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TRANSMISSION LOSSES IN EPHEMERAL STREAM BEDS[a]

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SYNOPSIS

Transmission losses, as measured in two reaches of Walnut Gulch, an ephemeral stream in southeastern Arizona, are large. They are influenced by antecedent moisture of the channel alluvium, peak discharge at the upstream gaging station, duration of flow, width of channel, and the quantity and texture of the channel alluvium. In a very dry channel system, losses of 25 acre-ft per mile were measured in a channel reach where the computed possible maximum, based on quantity and texture of the alluvium, was 30 acre-ft per mile.

A series of intense, convective thunder storms, close together in space and time, and steep channel gradient give rise to over-riding, translatory waves that, in conjunction with such large channel losses, may result in peak discharge at the lower station nearly equal to that at the upper, even though the volume of runoff measured is much less. This condition is accompanied by a shortened rise time in the hydrograph at the lower station.

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INTRODUCTION

In the southwestern United States, transmission losses in ephemeral streams having coarse-textured alluvial beds are frequently a significant factor in the hydrologic evaluation of watersheds. Because of the high intake rates and low moisture content of the channel alluvium, the decreases in flow volume in the downstream direction are typically large. These flow abstractions exert a profound influence on hydrograph characteristics of ephemeral streams and also affect the water yield-area relation of semiarid watersheds. Data herein reported are from the Walnut Gulch Experimental Watershed, Tombstone, Ariz.

DESCRIPTION OF AREA

Walnut Gulch is a westward draining ephemeral tributary of the San Pedro River, entering at Fairbank, Ariz. Its 58 sq mile drainage area above the lower gaging station is considered representative of the mixed grass-brush rangelands of southern Arizona and southwestern New Mexico. Elevations range from 4,200 ft at the watershed outlet to 6,000 ft at the upper end in the foothills of the Dragoon Mountains. Approximately 70% of the annual precipitation of 14 in. occurs during July, August, and September in the form of intense, small-diameter, convective thunderstorms that cause essentially all of the runoff. Runoff generated by one of these small thunderstorms usually traverses dry channels before reaching the watershed outlet. Most channel reaches carry water 1% of the time or less. On the average, five to ten flow events occur annually at most of the gaging stations. Flow from the first several showers of the season is generally completely absorbed in the channel system.

Unconsolidated sand and gravel deposits, varying in depth from 6 ft to 15 ft, overlie tight conglomerate bedrock in much of the channel system. Fig. 1 shows, on logarithmic probability paper, an average sieve analysis curve for the channel-bed material. The data plot as a straight line, except for the extreme upper portion of the curve, indicating a close approximation to a log-normal distribution of particle size. To characterize the particle-size distribution, two parameters are deduced graphically: D_{mg}, the geometric mean grain size (that is, the value of sieve size for which 50% by weight is coarser and 50% finer); and σ_g, the geometric standard deviation

$$\sigma_g = \sqrt{\frac{D_{84.1}}{D_{15.9}}} \qquad \text{.............. (1)}$$

The values of D_{mg} = 2.3 mm, and σ = 3.65, are considerably greater than those listed[3] by Vito A. Vanoni, F. ASCE, Norman H. Brooks, M. ASCE, and John F. Kennedy, M. ASCE, for a large number of stream-bed materials, thus indicating a large mean grain size, and a large scatter; that is, a wide range

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[3] "Lecture Notes on Sediment Transportation and Channel Stability," by Vito A. Vanoni, Norman H. Brooks, and John F. Kennedy, Publication No. KHWR-1, California Inst. of Tech., Pasadena, Calif., September 1, 1960, p. 14.

of particle sizes, for the Walnut Gulch sample. The grain diameter of 88% of the material is greater than 0.5, and 54% of the material is in the gravel range(> 2.0 mm).

Fig. 2 is a map of the experimental watershed showing the five gaging stations, the recording rain gages, and the two channel reaches (5 – 2, and 2 – 1)

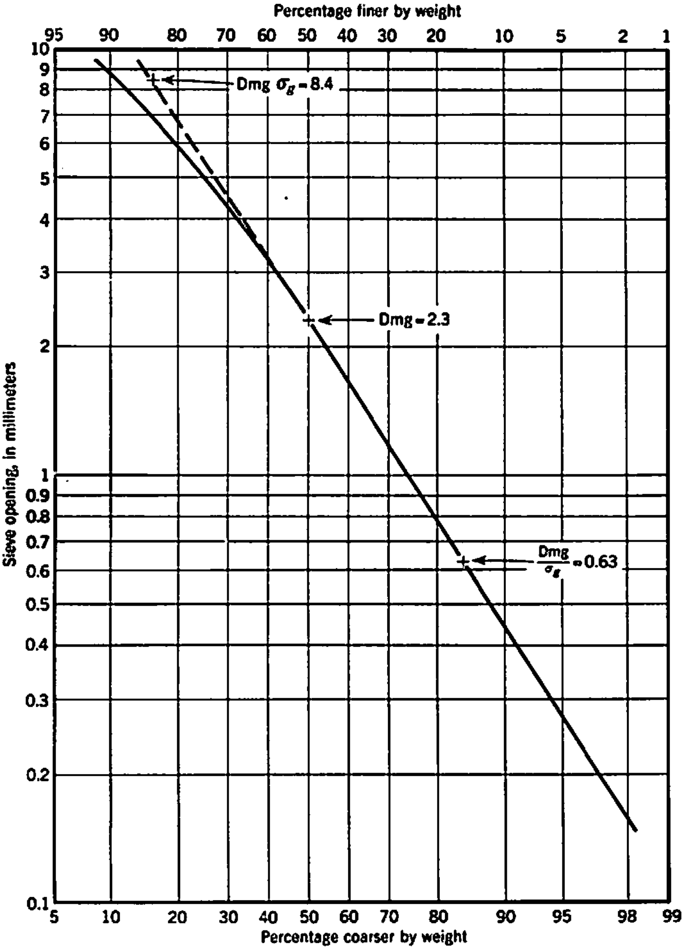

FIG. 1.—SIEVE ANALYSIS OF CHANNEL BED MATERIAL

in which transmission losses have been measured. Reach 5 – 2 is 5 miles long; the mean channel width is 115 ft for depths less than 2 ft and 150 ft for depths greater than 2 ft. Reach 2 – 1 is 4 miles long, with a mean width of 217 ft. Channel gradients in both reaches are 0.01 ft per ft. Although several

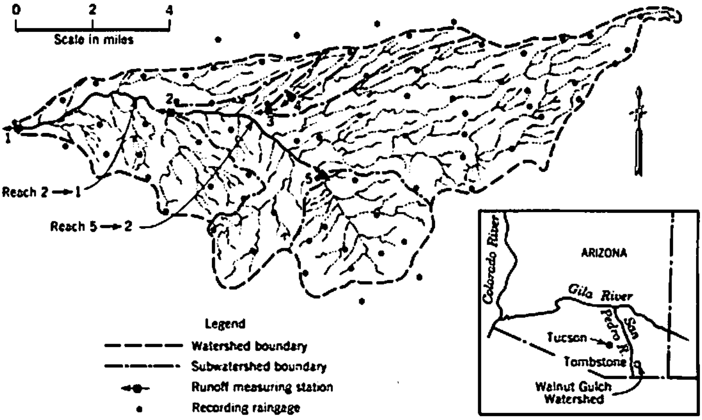

FIG. 2.—AREA OF EXPERIMENTAL WATERSHED

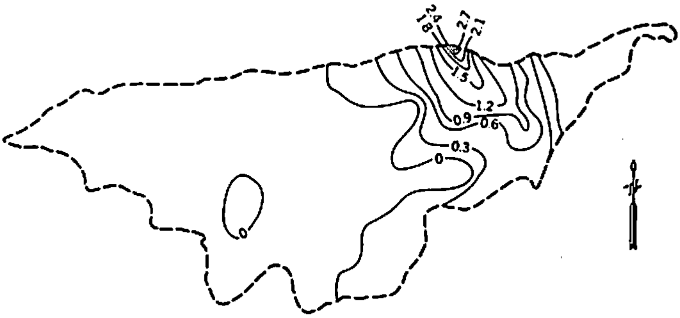

FIG. 3.—ISOHYETAL MAP FOR STORM OF AUGUST 10, 1959

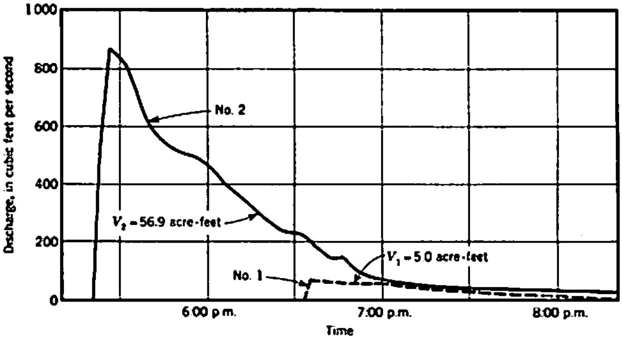

FIG. 4.—HYDROGRAPHS OF AUGUST 10, 1959, AT MEASURING STATIONS 1 AND 2

ungaged tributaries enter the main stem in both of these channel reaches, the small size of the runoff-producing thunderstorms permits selection of individual events during which the reach has received no tributary inflow. Under these conditions, measurements of transmission loss may be obtained by comparison of flow volume at the upper station of the reach with that at the lower.

TRANSMISSION LOSSES

A runoff event uncomplicated by tributary inflow is illustrated in Fig. 3 and 4. Fig. 3 is the isohyetal map of the August 10, 1959 thunderstorm that occurred on the upper end of the watershed. Based on rainfall-runoff relations derived for similar small watersheds, approximately 92.5 acre-ft originated as one-site runoff and entered the channel system at a point 10 miles upstream from gaging station 2. Fig. 4 shows the hydrographs at stations 2 and 1. Volume of flow passing station 2 was 56.9 acre-ft, and the peak discharge was 850 cfs. At station 1, 4 miles downstream, the flow volume had diminished to 5 acre-ft, and the peak discharge was reduced to 70 cfs. Estimated transmission loss for the 10-mile reach upstream from station 2 was 3.6 acre-ft per mile, and the measured loss for reach 2 → 1 was 13 acre-ft per mile.

Transmission losses for flow events similar to the one just mentioned have been evaluated for two reaches of channel. The relation between transmission loss in acre-feet per mile of channel and peak discharge at the upstream station is shown in Fig. 5. Also shown are the computed maximum losses based on calculated values of pore space and volume of alluvium in the two channel reaches. The maximum measured loss of 25 acre-ft per mile on reach 5 → 2 closely approaches the computed maximum of 30 acre-ft per mile. This flow event followed a period of no runoff during the preceding six weeks, and consequently, the channel alluvium was extremely dry. No flows of comparably high peak discharge occurring with low antecedent runoff have been measured on reach 2 → 1. When such an event does occur, the transmission loss might be expected to approach the computed maximum of 80 acre-ft per mile. Dashed portions of the curves represent estimated extrapolation up to the computed maximum values of transmission loss.

Fig. 6 shows the relation between transmission loss per unit of time (acre-feet per mile per hour of flow duration at the upstream station) and peak discharge at the upstream station. The curve for reach 2 → 1 becomes nearly horizontal for discharge greater than 850 cfs, and the loss rate appears constant at 4.3 acre-ft per mile per hr. It should be emphasized that the antecedent runoff for the largest peak discharge event in this reach was high. Undoubtedly, this fact strongly influences the shape of the curve. It is entirely logical to expect that the shape of the curve for reach 2 → 1 will approach that of the curve for reach 5 → 2 as flows of higher peak discharge and lower antecedent runoff are experienced.

In both reaches of channel, the depth-discharge relation has been ill-defined for discharges lower than 1,000 cfs to 1,500 cfs. For discharges below this range, the flow cross section is controlled by the irregular configuration of sand and gravel bars deposited by preceding flows. For discharges above this range, the sand and gravel bars are swept along by the flow, and the entire coarse-textured channel bottom, including the permanent islands, is wet-

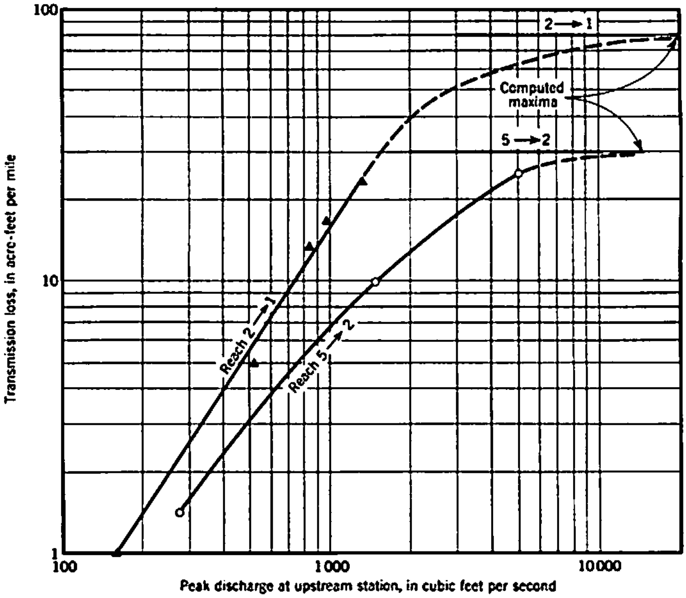

FIG. 5.—TRANSMISSION LOSS VERSUS PEAK DISCHARGE

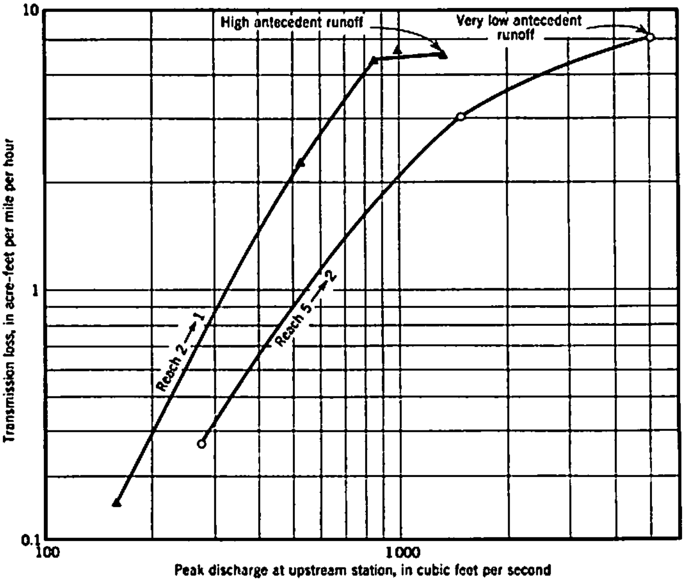

FIG. 6.—TRANSMISSION LOSSES PER HOUR VERSUS PEAK DISCHARGE

ted. As discharge increases from zero to the point at which the entire channel bottom is wetted, the wetted area increases rapidly with increasing discharge. Beyond this point, only the effect of increasing head is operating to increase the rate of loss. Thus, there is some physical basis for expecting the loss-rate curves to flatten out in the 1,000 cfs to 1,500 cfs discharge range.

For the largest flow event in reach 2 → 1, the average infiltration rate into the channel alluvium was 2.0 in. per hr, compared with a rate of 3.0 in. per hr for the largest event in reach 5 → 2. This difference may be attributed to the large difference in antecedent runoff for the two events. The foregoing infiltration values are considerably greater than those reported[4] by H. M. Babcock and E. M. Cushing, M. ASCE, for Queen Creek in Central Arizona.

HYDROGRAPH CHARACTERISTICS

As might be expected, these transmission losses have a pronounced effect on the downstream hydrograph. Two distinctly different phenomena have been observed:

$$\begin{array}{ll} \text{Case 1:} & V_d < V_u \\ & Q_d < Q_u \\ \text{Case 2:} & V_d < V_u \\ & Q_d \simeq Q_u \end{array}$$

in which V_d is the runoff volume at the downstream station; V_u denotes the runoff volume at the upstream station; Q_u refers to the peak discharge at the upstream station; and Q_d is the peak discharge at the downstream station. Using the August 10, 1959 hydrographs for stations 2 and 1 (Fig. 4) to illustrate Case 1, it is apparent that both the peak rate and volume of runoff have been greatly reduced. During the lower discharges, channel resistance effects appear to dominate the flow regime. In case 2, illustrated by the hydrographs from the same two stations for the event of August 3-4, 1959 (Fig. 7), volume of runoff has been substantially reduced, but the hydrograph peaks are of approximately the same magnitude.

At the higher discharges, it appears that translatory waves control the flow regime. Because of the unusually high intensity of the convective thunderstorms and the steep channel gradients, the runoff moves through the channel system as abrupt translatory waves. A second such storm, displaced only slightly in time, generates waves that move through an already wetted channel. These second waves are consequently moving faster than the first and tend to override the existing flow. The result is an extremely rapid rise in the modified hydrograph at the downstream station, and the peak discharge downstream will be approximately equal to the peak discharge upstream, even though the runoff volume has been substantially reduced by transmission loss.

Fig. 8 shows the relation of hydrograph rise time to watershed area for semiarid watersheds in southern Arizona. Rise time, as used herein, is defined as the time from beginning of runoff at the measuring station to the hy-

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[4] "Recharge to Ground Water from Floods in a Typical Desert Wash, Pinal County, Arizona," by H. M. Babcock and E. M. Cushing, Transactions, Amer. Geophysical Union, Vol. 23, Part I, 1942, p. 49.

drograph peak. With the range of watershed areas represented by the Walnut Gulch and Safford watersheds, that is, 1 sq mile to 58 sq miles, rise time decreases with increasing watershed size. The least squares regression equation is

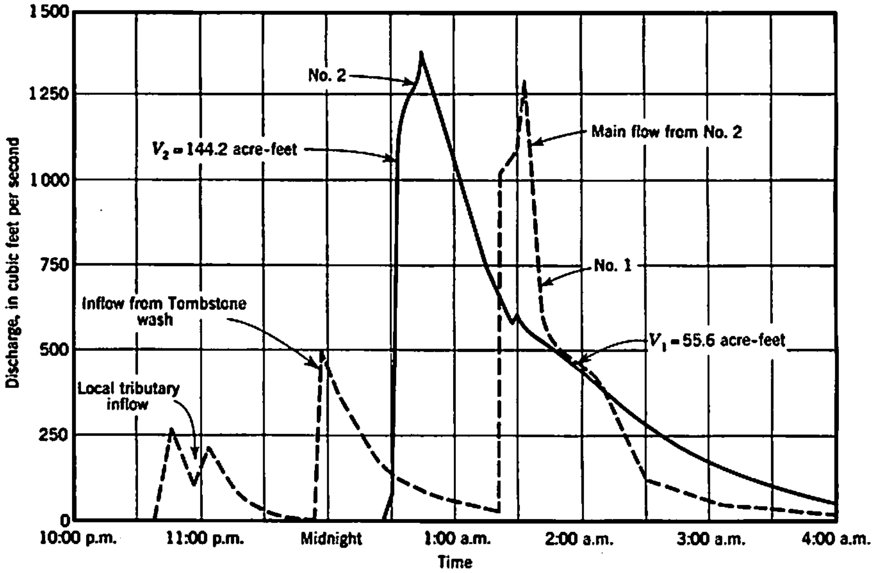

FIG. 7.—HYDROGRAPHS OF AUGUST 3-4, 1959, AT MEASURING STATIONS 1 AND 2

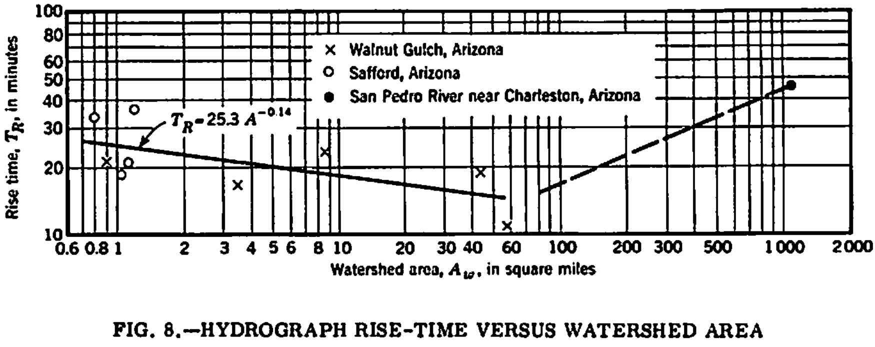

FIG. 8.—HYDROGRAPH RISE-TIME VERSUS WATERSHED AREA

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

in which T_r denotes the hydrograph rise time, in minutes, and A_w is the watershed area, in square miles.

This decrease in rise time with increase of drainage area is probably due to two interrelated factors: The occurrence of most of the transmission loss during rising stages of the flow; and the presence of overriding translatory waves as the flow moves through the channel. Contributing factors are the coarse texture of the channel materials and the length of the channel system, because the greater the area, the longer is the channel system and the more time is available for these factors to exert their influence. It seems probable that this relation of rise time with area is valid only for ephemeral streams such as Walnut Gulch, and that there is a reversal of the trend in perennial streams such as the San Pedro, where hydrographs from the Geological Survey, United States Department of the Interior (USGS), at the Charleston gaging station, below an area of 1,300 sq miles, show an average rise time of 45 min (Fig. 8).

WATER YIELD

The effect of transmission losses on the water yield-area relation for semi-arid watersheds has been demonstrated[5] by Keppel. Water yield per unit area was shown to decrease with increasing area according to the equation

$$V = 1.95\,A_d^{-0.31} \qquad \ldots\ldots\ldots\ldots\ldots (3a)$$

for Walnut Gulch Watershed and

$$V = 1.75\,A_d^{-0.34} \qquad \ldots\ldots\ldots\ldots\ldots (3b)$$

for the Santa Cruz river basin, in which V is the annual water yield, in inches, and A_d denotes the drainage area, in square miles.

The abstractions from surface flow that occur in ephemeral streams with coarse-textured beds have been referred to in this presentation as transmission losses. Whether they actually constitute losses as far as ultimate beneficial use is concerned depends on the geology of the particular watershed being considered. In many cases, the transmission loss water may reach the regional water table and, therefore, constitute an important source of recharge. In others, and preliminary evidence indicates that Walnut Gulch is in this latter category, direct evaporation and transpiration by riparian vegetation remove a large portion of the transmission loss water.

CONCLUSIONS

1. In ephemeral streams having coarse textured beds, transmission losses are large and may comprise a significant fraction of the total on-site runoff. On Walnut Gulch watershed, maximum values of 25 acre-ft per mile of channel have been measured, and maximum anticipated values are of the order of 80 acre-ft per mile.
2. Transmission losses, acting in conjunction with translatory wave movements resulting from steep channel gradients and highly intense bursts of rainfall, give hydrographs that show a shortened rise time as the size of the

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[5] "Water Yields from Southwestern Grassland," by R. V. Keppel, presented to the Amer. Assn. for the Advancement of Science, Southwestern and Rocky Mountain Div., May, 1960 (in press, as of January, 1962).

drainage area increases. This relation appears to hold for semiarid watersheds up to the maximum size included in this study—58 sq miles.

3. Reduction in water yield per unit area with increasing drainage area appears to be due in large part to transmission losses.

4. Water entering the channel alluvium as transmission loss may contribute to the regional water table, or, as is probably the case at Walnut Gulch watershed, it may be dissipated by direct evaporation or by transpiration by riparian vegetation.