and size were made. Of some 50

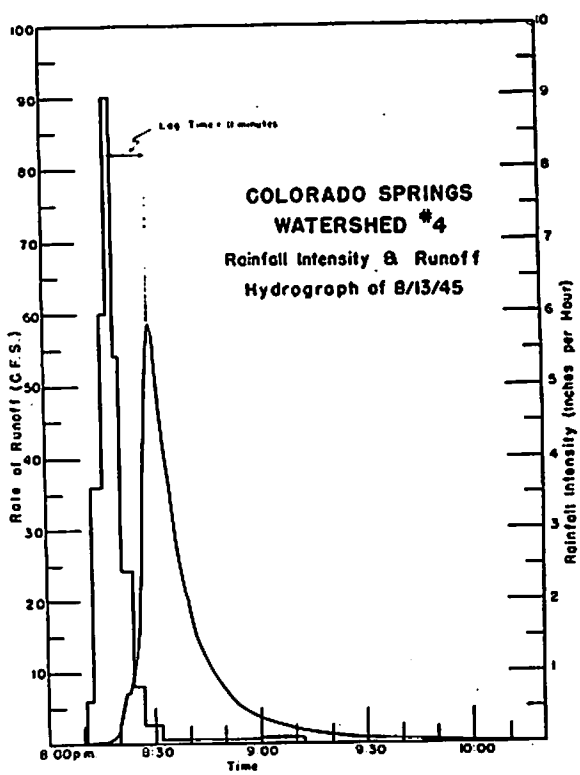

Fig. 2 Typical rainfall intensity (hydrograph plot shows lag time determinations)

*Numbers in parentheses refer to the appended references.

such multiple correlations, two were decidedly superior. These relationships are described in equations [1] and [2].

$$T_L = K_1 \left[\frac{A^{0.3}}{S_a \sqrt{DD}} \right]^{0.61} \quad . \quad . \quad . \quad . \quad . \quad [1]$$

Where:

T_L=lag time (time from limited block of intense rainfall to peak of hydrograph)

A=watershed area

S_a=average landslope of the watershed

DD=drainage density (total length of visible channels per unit area)

When length is in feet, area in acres, slope in percent, and lag time in minutes, $K_1=106$.

Equation [1] gave a standard error of estimate of 10.1 percent and a maximum deviation of 20.0 percent (Fig. 3).

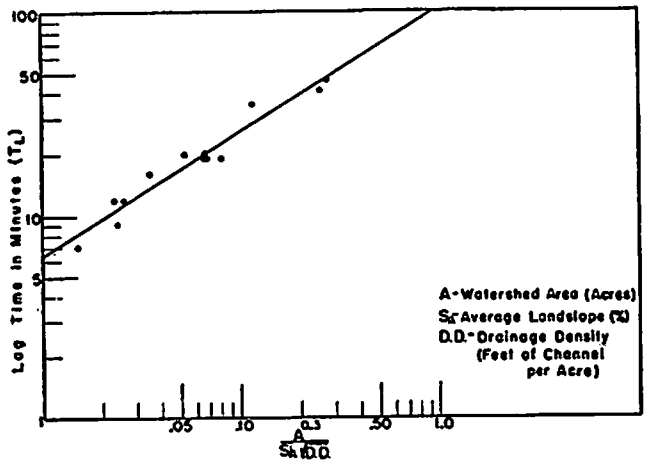

Fig. 3 Correlation of lag time with watershed parameters

In correlating lag time with watershed slope, it was noted that the slope of the half of the watershed having the largest average slope gave better correlation than did the slope of the entire watershed. This seemed to indicate that the steeper portion of the watershed may control the time of peak of the hydrograph even though rainfall excess occurs over the entire area. This gave rise to the concept of a controlling source-area for each watershed. The regression equation expressing lag time as a function of source-area parameters is:

$$T_L = K_2 \left[\frac{\sqrt{L_{sa} + W_{sa}}}{S_{sa} \sqrt{DD}} \right]^{0.65} \quad . \quad . \quad . \quad . \quad [2]$$

Where:

L_{sa}=length from outlet of the watershed to center of gravity of source area

W_{sa}=average width of source area

S_{sa}=average land slope of the source area

DD=drainage density for entire watershed

When length is in feet, slope in percent, and lag time in minutes, $K_2=23$. Equation [2] was derived by considering the half of the watershed with the highest average landslope as the source area. Limited use of the equation in estimating lag times for larger heterogeneous watersheds indicates that the source area may be any important fractional part of the total watershed area which has distinctly greater slope or drainage density than the rest of the area.

Estimates based on equation [2] gave a standard error of estimate of 8.4 percent, and a maximum deviation of 12.6 percent (Fig. 4).

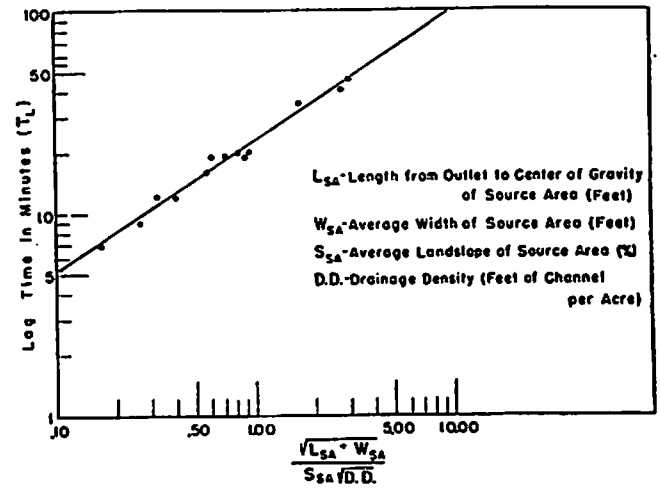

Fig. 4 Correlation of lag time with source area parameters

Equation [1] provides an estimate of lag time within practical confidence limits for reasonably homogeneous semi-arid rangeland watersheds up to about 1,000 acres in area. Very likely the size limitation is dependent on the character of rainfall and should be considered to be the upper limit of area from which the maximum runoff is expected to occur from rainfall excess over the entire area.

The source-area concept, equation [2], gives a more refined estimate of lag time for watersheds which differ widely in physiographic characteristics in some major portion of the area from the rest of the watershed, or which are large enough so that maximum runoff may occur as a result of rainfall excess occurring over only a portion of the watershed.

Correlation of Peak Rate — Volume Ratio with Lag Time

Lag time was found in this study to be a major determinant of hydrograph shape, and it is logical to express the ratio of the peak rate of runoff (q_p) to the total runoff volume (V) as a function of lag time. Fig. 5 shows this corre-

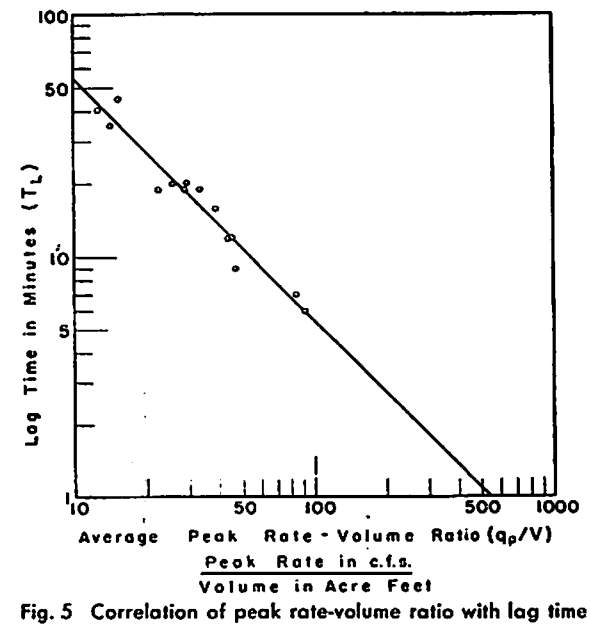

Fig. 5 Correlation of peak rate-volume ratio with lag time

lation of peak-volume ratio with lag time. The regression equation is:

$$q_p/V = K_3/T_L \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad [3]$$

When q_p is in cfs, V in acre feet, and T_L in minutes, $K_3=545$.

Equation [3] gave a standard error of estimate of 14.6 percent with a maximum deviation of 29.0 percent.

Equation [3] is useful in estimating peak rate of runoff for any total volume of runoff. The relationship of peak-volume ratio to lag time also enables utilization of very limited hydrograph data for minor flows to predict peaks and estimate the hydrograph shape of much larger flows.

Development of Generalized Dimensionless Hydrograph and Mass Curve

For each of the 13 uncultivated watersheds included in the study, an average dimensionless distribution graph was prepared, using all suitable runoff hydrographs. The time base was made dimensionless in terms of the watershed lag time, and time increments of 20 percent of lag time were considered. The dimensionless distribution graphs for all watersheds were averaged, and a generalized dimensionless hydrograph and mass curve were computed (Fig. 6). The

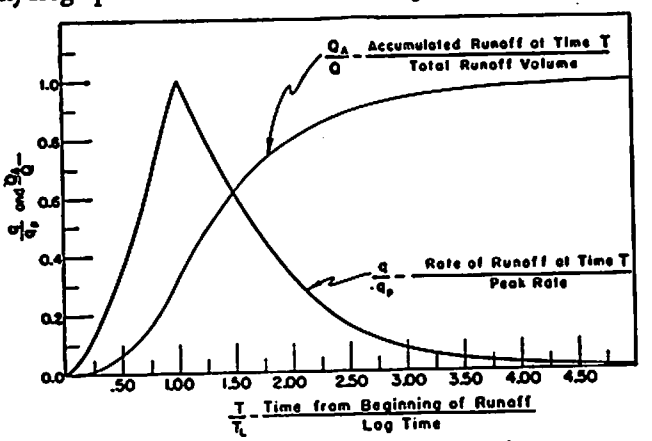

Fig. 6 Generalized dimensionless hydrograph and mass curve

synchronizing and averaging steps were more easily accomplished by working with distribution graphs rather than by working directly with hydrographs, since minor irregularities in the hydrographs were smoothed in preparing the distribution graphs. Coordinates defining the generalized dimensionless hydrograph and mass curve are given in Table 2.

TABLE 2. DATA FOR DIMENSIONLESS HYDROGRAPH AND MASS CURVE (Fig. 6)

T/T_L	q/q_p	Q_a/Q	T/T_L	q/q_p	Q_a/Q
0	0	0	1.6	0.545	0.671
0.1	0.025	0.002	1.7	0.482	0.707
0.2	0.087	0.007	1.8	0.424	0.742
0.3	0.160	0.020	1.9	0.372	0.773
0.4	0.243	0.036	2.0	0.323	0.799
0.5	0.346	0.063	2.2	0.241	0.841
0.6	0.451	0.096	2.4	0.179	0.875
0.7	0.576	0.136	2.6	0.136	0.900
0.8	0.738	0.180	2.8	0.102	0.917
0.9	0.887	0.253	3.0	0.078	0.932
1.0	1.000	0.325	3.4	0.049	0.953
1.1	0.924	0.400	3.8	0.030	0.965
1.2	0.839	0.464	4.2	0.020	0.973
1.3	0.756	0.523	4.6	0.012	0.979
1.4	0.678	0.578	5.0	0.008	0.983
1.5	0.604	0.627	7.0	0	0

Illustration of Method for Hydrograph Synthesis

The following example will illustrate the method of hydrograph synthesis. Walnut Gulch experimental watershed No. 4, located near Tombstone, Ariz., has been selected for the example because it is within the size range and climatic region represented by the watersheds from which the method was developed. The measured hydrograph having the largest peak flow for the four-year period of record was used for comparison with a computed hydrograph. Pertinent physical features for Walnut Gulch watershed No. 4 are:

Area *(A)*	— 590 acres
Average land slope *(S_a)*	— 9 percent
Drainage density *(D.D.)*	— 93 feet per acre

The average landslope was determined from a sample of slope measurements with an Abney hand level. Drainage density was determined by measuring the length of all drainage detail visible on an aerial photograph with a scale of 2 inches to the mile. Physiography of the watershed is relatively homogeneous; hence, equation [1] is used, which results in a value of 22.3 min for the lag time *(T_L)*. This compares closely with an average measured lag time of 24 min for five of the major runoff events for this watershed.

The next step is to compute, from equation [3], the peak rate of runoff *(q_p)* for any assumed total volume of runoff *(V)*. For a particular design application, V may be estimated from the assumed design storm rainfall volume and an estimated rainfall-runoff relationship, or a design storm runoff volume may be established directly. For this example, $V=62.7$ acre-feet, the actual measured volume of runoff for the storm of July 19, 1955, was used for a realistic comparison of an actual and a computed hydrograph. Thus q_p is computed to be 1530 cfs. The measured peak was 1425 cfs. Fig. 6, is entered with values of T/T_L to obtain values of q/q_p, enabling the computed hydrograph to be determined in its entirety with any desired degree of detail. The computed and measured hydrographs are compared in Fig. 7.

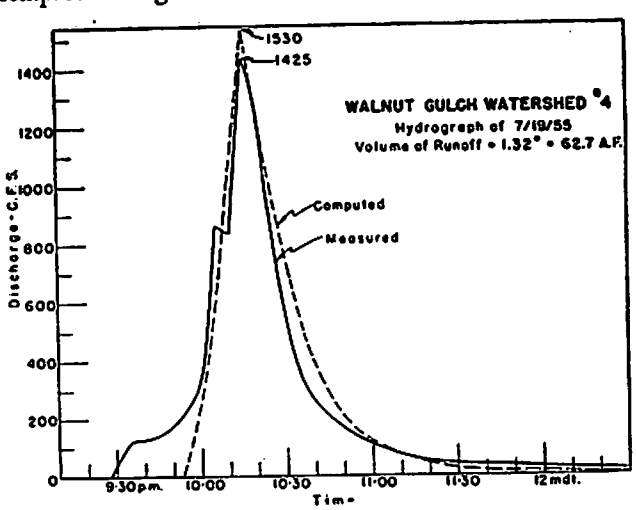

Fig. 7 Comparison of measured and computed hydrographs

Discussion and Conclusions

For the watersheds considered in this study, lag time as herein defined is the most significant time parameter in relating watershed influences to hydrograph shape. It was found that for a given watershed the rise time of the hydrograph (time from beginning of runoff to the peak) varied

between much wider limits than did the lag time. Rise time is frequently affected by the duration of rainfall excess and minor variations in rainfall intensity—whereas lag time is relatively independent of the rainfall pattern. Rise time varied from 74 percent to 145 percent of lag time for the individual watersheds in this study. The average for all watersheds was 102 percent. Accordingly the generalized dimensionless hydrograph was constructed with lag time and rise time equal. However, it may not be concluded from this coincidence that the time of rise of the hydrograph affords a generally satisfactory index of watershed influence on the hydrograph shape. The measured hydrograph of Fig. 7 illustrates this point. The first portion of the rising limb of the hydrograph, from 9:38 p.m. to about 9:55 p.m., was caused by a minor burst of intense rainfall. That this portion is relatively insignificant in characterizing the overall hydrograph shape is indicated by the fact that only 8 percent of the total volume of runoff occurred during this 17-min period. The rise time of this hydrograph is 47 min compared with a measured lag time of 20 min. It is the latter time factor which is important in describing hydrograph shape and its relation to watershed physiography.

It should also be pointed out that lag time as defined in this paper does not correspond, except for very small watersheds with extremely simple drainage patterns, to the classical concept of "time of concentration." For natural watersheds of any size and complexity of drainage, runoff water originating from the most remote portion may and usually does arrive at the outlet too late to contribute to the flood peak. Accordingly, lag time will generally be less than the time of concentration for a given watershed.

For determination of lag time in the watersheds considered in this study, it is evident from equations [1] and [2] that the most important physiographic feature is land slope. All of the correlations involving channel slope were distinctly poorer than those involving land slope. Where flood peaks are almost exclusively the result of cloudburst-type convectional thunderstorms, it is highly probable that runoff water moves off the watershed and into the main channel in the form of abrupt translatory waves. Momentum effects might be expected to predominate over channel resistance effects in this type of flow. Consequently, from theoretical considerations, one would expect land slope to be of more importance than channel parameters in determining lag time, as was found in this case.

In equation [1] watershed area (A) provides an index of distance travelled, while in equation [2] the width of source area (W_{sc}) and the length of source area (L_{sc}) constitute a direct measure of travel distance. In both equations, the drainage density term (DD) provides a measure of what might be termed the hydraulic efficiency of the watershed i.e., the relative proportion of channel versus overland flow.

Within the range of conditions encountered in the present study, the shapes of the dimensionless hydrograph and mass curve (Fig. 6), were found to be independent of rainfall pattern and of soil and cover condition.

Experience has shown that estimates of runoff volume-frequency relations made from short-period records may be transferred to somewhat dissimilar watersheds with much greater confidence than is possible with similar estimates of peak runoff rates. Conversion of such a volume estimate to a corresponding estimate of peak rate on the basis of a lag time and correlated estimate of peak rate-volume ratio for the specific watershed being considered results in a substantially better estimate of the runoff peak.

The method of hydrograph synthesis presented is directly applicable to uncultivated arid-land watersheds of such size that major floods result from single thunderstorms producing runoff from the entire watershed. The authors feel that in order to satisfy this restriction the limit on size should be about 1000 acres for most areas of the Southwest. Work is currently under way to test the validity of this approach for watersheds of much greater area.

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