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HYDROGRAPHS OF EPHEMERAL STREAMS IN THE SOUTHWEST

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INTRODUCTION

Numerous methods are presently used to compute the total volume of runoff associated with a particular combination of storm rainfall and antecedent conditions.[3,4,5] In most instances, however, the estimate of runoff volume is only a preliminary step in the determination of the outflow hydrograph from a basin.

The high-intensity, short-duration convective thunderstorms that cause most of the runoff in ephemeral streams of the southwestern United States rarely cover an entire watershed if its area is larger than a few square miles. The processes by which excess rainfall is transmitted from various parts of a drainage basin to a downstream channel section are reflected in the shape of the runoff hydrograph. The downstream hydrograph in arid and semiarid areas of the Southwest is greatly affected by the storm pattern, the

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3 Gray, Don M., "Derivation of Hydrographs from Small Watersheds from Measurable Physical Characteristics," Research Bulletin No. 506, Iowa State Univ., Ames, Iowa, June, 1962.

4 Reich, B. M., "Design Hydrographs for Very Small Watersheds from Rainfall," CER62BMR41, Colorado State Univ., Fort Collins, Colo., July, 1962.

5 "Section 4: Hydrology," National Engineering Handbook, Soil Conservation Service, U. S. Dept. of Agric., Washington, D. C., 1957.

high intake rates in the coarse-textured alluvial stream beds that are typical of the area, and by the overriding translatory waves developed in the channels.

DESCRIPTION OF WATERSHEDS

Data presented herein are derived from the Walnut Gulch Experimental Watershed, a mixed grass and brush rangeland watershed in southeastern Arizona, and the Alamogordo Creek Experimental Watershed, a blue grama grassland watershed in east-central New Mexico. Annual precipitation on these watersheds is approximately 14 in. with between 50% and 70% of the annual precipitation, and essentially all of the runoff, occurring during the June-to-September period as a result of intense, small-diameter, convective storms. Elevations vary from 4,200 ft above mean sea level at the watershed outlet to over 6,000 ft at the upper end of Walnut Gulch, and from 4,500 ft to 5,200 ft on Alamogordo Creek.

The 58-sq-mile Walnut Gulch watershed is an ephemeral tributary of the San Pedro River (Fig. 1). Stream channels in the watershed are typical of the semiarid Southwest. The channel gradients are steep (approximately 1%), and, consequently, the flow velocities are high. In most of the channel system, several feet of unconsolidated sand and gravel overlie bedrock or fine-textured sediment. The particles comprising the bed material exhibit a logarithmic normal distribution with a geometric mean particle size of 2.3 mm. Of the total material 54% lies in the gravel range (>2.0 mm).

Precipitation in the Walnut Gulch watershed is measured with a network of 82 recording rain gages. Runoff is measured at the watershed outlet and from seven subwatersheds (Fig. 1) with the Walnut Gulch supercritical measuring flume.[6,7]

The 67-sq-mile Alamogordo Creek Experimental Watershed (Fig. 1) is located on the western edge of the Llano Estacado approximately 35 miles east of Santa Rosa, N. Mex. It is in the headwaters of Alamogordo Creek, a tributary to the Pecos River, entering just upstream from the Alamogordo Reservoir. The watershed consists primarily of a flat, recessed basin almost entirely surrounded by a steep escarpment.

Channel gradients in the lower parts of the watershed are approximately 0.5% and are considerably less in the central part. Channel materials in this watershed are considerably finer than those on Walnut Gulch containing approximately 30% silt and clay in the lower part of the watershed with more than 40% silt and clay in the upper and central parts.

The main channel of Alamogordo Creek is incised for only about 2.8 miles upstream from the runoff measuring station. Upstream progress of the head cutting has been arrested by sandstone outcrops on the main stem. Above the incised reach, the channel widens abruptly into broad swales. This poorly defined drainage system with the large valley storage has a marked effect on the hydrograph. Two large tributaries (the southeast and southwest branches, Fig. 1) enter the main stem about 1 mile above the outlet of the experimental

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6 Gwinn, W. R., "Walnut Gulch Supercritical Measuring Flume," Transactions, Amer. Soc. of Agric. Engrs., St. Joseph, Mich., Vol. 7, No. 3, 1964, pp. 197-199.

7 Osborn, H. B., Keppel, R. V., and Renard, K. G., "Field Performance of Large Critical Depth Flumes for Measuring Runoff from Semiarid Rangelands," ARS 41-69, U. S. Dept. of Agric., Washington, D. C., March, 1963.

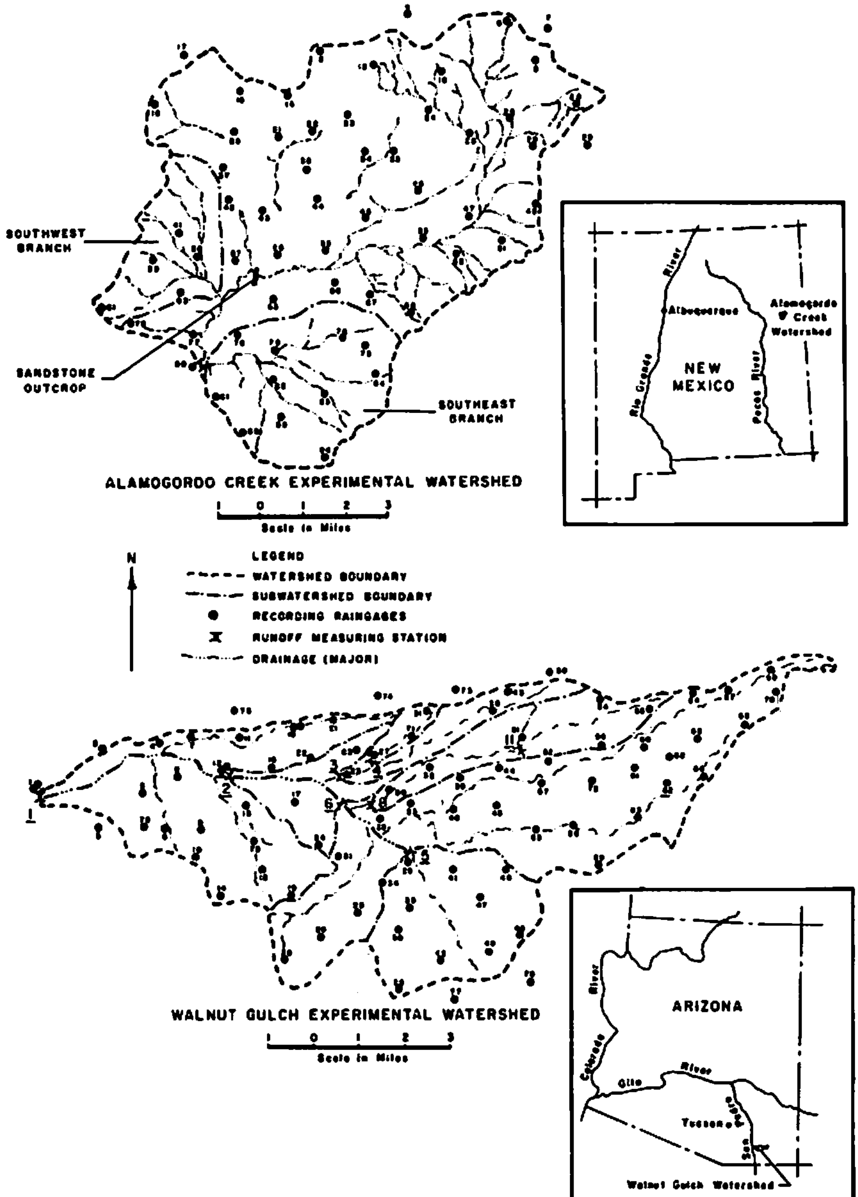

FIG. 1.—LOCATION MAPS OF THE EXPERIMENTAL WATERSHEDS SHOWING HYDROLOGIC INSTRUMENTATION

area. These tributary areas do not have the broad swales characteristic of the main stem, but have incised channels similar to those in the lower reach. Hydrographs caused by runoff from these tributaries show the rapid rise and short peak discharge characteristic of ephemeral streams; whereas hydrographs originating from runoff on the central or upper valley floor are characterized by sustained peak discharges with a duration of 1 hr to 2-1/2 hr.

As a part of the watershed research program being conducted in the area, a network of 60 recording rain gages has been in continuous operation since 1955. Runoff at the watershed outlet is measured with a laboratory-rated, critical-depth flume.

HYDROGRAPH PARAMETERS

For water resource development projects where runoff data are not available, the design hydrologist must resort to some method of estimating hydrograph characteristics, considering general climatic and hydrologic information for the locality, and physiographic features of the particular watershed. This may involve (1) estimating the magnitude and frequency of peak discharges, (2) developing estimates of corresponding storm runoff volumes, (3) estimating a time parameter based on characteristics of the watershed, and (4) synthesizing complete hydrographs based on the expected volumes of runoff, the watershed time parameter, and a dimensionless hydrograph. Herein, investigation is limited to items (2), (3), and (4) above.

Peak-Volume Correlations.—Table 1 shows the results of correlations of peak discharge with runoff volume from eight experimental subwatersheds at Walnut Gulch watershed and from the Alamogordo Creek watershed. In this analysis, multipeak storms were subdivided in instances when the first storm had nearly receded or were disregarded in instances when an examination of the isohyetal map indicated more than one runoff-producing area during the storm period. The values of K and b in Table 1 indicate the values for the prediction equation

$$\hat{Y} = K + bX \qquad (1)$$

in which $\hat{Y}$ = predicted runoff volume, in acre-feet; X = the peak discharge, in cubic feet per second; and K and b = constants determined from a least squares regression analysis.

The linear relationship between peak and volume appears to be valid for the type storms producing the runoff in this analysis. The runoff producing convective storms in the Southwest are generally about 1 hr's duration with the runoff producing part of the storm generally occurring in less than 30 min.

All of the correlation coefficients, shown in column 6 of Table 1, are significant at the 0.1% level except that for the flat top hydrographs on Alamogordo Creek watershed, which is significant at the 10% level. The flat top hydrographs result from the configuration of the main channel in the lower central part of the watershed as previously described. The duration of the nearly constant discharge of runoff from above, resulting from channel control at this point, is quite variable and varies with peak discharge.

The coefficient of determination, r^2 (which would average approximately 0.75 for the Walnut Gulch subwatersheds), is the fraction of Σy^2 (sum of the squares of the deviation from regression) associated with the correlated changes in the peak discharge and the volume of runoff whereas the coefficient of nondetermination ($1 - r^2$, approximately 0.25) is the part of the variation in runoff volume that cannot be explained by differences in the peak discharge. The variation unexplained by the peak discharge might be attributed to variations in channel moisture conditions, variation in rainfall intensity within a strom, etc.

The assumption of a linear regression leads to estimated positive values for runoff volume when peak discharge is zero, a result that is physically impossible. However, forcing the line through the origin, using the regression equation $Y = bX$, $(K = 0)$, departs materially from a least squares regression for significant peak discharges. For example, the slope of the line, b, through the origin for Watershed 3 would be 0.0589 compared to the 0.0570 for the least squares regression, a difference of 3.3%. It is believed that the computed linear regression provides the best volume estimate, subject to the restriction that the equations do not hold as $X \longrightarrow 0$.

TABLE 1.—STATISTICAL PARAMETERS FOR PEAK-VOLUME RELATIONSHIPS

Watershed Number (1)	Drainage Area, in Square miles (2)	Number of Events (3)	K (4)	b (5)	r (6)
		Walnut Gulch			
1	57.7	83	12.65	0.0658	0.917
2	43.9	93	9.41	0.0736	0.935
3	3.47	51	2.32	0.0570	0.786
4	0.88	55	1.28	0.0530	0.845
5	8.61	78	0.86	0.0672	0.895
6	36.7	29	10.63	0.0742	0.809
8	5.98	20	4.47	0.0247	0.920
11	3.18	17	4.71	0.0433	0.878
		Alamogordo Creek			
Flat top	67	9	158	0.558	0.612
Sharp peaked	67	21	12.27	0.189	0.745

The values of K and b in the least squares regression equations for Walnut Gulch watershed generally seem to vary in an exponential manner with drainage area (Fig. 2).

On subwatershed 5 of Walnut Gulch, the constant K is considerably lower than the predicted line, an unexplained deviation. This watershed contains two large stock ponds and is considerably different physically from other subwatersheds of Walnut Gulch. Subwatershed 5 is nearly circular, and unlike the other areas, which have rather deep, coarse sand and gravel beds, much of the channel of this watershed is devoid of gravel with the streambed being formed by conglomerate for most of its length.

On the Alamogordo Creek watershed, two types of hydrographs occur, depending on the part of the watershed producing the runoff. Storms originating in the upper and middle parts of the watershed typically have a flat top (i.e., constant peak discharge) hydrograph. The broad swales of the poorly defined drainage network in this area cause considerable storage. Outflow from this

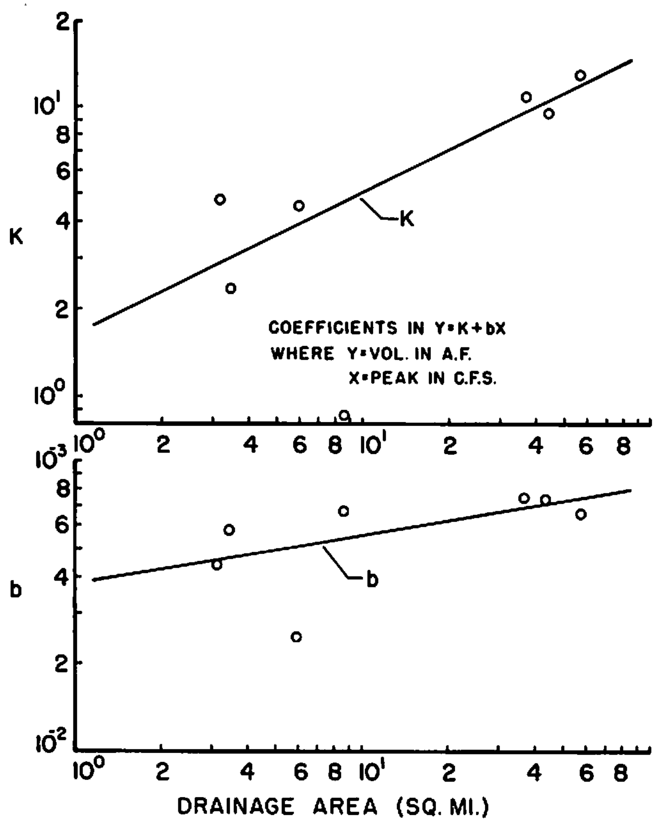

FIG. 2.—STATISTICAL PARAMETERS OF PEAK VOLUME PREDICTION VERSUS DRAINAGE AREA—WALNUT GULCH

area into the incised channel on the lower part of the watershed over the sandstone outcrops at the head of the incised channels occurs at a nearly constant rate and for relatively long periods until the valley storage is gradually depleted. The two incised tributaries entering the main channel above the outlet of the experimental area exhibit the short rise time and sharp peak typical of the Walnut Gulch watersheds.

Hydrograph Rise Time.—Time of concentration is frequently used as the time parameter in hydrograph analyses and is defined as the time required for water to travel from the hydraulically most distant point to the watershed outlet. In hydrograph studies where runoff-producing rainfall seldom covers the entire watershed, the time of concentration is a difficult parameter to use. The thunderstorms that cause most of the runoff in the Southwest are typically of small areal extent and appear to occur in a more or less random pattern, as single- or multiple-celled events. On a given watershed, each storm pattern would have a different time of concentration as influenced by such factors as the size of the storm (areal coverage and depth), position on the watershed, and antecedent moisture conditions of the channel alluvium. For multicelled events, numerous concentration times would be involved in a single hydrograph, dependent on the same variables enumerated for a single-celled event plus the time and spatial variations associated with the individual storm cells.

Similar objections may be raised to the use of lag time, another commonly used time parameter that is defined as the time from the center of mass of a limited block of intense rainfall to the resulting peak of the runoff hydrograph. This time parameter was used by R. B. Hickok, R. V. Keppel, and B. R. Rafferty[8] and was related to physiographic parameters on small watersheds (to 1,000 acres) in the Southwest. For the watersheds considered in their study, the hydrograph rise time (time from beginning of runoff to the time of peak discharge) varied from 74% to 145% of the lag time with an over-all average of 102%. Therefore, they constructed a dimensionless hydrograph with basin lag time and rise time equal. For the Walnut Gulch and Alamagordo Creek watersheds considered in this study, hydrograph rise time would generally be a small percentage of the lag time.

For the watersheds examined herein, hydrograph rise time is believed to be a more reliable time parameter than either time of concentration or lag time. In a paper by Keppel and Renard,[9] an equation for average rise time for the Walnut Gulch watersheds was given as

$$T_r = 25.3\, A_w^{-0.14} \qquad (2)$$

in which T_r = rise time, in minutes, and A_w = watershed area, in square miles. As explained in that paper,[9] the decrease in rise time with increase of drainage area is probably the result of two interrelated factors, namely (1) the occurrence of most of the transmission losses during rising stages of the flow, and (2) the presence of overriding translatory waves as the flow moves through the channel. Table 2 shows the range of T_r-values used in developing the dimensionless hydrographs subsequently presented herein.

Rise time for an alluvial bed stream such as Walnut Gulch is a function of numerous hydrologic, hydraulic, and topographic variables. The data presently (as of 1966) available are not sufficient to quantitatively evaluate the variables. However, with the information from storms that have occurred, the areal

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[8] Hickok, R. B., Keppel, R. V., and Rafferty, B. R., "Hydrograph Synthesis for Small Aridland Watersheds," Agricultural Engineering, St. Joseph, Mich., Vol. 40, No. 10, October, 1959, pp. 608-611.

[9] Keppel, R. V., and Renard, K. G., "Transmission Losses in Ephemeral Stream Beds," Journal of the Hydraulics Division, ASCE, Vol. 88, No. HY3, Proc. Paper 3116, May, 1962, pp. 59-68.

extent, the maximum 5-min or 10-min storm intensity, position of storm with respect to the outlet, peak discharge, transmission losses, and the overriding waves are all observed to affect the rise time of the runoff hydrograph. Also, their affects are modified by the occurrence of a multicellular thunderstorm.

The influence of areal extent of precipitation on rise time is evident. Small diameter convective cells, typical of the Southwest, tend to cause short hydrograph rise times because of the usually short duration of such storms and because, generally, there is no preliminary flow from runoff generated in and adjacent to the channel in the immediate vicinity of the runoff measuring station. Although most thunderstorms in the Southwest are limited in areal extent to a few square miles,[10,11] runoff occasionally results from a system of convective cells associated with a frontal storm pattern,[12] and a large part or all of the watershed may experience precipitation in excess of infiltration.

The maximum 5-min or 10-min rainfall intensity is closely related to rise time. Thunderstorms, typically, are less than 1 hr in duration, and the rain

TABLE 2.—HYDROGRAPH RISE TIMES FOR WATERSHEDS USED IN THIS STUDY

	Walnut Gulch					Alamogordo Creek	
	Watershed no.					Hydrograph type	
	1	2	3	4	6	flat top	sharp peaked
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
			T_r, in minutes				
Maximum	60	50	40	40	63	42	120
Minimum	5	6	8	7	4	15	30
Average	17.9	21.8	17.9	22.5	19.7	32	75

falling within short time intervals generally includes the part of the storm causing the most significant runoff. For the Walnut Gulch watershed, the maximum 5-min depth was found to be about one-half the maximum 20-min depth, and about one-third the total storm precipitation.[13] The maximum short-time interval intensity is also related to rise time through its effect on translatory waves. Runoff resulting from high intensities moves off the land into channels

[10] Osborn, H. B., and Reynolds, W. N., "Convective Storm Patterns in the Southwestern United States," Bulletin, Internatl. Assn. of Scientific Hydrology, Melle, Belgium, Vol. 8, No. 3, 1963, pp. 71-83.

[11] Osborn, H. B., "Effect of Storm Duration on Runoff from Rangeland Watersheds in the Semiarid Southwestern United States," Bulletin, Internatl. Assn. of Scientific Hydrology, Melle, Belgium, Vol. 9, No. 3, 1964, pp. 40-47.

[12] Keppel, R. V., "A Record Storm Event on the Alamogordo Creek Watershed in Eastern New Mexico," Journal of Geophysical Research, Washington, D. C., Vol. 68, No. 16, August, 1963, pp. 4877-4880.

[13] Renard, K. G., and Osborn, H. B., "Rainfall Intensity Comparisons from Adjacent 6-Hour and 24-Hour Recording Rain Gages," Water Resources Research, Amer. Geophys. Union, Washington, D. C., January, 1966.

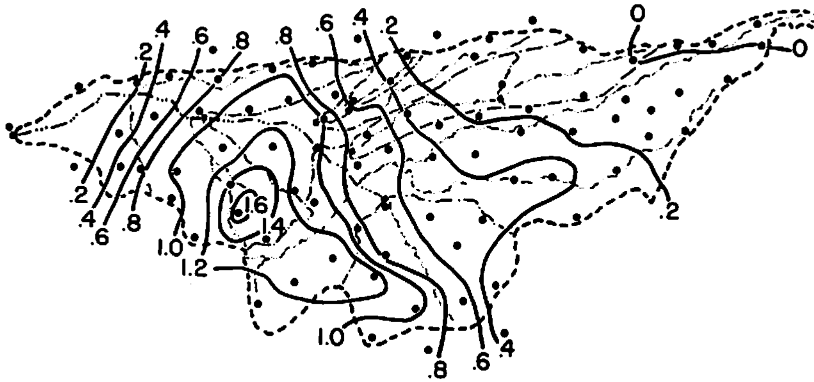

FIG. 3.—ISOHYETAL MAP OF WALNUT GULCH FOR THE STORM OF SEPTEMBER 7, 1963 (RAINFALL AMOUNT, IN INCHES)

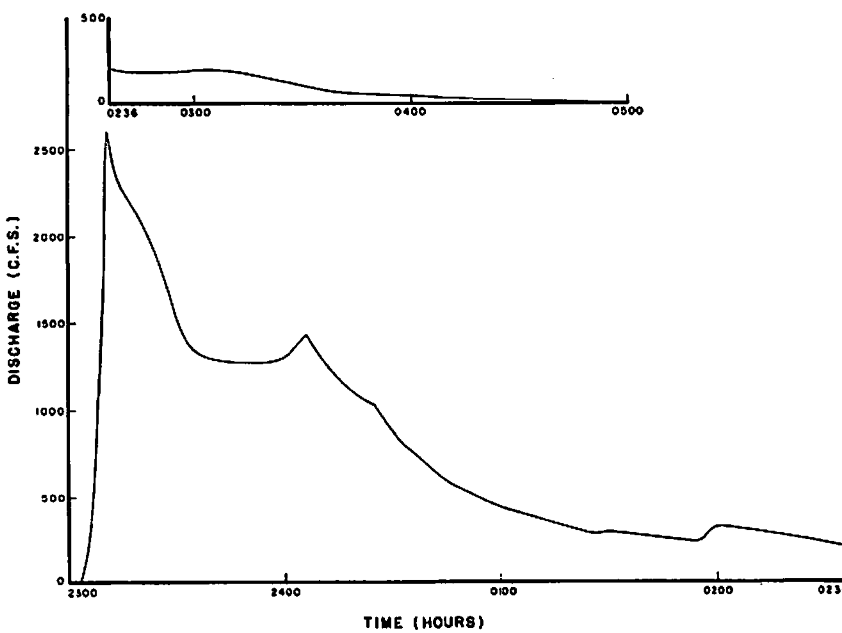

FIG. 4.—HYDROGRAPH FOR THE STORM OF SEPTEMBER 7-8, 1963, ON WATERSHED 1 ON WALNUT GULCH

as abrupt slugs, therby creating the potential for waves to move through the channels, combining into an abrupt wave near the front of the runoff mass.

Position of the storm on the watershed can affect the rise time of the runoff hydrograph in more than one way. The farther the storm is from the watershed outlet, the greater the potential for transmission losses and overriding or translatory waves to occur. The position of the storm within a watershed can also affect the rise time by a multiple routing of flows in much the same manner as a multicellular event. This can best be demonstrated with the isohyetal map of the storm of September 7, 1963 (Fig. 3).

Runoff from the storm which had its center near rain gages 18 and 19, near the divide of subwatersheds 2 and 6, moved through various channels to the watershed outlet. It is about seven miles via the shortest channel route from rain gage 19 to the watershed outlet. However, considerable runoff did not take the shortest route, but traversed nearly three additional miles of channel before reaching the watershed outlet. The result was a compound hydrograph at the watershed outlet (Fig. 4).

Rise time varies with the peak discharge, but it is the relation to this variate that is undoubtedly most difficult to analyze quantitatively. R. K. Linsley, M. A. Kohler, and J. L. H. Paulhus,[14] Hickok, Keppel, and Rafferty,[8] and others propose formulas relating basin lag time to geometry of hydrograph. Lag time may be closely related to rise time in humid areas. However, N. E. Minshall,[15] working in the Midwest, reports effect of rainfall intensity on the geometry of the unit hydrograph and shows that rise time decreased with increasing peak discharge. Studies reported by Minshall[15] indicate no relationship of basin lag to the rise time for semiarid watersheds of more than a few square miles in area. Here storm pattern and sequence dominate watershed parameters in influencing the shape of the runoff hydrograph.

The peak discharge affects the rise time of the runoff hydrograph through its effects on channel storage. Higher peak discharge and its associated channel storage effects tend to increase the rise time at a downstream station. However, the channel storage and peak discharge also affect transmission losses. The higher peak discharges have a greater wetted perimeter and, consequently, higher transmission losses, a large part of which occur on the rising part of the hydrograph, thereby shortening the rise time. These two effects of peak discharge work in opposite directions on the rise time, and their relative effect varies with storm sequence and antecedent channel wetting.

In general, the rise time of the runoff hydrograph decreases with the channel distance traversed by the runoff. Table 3 shows, for the main stem of Walnut Gulch, the effects of stream routing and other factors on rise time for some of the larger storms when the three tandem runoff measuring flumes (i.e., 6, 2, and 1) have all operated.

Transmission Losses.—The importance of transmission losses in hydrograph analysis for ephemeral streams such as Walnut Gulch is often recognized by the design hydrologist familiar with the semiarid regions. Quantitative information on the effects of these losses on a downstream hydrograph is not, however, generally available.

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[14] Linsley, R. K., Kohler, M. A., and Paulhus, J. L. H., "Applied Hydrology," McGraw-Hill Book Co., Inc., New York, N. Y., 1949.

[15] Minshall, N. E., "Predicting Storm Runoff on Small Experimental Watersheds," Journal of the Hydraulics Division, ASCE, Vol. 86, No. HY8, Proc. Paper 2577, August, 1960, pp. 17-38.

On the Walnut Gulch watershed, transmission losses are being evaluated for several different channel reaches. The magnitude of the losses is determined by comparison of the measured hydrographs at both ends of several channel reaches for runoff events uncomplicated by intermediate tributary inflow.

An example of such an event is shown by the isohyetal map (Fig. 5) and the hydrographs for this event are shown in Fig. 6 for Flumes 6, 2, and 1.

TABLE 3.—PEAK DISCHARGES AND HYDROGRAPH RISE TIME FOR SELECTED EVENTS ON THE MAIN STEM OF WALNUT GULCH WATERSHED

	Flume 6		Flume 2		Flume 1	
Date (1)	Q_p, in cubic feet per second (2)	T_r, in minutes (3)	Q_p, in cubic feet per second (4)	T_r, in minutes (5)	Q_p, in cubic feet per second (6)	T_r, in minutes (7)
1962						
9/4	1,080	12	475	5	1,230[a]	10
1963						
8/10	1,300	29	840[a]	11	240	11
8/12	228	13	120	24	105	3
8/25	1,600	67	1,240	48	1,500[b]	24
8/31	1,440	12	785	2	1,710[a]	20
9/7-8	380	16	586[a]	21	2,600[a]	8
1964						
7/22	7,340	21	4,170[a]	18	4,490	15
8/2	370	5	484	25	268	7
8/8	325	16	200[a]	5	66	7
9/9	1,480	15	962	7	550	5
9/9-10	2,640	46	1,840[a]	28	3,060[a]	38
9/11	3,460	72	2,090	35	2,920[a]	22
Average	1,800	27	1,150	19	1,560	13

[a] Indicates tributary inflow between the main stem measuring stations
[b] Indicates partly estimated peak

The 1,480-cfs hydrograph peak and 74.8-acre-ft volume of runoff at Flume 6 were reduced to 962 cfs and 64.8 acre-ft at Flume 2 and to 550 cfs and 32.5 acre-ft at Flume 1. Similar events were reported for other channel reaches of Walnut Gulch by Keppel and Renard[9] in 1962.

Fig. 7 shows the relationship between transmission loss rate and the average peak discharge in the channel reach 6 ⟶ 2. (Durations were arbitrarily limited to the time during which discharge exceeded 10% of peak discharge.) The average channel width for the 2.8-mile channel reach between Flumes 6

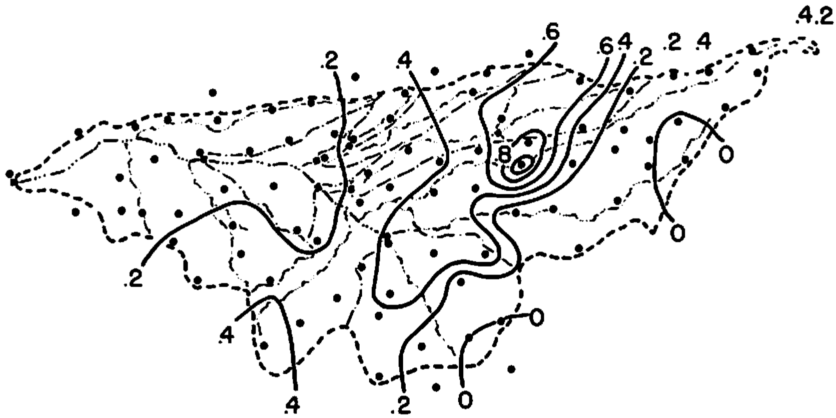

FIG. 5.—ISOHYETAL MAP OF WALNUT GULCH FOR THE STORM OF SEPTEMBER 9, 1964

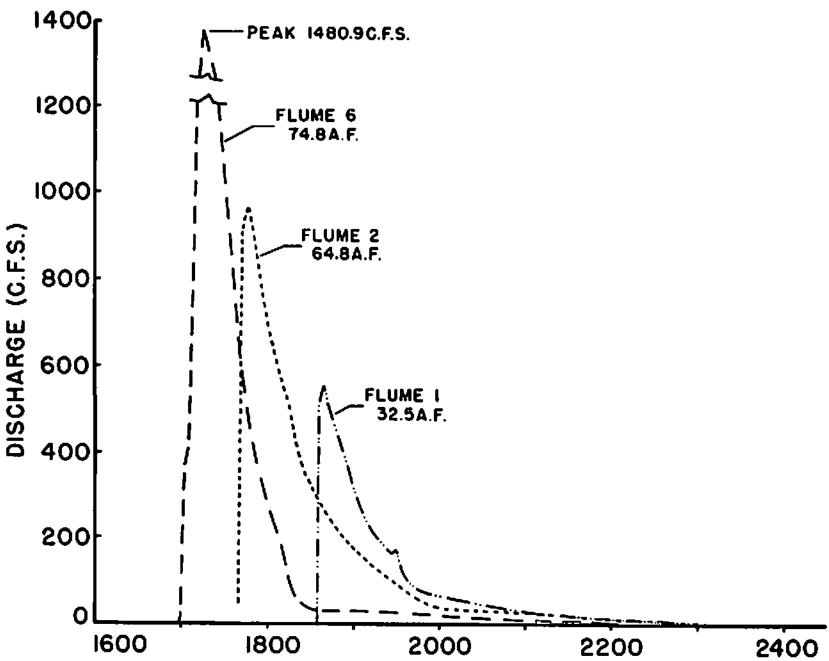

FIG. 6.—HYDROGRAPHS FOR THE STORM OF SEPTEMBER 9, 1964 AT MEASURING FLUMES 6, 2, AND 1 ON WALNUT GULCH

and 2 is 160 ft for flows less than 3-ft deep. Flows greater than 3 ft in depth spread out in some reaches to more than 300 ft, causing large losses in the coarse-textured alluvium of the floodplain.

The curve shows considerable scatter at discharges less than 1,000 cfs, primarily reflecting differences in antecedent moisture conditions. In addition, the sequence of flows may greatly affect the wetted perimeter at the lower

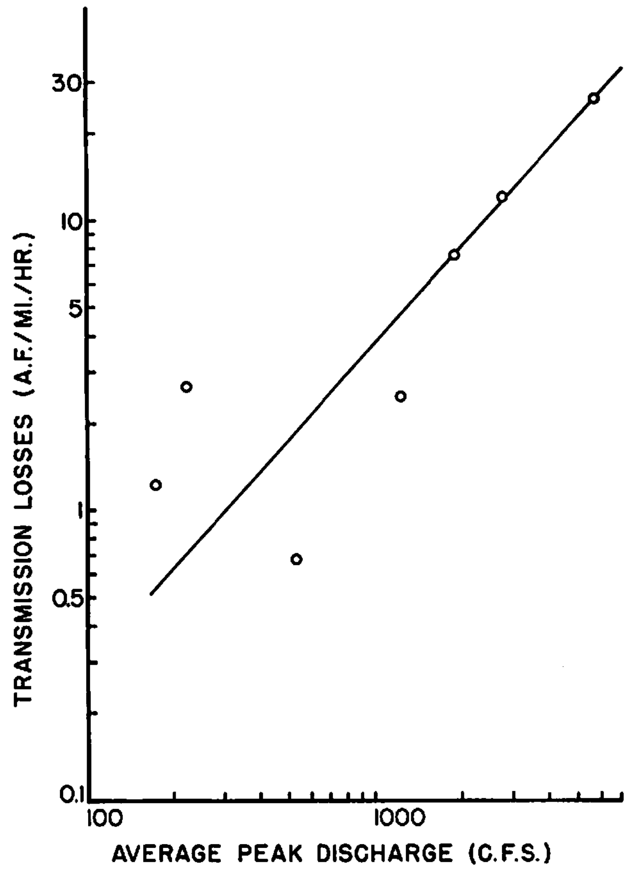

FIG. 7.—TRANSMISSION LOSSES FOR CHANNEL REACH 6⟶2 ON THE WALNUT GULCH WATERSHED

discharges by changing patterns of braided flow. The points above the line occurred during drier periods than those below the line. The largest peak flow and greatest transmission loss for this channel reach occurred on a dry channel on July 22, 1964, when a large borrow pit existed between the two measuring stations. The 51 acre-ft per mile loss, which was greatly influenced by the borrow pit, probably represents a near maximum loss rate for this channel reach.

The greatest part of the transmission loss is believed to occur during the early part of a runoff event. The coarse alluvial beds near the surface dry out rapidly between runoff events. The upper foot or more of the alluvium is coarse with a porosity of more than 25%. With increasing depths, the coarse grains are generally found to be covered with fine alluvium and clay, gradually changing to increased clay in the gravel voids at greater depths. Undoubtedly, this increasing content of fines encountered with depth, results from deposition material suspended in the percolating transmission loss water. Once the surface voids are filled, the rate of loss should become nearly constant, proportional to the hydraulic conductivity and depth of flow. Because the abstractions are so large during the first contact of the advancing flow front, while stages are increasing upstream, the rise time of the hydrograph decreases with increasing distance the flow has traversed over a dry bed.

Translatory Waves.—Along the channel reach between Walnut Gulch Flumes 6 and 2 are six stilling wells with 6-hr-per-revolution water-level recorders. Their purpose is to study the flood wave movement through a typical channel reach. Although data from these recorders are still sparse, they are adequate to indicate trends in the mode of flood wave travel.

With watersheds on which the rise time decreases with increasing watershed area, the flow regime might be expected to approximate the "wall of water" so prevalent in the folklore of the Southwest. Actually, the data indicate that, although such abrupt translatory waves or bores moving along a dry channel occasionally occur, they are by no means typical. Perhaps the best photograph of an abrupt translatory wave was presented by D. S. Hubbell and J. L. Gardner[16] (see Fig. 8), and was taken on the Soil Conservation Service Navajo Experiment Station at Mexican Springs, N. Mex. A more common flow regime is described by L. B. Leopold and J. P. Miller.[17] They reported the occurrence of a series of abrupt translatory waves a few inches in depth separated by short time intervals. The experience at Walnut Gulch watershed substantiates the data of Leopold and Miller,[17] i.e., a train or series of shallow translatory waves moving along an established channel flow, with the later waves tending to override the earlier ones as the flow progresses downstream. This results in a mechanism shortening the rise time with increasing watershed size which seems to be independent of the channel storage. Thus, it would appear that the conventional theory for flood routing is not applicable to ephemeral streams of the Southwest.

It is beyond the scope of this paper to examine the hydraulic theory applicable to the types of flow observed, but rather it is intended to present the results of experimental observations and to hypothesize on the influence of the unique channel hydraulic factors on the shape of the runoff hydrograph.

Fig. 9 presents curves for three different channel flow regimes as follows:

1. Computed steady flow with Mannings' "n" of .035;
2. measured flood wave velocities for reach 6 ⟶ 2; and
3. computed velocities for $V = \sqrt{gd}$.

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16 Hubbell, D. S., and Gardner, J. L., "Some Edaphic and Ecological Effects of Water Spreading on Range Lands," Ecology, Vol. 25, No. 1, January, 1944, pp. 27-44.

17 Leopold, Luna B., and Miller, John P., "Ephemeral Streams—Hydraulic Factors and their Relation to the Drainage Net," Professional Paper 282-A, Geol. Survey, U. S. Dept. of the Interior, Washington, D. C., 1956.

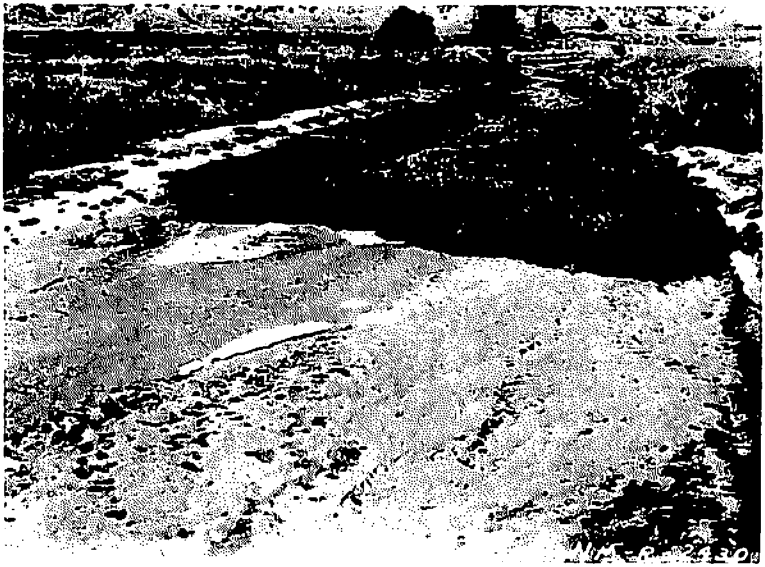

FIG. 8.—FLOW FRONT IN MEXICAN SPRINGS WASH ON JULY 23, 1941: DEPTH OF FLOW APPROXIMATELY 2 FT

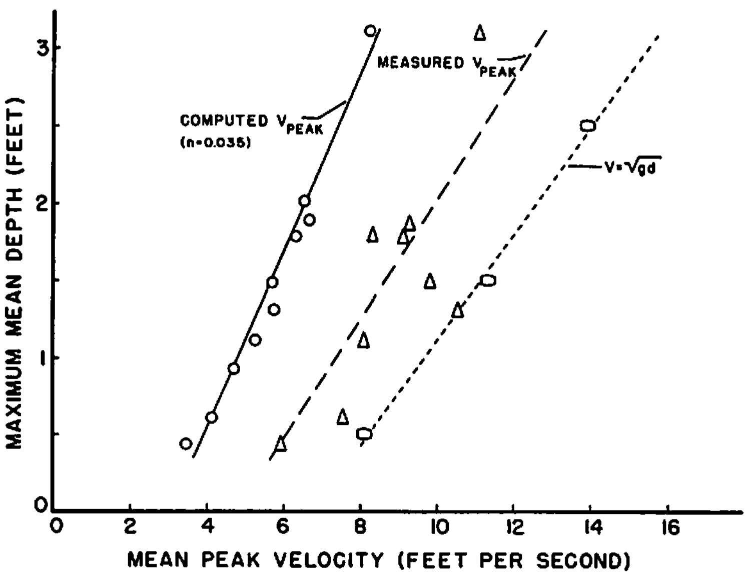

FIG. 9.—WAVE VELOCITIES FOR CHANNEL REACH 6 ⟶ 2 ON WALNUT GULCH

It can be seen that the measured velocities lie approximately halfway between the two conditions computed to define the limits of channel flow. In one instance, the measured velocity fell on the line defining $V = \sqrt{gd}$. In this case, an abrupt translatory wave, approximately 1.8 ft in depth, was detected on the flood wave recorders, and the velocity approximated that for a pure gravity wave, $V = \sqrt{gd}$.

The causative factors related to either an abrupt translatory wave on a dry bed, or a series of top riding waves, are of interest. There are those who believe that the channel geometry alone is responsible for these phenomena.[17]

During the summer thunderstorms, the writers have observed extremely high intensities for time intervals of 5 min and less.[10,11,12] It is thus possible that these extremely high bursts of rainfall intensity may generate an abrupt translatory wave moving off the land and entering the channel system. The effect of transmission loss is to damp out the conventional channel flow (rising side of the hydrograph) and allow free rein to the abrupt translatory waves. It is believed that the combination of these two factors gives rise to the relationship described herein, i.e., decreasing hydrograph rise time with increasing watershed area.

Dimensionless Hydrographs.—Dimensionless hydrographs were constructed from the records of simple runoff hydrographs for Watersheds 1, 2, 3, 4, and 6 on Walnut Gulch and for both the flat-top and sharp-peak hydrographs on Alamogordo Creek. These dimensionless hydrographs with Q/Q_p as the ordinate and T/T_r as the abscissa are shown in Figs. 10 to 13 in which Q = discharge at time T, Q_p = peak discharge, T = time from beginning of runoff to the time Q occurs, and T_r = time from beginning of runoff to peak discharge.

The dimensionless hydrographs for Watersheds 3 and 4 show recession curves for three different antecedent moisture conditions (Fig. 10). The criteria used to develop these three curves were the same for both stations, although there were a few storms on Watershed 3 where the effects of traversing a dry channel caused a shorter rise time, i.e., the entire watershed did not have precipitation. A storm preceded by a runoff event by not more than one day was classified as having high antecedent moisture conditions. Storms were assumed to fall into the low antecedent moisture conditions if there had not been any significant flows in the preceding week. All other storms were assumed to have medium antecedent moisture conditions.

Criteria for developing the dimensionless hydrographs for the three runoff stations on the main stem of Walnut Gulch (Flumes 6, 2, and 1) were the same as those for the smaller watersheds (Watersheds 3 and 4) with an additional modification for the effects of channel routing. At Flume 1, for example (Fig. 11), the dimensionless hydrograph in the high group represents either wet antecedent conditions or a rise time of less than 15 min. The dimensionless hydrograph in the low group represents either dry antecedent conditions or a rise time of more than 25 min. The dimensionless hydrograph labeled medium, in addition to the medium antecedent moisture condition, represents a rise time of between 15 min. and 25 min. If a hydrograph for inclusion in the dimensionless analysis had medium antecedent moisture conditions, but a short rise time, it was then considered with the high group. If a hydrograph was determined to have medium antecedent conditions, but a long rise time, it was considered with the low group, etc. This additional modifying factor then created three recessions, which show more variation on the recession

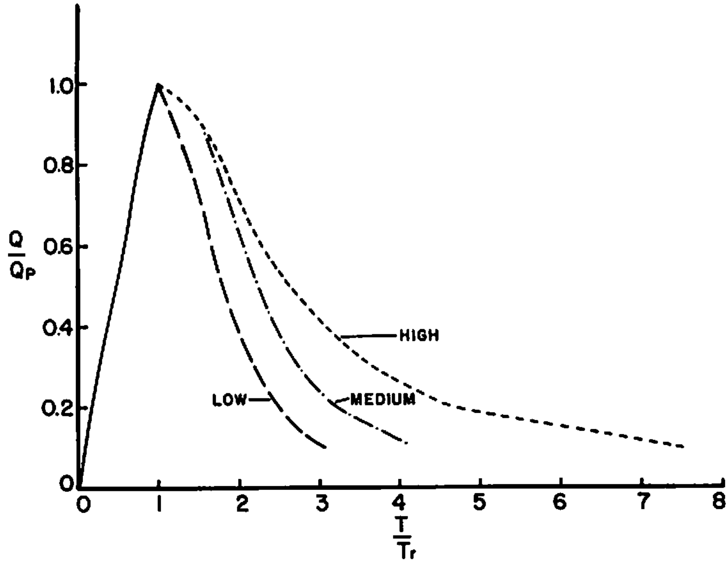

FIG. 10.—DIMENSIONLESS HYDROGRAPH WATERSHED 4 ON THE WALNUT GULCH WATERSHED

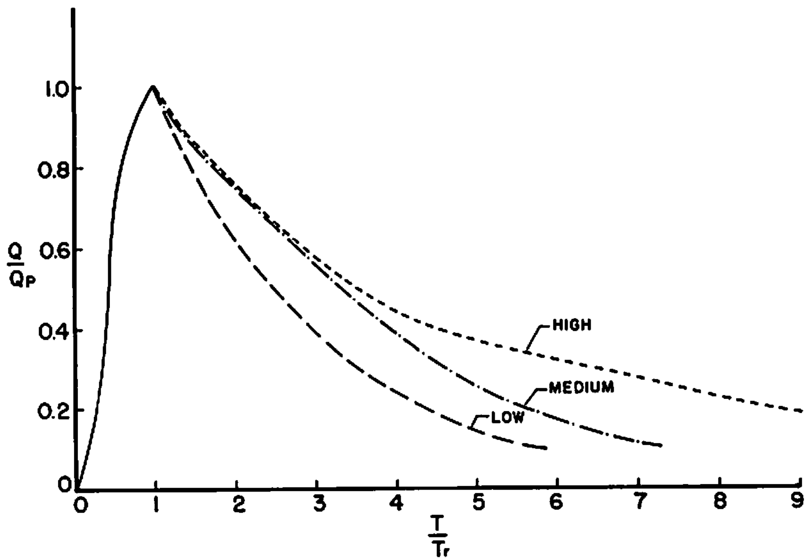

FIG. 11.—DIMENSIONLESS HYDROGRAPH AT THE OUTLET OF WALNUT GULCH WATERSHED (WATERSHED 1)

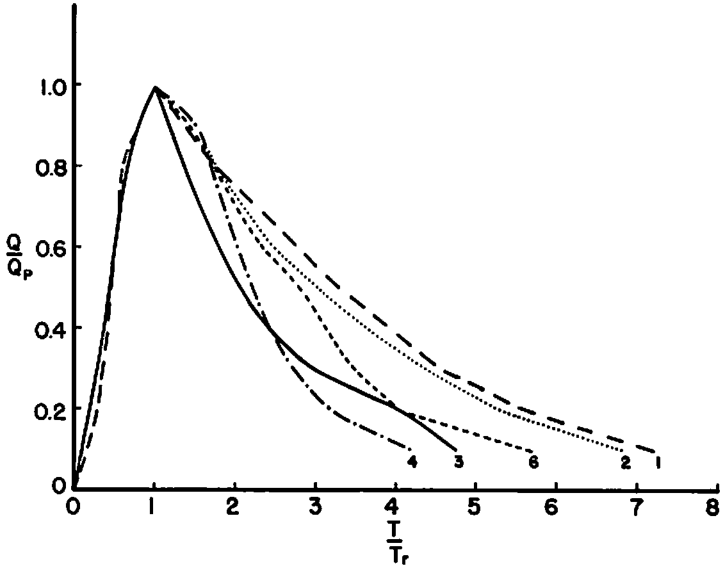

FIG. 12.—MEDIUM DIMENSIONLESS HYDROGRAPH WATERSHEDS 1, 2, 3, 4, &, 6 ON WALNUT GULCH

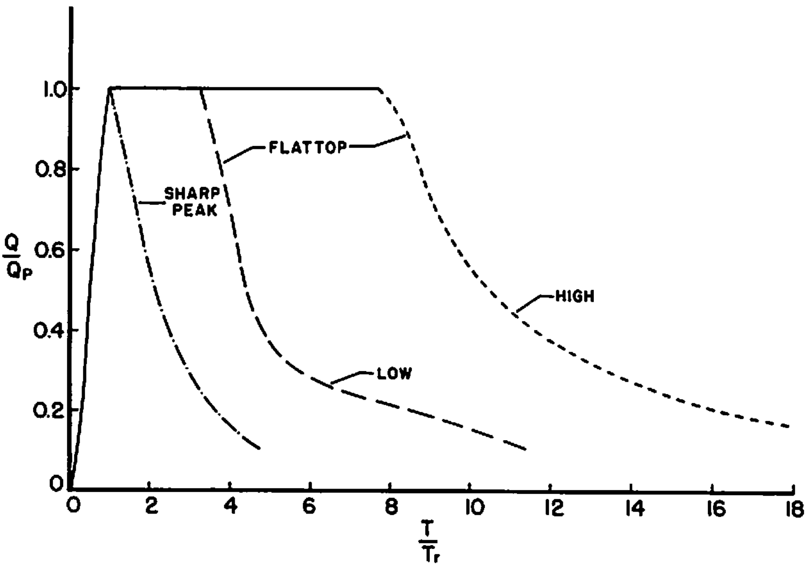

FIG. 13.—DIMENSIONLESS HYDROGRAPH ON ALAMOGORDO CREEK WATERSHED

side than those for the small watersheds. The greater difference seems to be consistent with the tendency for a shorter rise time on the larger watersheds.

The rising side of the dimensionless hydrograph, in almost all instances, can be approximated by a straight line. The rises shown in Figs. 10 to 12 do not exhibit the S-shape, which has been found to be typical of humid areas.

Fig. 12 shows the medium dimensionless hydrograph for each of the watersheds on Walnut Gulch on a common graph. The recessions of these dimensionless graphs show a trend for a greater T/T_r for any Q/Q_p increasing with watershed area. This increase reflects both the increased runoff volume for a given peak discharge at the larger stations and the tendency of the rise time to decrease with increasing drainage area (i.e., dividing by a shorter rise time displaces the recessions).

The dimensionless hydrographs for the Alamogordo Creek Watershed are shown in Fig. 13. Runoff originating in the lower parts of the watershed, where the drainage pattern is typical of that which develops in most ephemeral streams of the Southwest, causes a hydrograph similar in time distribution to that labeled sharp peak. Runoff from the central and upper parts of the watershed characteristically exhibits a flat top hydrograph, (i.e., nearly constant discharge for long periods). Dimensionless hydrographs developed from these storms were separated into a high and low antecedent moisture classification. The average rise time for each of these classes was approximately 30 min, but the peak discharge and duration at the nearly constant discharge varied

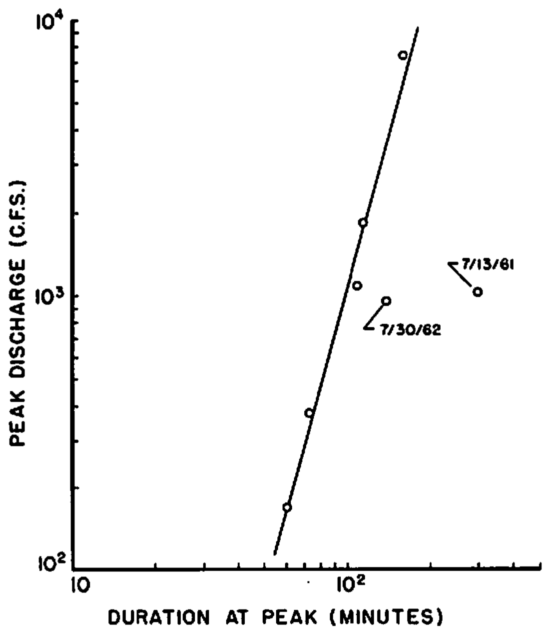

FIG. 14.—DURATION OF CONSTANT DISCHARGE OF FLAT TOP HYDROGRAPHS VERSUS PEAK DISCHARGE ON ALAMOGORDO CREEK WATERSHED

considerably. The group labeled low included those storms that occurred with lower peak discharges, an average peak of 540 cfs, whereas those called high had an average peak discharge of 3,450 cfs.

The duration of the flat top hydrograph appears to be closely related to the peak discharge (Fig. 14). Undoubtedly, antecedent moisture conditions of both the channels and the watershed will cause deviations from this line, but the limited number of flows available for analysis indicate a definite trend. The point dated 7/13/61 has the long peak discharge because of an unusual giant hail storm that caused an accumulation of hailstones nearly 1 ft deep in the upper parts of the watershed. The resulting melting caused the steady discharge to last approximately 5 hr. The point dated 7/30/62 was preceded by another rather large convective storm only two days prior, and, therefore, may represent the peak duration for a very wet condition.

CONCLUSIONS

Data are presented to illustrate the unique character of runoff hydrographs from semiarid watersheds with absorbent stream beds. Some of the pertinent characteristics are as follows:

1. Total runoff volumes for simple events are highly correlated with peak discharge for the event. (Significant at the 0.1% level except for the Alamogordo Creek flat top hydrographs where the correlation coefficient was significant at the 10% level.)
2. Hydrograph rise time decreased with increasing watershed area within the range of areas included in this study.
3. Transmission losses, most of which probably occur during the rising part of the hydrograph, have a pronounced effect on the hydrograph shape, i.e., the longer the reach of channel traversed, the more pronounced the effect of transmission loss in shortening the rise time.
4. Although abrupt translatory waves of considerable height have been measured, the more common case is that of waves a few inches in height separated by short time intervals. As these waves progress downstream, there is an overriding effect that contributes to the shortened rise time.
5. Dimensionless hydrographs based on the time parameter, T_r (hydrograph rise time), exhibit straight-line rises and a family of recessions depending on the antecedent channel moisture conditions and the distance of dry alluvial stream bed traversed by the runoff.
6. The Alamogordo Creek watershed falls in a different class than the Walnut Gulch watersheds. Transmission losses are undoubtedly considerably smaller at Alamogordo Creek because of the fine-textured channel alluvium present. Two classes of hydrographs have been observed—conventional sharp-peaked hydrographs originating from the southeast and southwest branches, and flat-topped hydrographs caused by flow from the upper and central part of the valley floor.

For ephemeral streams of the Southwest similar to those examined in this paper, runoff-producing rainfall typically covers only a part of the watershed area. Conventional unit-hydrograph techniques are not well adapted to synthesis of hydrographs of runoff for these watersheds, and flood routing methods must be modified to take into consideration transmission losses and abrupt translatory waves.

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KEY WORDS: channels (waterways); discharge; hydraulics; hydrography; hydrology; rainfall; runoff; statistical analysis; stream flow; streams; transmission loss; watersheds

ABSTRACT: For ephemeral streams of the Southwest, runoff producing rainfall typically covers only a part of the watershed area. Conventional unit hydrograph techniques are not well adapted to the synthesis of hydrographs of runoff for such watersheds and flood routing methods must be modified to consider transmission losses and abrupt translatory waves. Hydrograph rise time was used as the time parameter for developing the dimensionless hydrographs. Average hydrograph rise time was found to decrease with increasing watershed size for the size watersheds analyzed. Dimensionless hydrographs developed in the paper were found to have a family of recessions based on antecedent channel moisture and the distance of dry streambed over which the runoff has traversed. Total runoff volumes for simple runoff events were found to be significantly correlated with the peak discharge for the event.

REFERENCE: Renard, Kenneth G., and Keppel, Robert V., "Hydrographs of Ephemeral Streams in the Southwest," Journal of the Hydraulics Division, ASCE, Vol. 92, No. HY2, Proc. Paper 4710, March, 1966, pp. 33-52.