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INPUT-OUTPUT RELATIONSHIPS FOR AN EPHEMERAL STREAM CHANNEL SYSTEM*

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Abstract: A method has been developed to predict outflow hydrographs for a specific reach of ephemeral stream channel on the Walnut Gulch Experimental Watershed in southeastern Arizona. The volume and peak discharges of the outflow hydrographs were predicted from the volumes of the inflow hydrographs. A three-parameter gamma distribution function was used to represent the inflow and outflow hydrographs. Two methods were used to fit the gamma distribution to the shape of the outflow hydrograph. Regression equations were developed to relate the parameters of the outflow distribution to the parameters of the inflow distribution graph. Best results were obtained when both the inflow and outflow hydrographs were single-peaked.

Introduction

The passage of a flood wave along a stretch of a river is usually described in terms of a flood routing procedure. Looking at the problem from a system analysis point of view, this procedure treats the stretch of the river as a system receiving an input in the form of an upstream flood wave or inflow hydrograph and delivering an output in the form of an outflow hydrograph. The system itself is represented by the set of equations for carrying out the flood routing, but it can be represented equally by an impulse response function[1]) which, if convoluted with the input function, will yield the output function. The two representations are identical.

As an alternative to the flood routing approach, the system representing the river stretch may be defined in terms of its effect on certain parameters of the inflow and outflow hydrographs. Thus a set of equations describing the attenuation of the peak of the flood wave along the given river stretch,

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the change in the time to peak, and the time of travel of the wave front is an example of this approach. The input to the system consists in this case of the parameters of the inflow hydrograph, and the output consists of the parameters of the outflow hydrograph. While the system in the alternative approach is not represented by an impulse response function, it is, nevertheless, a clearly defined system in the sense that a given input in the form of an inflow hydrograph produces a unique outflow hydrograph which is the output of the system.

The two systems defined by the two approaches are not identical, but the information produced by the two is similar and may be considered of equal value for most engineering purposes.

Ephemeral streams in arid or semiarid zones present a difficult problem in the flood routing approach because of large transmission losses[2]). It is impossible to solve the continuity equation, which is one of the bases of all flood routing methods, without a knowledge of the losses along each section of the stream during passage of the flood wave.

To use a flood routing procedure, the factors affecting streambed in-

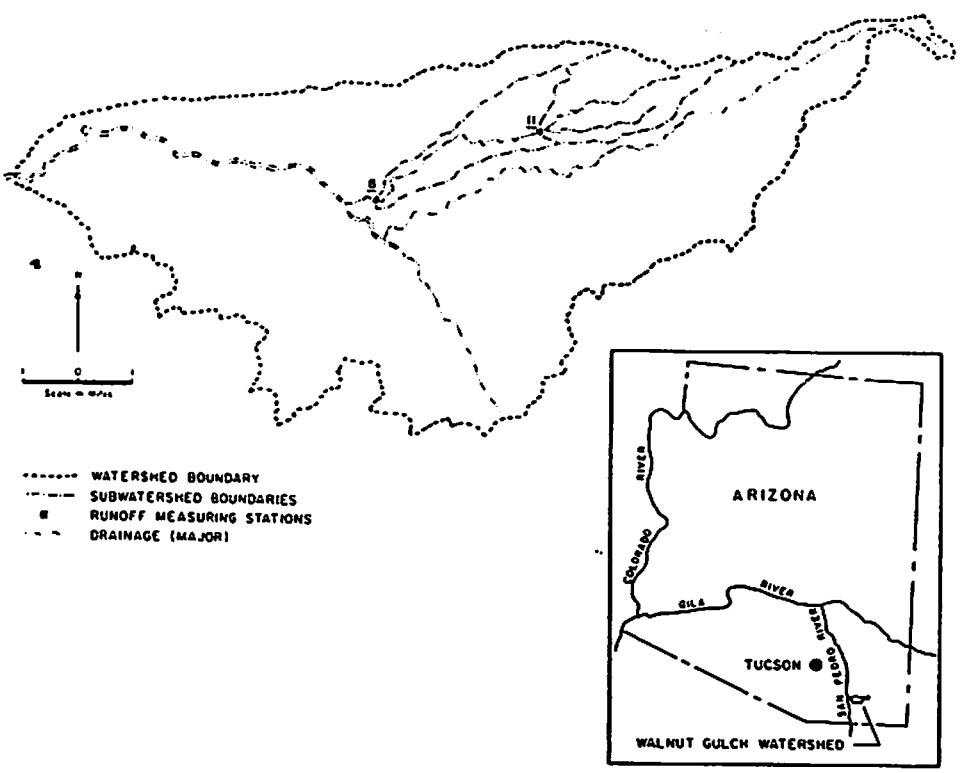

Fig. 1. Walnut Gulch watershed.

filtration must be completely known, and their variation in time and space must be specified. In the absence of such a description of the transmission losses, it appears that for ephemeral streams, the alternate approach of system definition, whereby the parameters of the outflow hydrograph are predicted, is preferable.

The situation would be different if information could be obtained about the spatial and temporal variation of transmission losses. In such a case it may be possible to use the lateral inflow equation, which is extensively treated in literature[3]), with the sign of the inflow term reversed so that it represents outflow or losses from the channel.

This paper deals with the identification and description of a system representing a 4.0-mile stretch of an ephemeral stream on the Walnut Gulch Experimental Watershed, which is a 58-square-mile brush- and grass-covered watershed in southeastern Arizona (Fig. 1). A detailed description of the Walnut Gulch watershed is available in a recent publication by Renard[4]). The approach chosen for the present study was that of defining the system in terms of its effects on the parameters of the inflow hydrograph. Data from a number of events were used to derive the regression equations that constitute the transfer function of the system considered. These equations were used to predict the parameters of the outflow hydrographs, and a comparison is given between the measured hydrographs and those predicted by the system representing the channel reach.

The shape of the outflow hydrograph was represented by a gamma distribution. Two methods were used to obtain the parameters of the distribution from predicted values of the outflow at the end of the reach. One method matches the time to peak and the time to centroid of the hydrograph. The second method matches the magnitude of the peak and the time difference between the peak and the centroid. A comparison is given between hydrographs obtained by the two methods.

Description of channel reach and data

The analysis in this paper is based on data derived from the 4.0-mile stretch of a stream identified as Hughes Wash, located on the upper end of the Walnut Gulch Experimental Watershed. The reach of stream studied is bounded at its upper and lower ends by supercritical-depth flumes which measure the inflow and outflow for the channel reach[5]). The flume at the downstream end of the reach (Flume 8) defines a 5.98-square-mile subwatershed (W-8 of the Walnut Gulch watershed) and the upstream flume (Flume 11) defines a 3.18-square-mile watershed (W-11), which is the uppermost part of W-8 (Fig. 1).

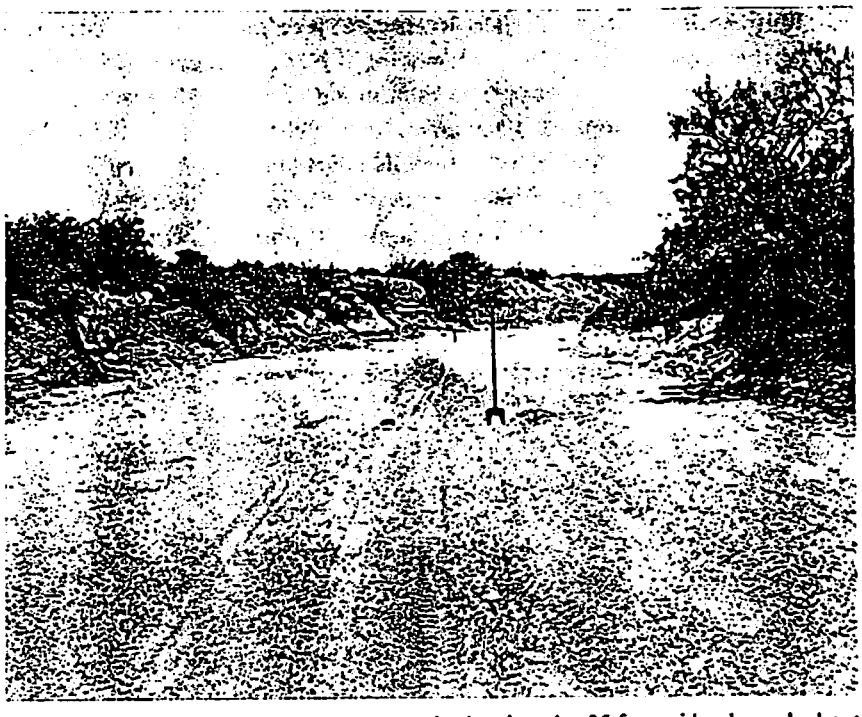

Fig. 2. Typical channel section photograph showing the 35-foot-wide channel about 1.5 mi. below Flume 11.

The channel reach between Flumes 11 and 8 (Fig. 2) is a shallow, steep channel having along most of its length a sand and gravel bed ranging in thickness from zero to about 11 feet. The width of the channel along the reach ranges from about 15 ft to over 45 ft, and averages about 36 ft. In a few places the channel is braided. The formation below the alluvial bed is fairly well cemented conglomerate which is probably not continuous along the channel, allowing water to escape to the regional groundwater table[6]). The mean thickness of the alluvial bed material is about 6 ft, and the total volume of alluvial material is estimated to be between 100 and 110 acre-feet. The porosity of the bed material was measured at 9 sampling sites along the reach (Fig. 3) taking an average of about 5 samples at each site at various depths. The porosity of individual samples ranged from about 30% to over 45%, with a mean value of about 36%. The corresponding values of specific yield, estimated from curves of porosity and specific yield[7]), were between 9% and 33% with a mean value of about 27%. Using the above figures, the maximum water-absorbing capacity of the bed material directly under the 4.0-mile reach of the stream was estimated to be between 25 and 35 acre-feet.

Figure 3 is a detailed map of the part of Watershed W-8 not included in

W-11. It shows the channel reach investigated and the channel system that drains the subwatershed. The locations of the nine sampling sites, at approximately half-mile intervals along the main channel are also shown in Fig. 3. The overall slope of the channel reach between Flumes 8 and 11 is about 1.2%. The depth of flow in the channel is estimated to be less than 1.0 to 1.5 ft in most of the flow events that occur in the channel. The mean velocity in the channel is estimated at between 4 and 7 ft per second.

Recording rain gages spaced at approximately one-mile intervals throughout Watershed W-8 and its vicinity (Fig. 4) give a fairly good representation

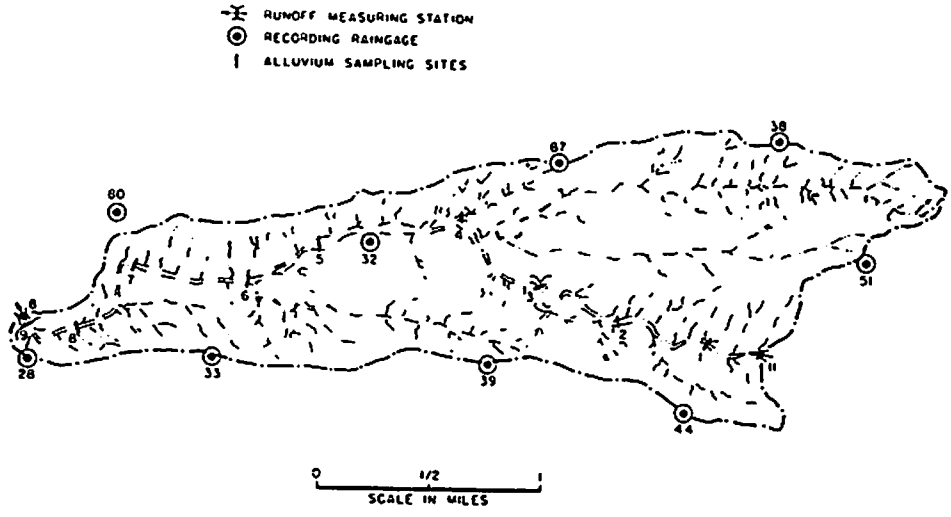

Fig. 3. Channel reach between Flumes 8 and 11 Walnut Gulch watershed.

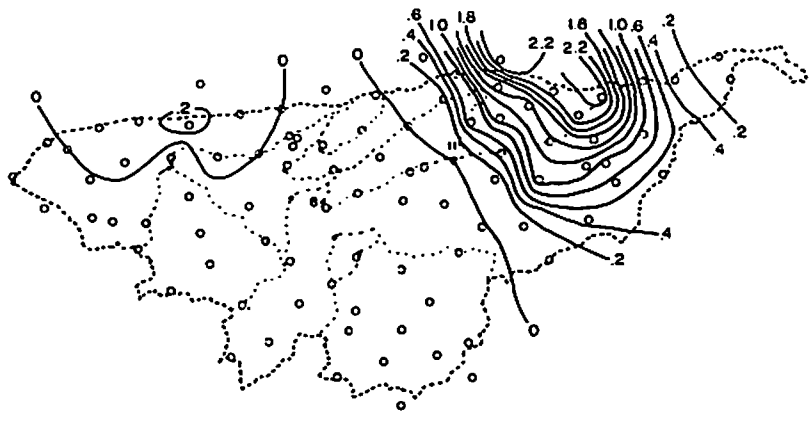

Fig. 4. Walnut Gulch watershed isohyetal map. July 30, 1966.

of the development and movement of storms across the watershed. Not all rainfall events produce runoff at the gaging stations, and past experience[8]) indicates that about 0.2 inch of rainfall is the minimum required to produce runoff in the watershed considered. Between 8 and 10 flow events take place each year. Each such flow event lasts 2 to 5 hr, with the peak occurring usually within the first 15 to 30 min of the runoff event. Fourteen of the storms that occurred in the period 1963 through 1968 were selected for the present study. The storms selected were those that produced runoff from W-11 but did not cover any appreciable portion of W-8 not included in W-11.

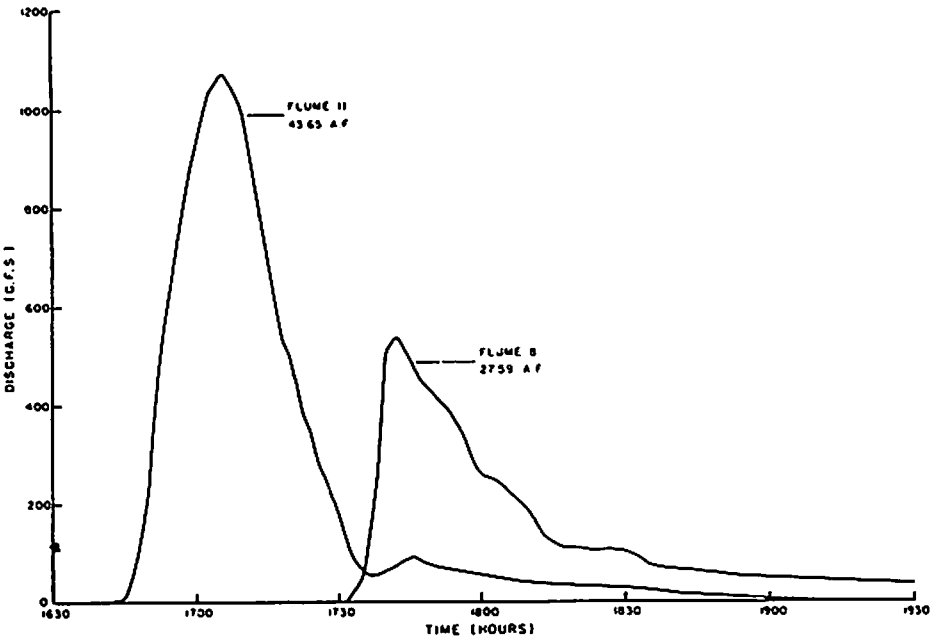

Fig. 5. Hydrographs at Flumes 11 and 8 for the event of July 30, 1966.

For these storms, tributary inflow to the reach between Flumes 11 and 8 is minimal or nonexistent. An example of such a storm is shown in Fig. 4 where the total rainfall isohyets for the storm of July 30, 1966 are shown.

In the absence of local inflow in the reach of the stream between Flumes 11 and 8, the hydrographs of flow at these two stations invariably indicated heavy transmission losses in the channel. The two hydrographs shown as an example in Fig. 5 are the result of the storm shown in Fig. 4. The volume of the upstream hydrograph was 43.6 acre-feet; that of the downstream hydrograph was 27.6 acre-feet, and the transmission losses were 16.0 acre-feet or some 4 acre-feet per mile of stream channel. The main characteristics

TABLE I

Characteristics of runoff events used in study.

Event No.	Date of event	Inflow		Outflow		Transmission losses (acre-feet)	Peak reduction (%)	Time of travel of Peak (min)
		Volume (acre-feet)	Peak Flow (cfs)	Volume (acre-feet)	Peak Flow (cfs)			
1	02-08-63	4.95	208.00	1.28	14.20	3.67	93	92
2	31-07-64	3.47	97.24	0.09	1.90	3.38	98	143
3	02-08-64	39.86	725.00	22.31	463.40	17.55	36	49
4	05-08-64	9.26	365.00	3.45	142.00	5.81	61	65
5	11-09-64	128.40	1960.00	46.49	1914.00	81.91	2.3	34
6	18-08-65	2.10	26.32	0.16	7.29	1.94	72	110
7	02-09-65	6.19	97.24	3.95	75.91	2.24	22	54
8	30-07-66	43.65	1074.00	27.59	539.80	16.06	50	36
9	11-09-66	0.08	6.05	0.00	0.00	0.08	100	–
10	07-07-67	3.71	82.90	0.00	0.00	3.71	100	–
11	13-08-67	10.57	260.80	3.08	97.28	7.49	63	51
12	25-09-67	1.83	69.61	0.60	17.55	1.23	75	25
13	02-08-68	7.51	331.80	1.89	63.72	5.62	81	63
14	05-08-68	27.40	1080.00	12.85	429.50	14.55	60	39

of the inflow and outflow hydrograph for the storms considered herein are listed in Table 1.

Two of the storms produced runoff hydrographs at Flume 11 and no hydrographs at Flume 8. The total volume of runoff in these two events was absorbed in the alluvial streambed between Flumes 11 and 8.

Procedure

The system developed in this study to represent the stream reach is a system that receives as input the parameters of the inflow hydrograph to the stream reach considered and produces as output the parameters that describe the outflow hydrograph. An attempt was also made to represent the outflow hydrograph by means of a 3-parameter gamma distribution curve[9]).

The parameters chosen to represent the inflow and outflow hydrographs were the volume of runoff (V), the peak discharge (Q_p), the duration of runoff (T_b), the time to peak (T_p), and the time to the centroid of the hydrograph (T_c). The hydraulic characteristics of the channel were represented by the hydraulic radius (R_h) in the channel (near Flume No. 11) corresponding to the peak flow observed in Flume No. 11. Parameters describing the antecedent moisture condition of the channel were also considered but were not found to enter any of the regression equations.

A generalized stepwise multiple linear regression analysis program (MLR) available at the Computer Center of the University of Arizona[10]) was used to develop the relationship between each of the outflow hydrograph parameters and the parameters of the inflow hydrograph and of the channel. The program considers all the variables entered and selects the variables that reduce most significantly the variance of the quantity for which the regression equation is sought in the order of their variance reduction.

In the second part of the study, two methods were used to fit a theoretical distribution to the outflow hydrograph using the parameters derived in the first part. The first method (Method A) involved equating the locations of the mean and of the mode of the theoretical distribution to the time to centroid (T_c) and time to peak (T_p) of the hydrograph, respectively. These two equations provided values of two parameters of the theoretical distribution. The third parameter was obtained from the time of the beginning of runoff. The volume represented by the theoretical distribution was made equal to the volume of the runoff hydrograph by taking the ordinate of the theoretical distribution to represent the discharge per unit volume.

An alternative method (Method B) for predicting the shape of the outflow hydrograph was to derive two parameters of the theoretical distribution by equating the peak of the distribution to the maximum discharge (Q_p) and

the difference between the mean and the mode of the distribution to the difference between the time to centroid and time to peak (T_c–T_p) of the outflow hydrograph. The third parameter of the theoretical distribution was again obtained from the location of the time of start of runoff relative to the time scale used. The correct volume of runoff was obtained by a proper choice of the variable represented by the gamma distribution, as was done in the previous case.

Prediction equations for outflow

The most significant result obtained in the various correlations tested was that describing the relationship between the outflow volume (V_8) and the inflow volume (V_{11}) or, stated in different terms, the relationship between the transmission losses (L) and the inflow volume (V_{11}). The final form of the relation between these variables was expressed by the following equations:

for $V_{11} > 3.58$ acre-feet

$$L = 0.36\, V_{11} + 2.29 \tag{1}$$

or $$V_8 = 0.64\, V_{11} - 2.29\,. \tag{2}$$

For $V_{11} < 3.58$ acre-feet

$$L = V_{11} \tag{3}$$

or $$V_8 = 0 \tag{4}$$

where all quantities are expressed in acre-feet (af). The coefficient of determination for Eqs. (1) and (2) was $R^2=0.94$ (coefficient of correlation $R=0.97$). A comparison between the prediction equations and the actual transmission losses is given in Fig. 6. The root mean square deviation of the predicted outflow volumes, except for Event No. 5, was 1.2 af.

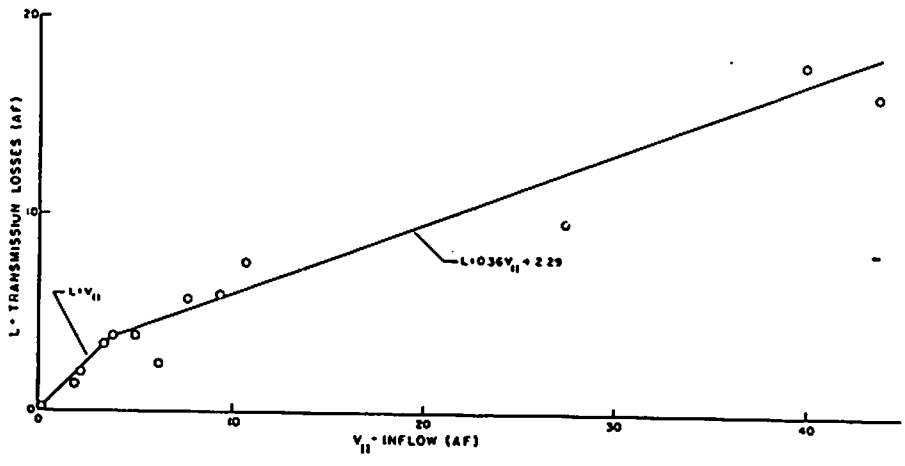

Fig. 6. Transmission loss volumes as a function of inflow volume.

The event of September 11, 1964 (Event No. 5) was not included in the derivation of the above equations. This event, in which the maximum discharge was nearly 2000 cfs, greatly exceeded the capacity of the channel, and the water flooded a wide strip of the adjacent flood plain. The transmission losses in this case included infiltration and detention in the flood plain as well as transmission losses in the channel. Obviously, it was not possible to relate this event with the others where flow was mostly within the banks of the channel. The predicted transmission losses for the maximum event, using Eq. (2), were about 49 af, which is, as expected, much below the measured losses of 82 af.

The peak discharge Q_{p8} of the outflow hydrograph also was highly correlated to the inflow volume. However, because of the high value of the coefficient of correlation between input volume and output volume, it was decided to correlate the peak discharge of the outflow hydrograph (Q_{p8}) with the volume of outflow (V_8). The linear regression equation between the two variables was forced to pass through the origin, and the equation obtained was

$$Q_{p8} = 34.3\ V_8 \tag{5}$$

where Q_{p8} is expressed in cfs and V_8 in af (acre-feet). The coefficient of determination for this relationship was $R^2 = 0.80$.

Of the three time elements used to describe the outflow hydrograph (T_c, T_p, T_b), two were found to be correlated with the outflow volume (V_8) and the third to both the outflow volume (V_8) and the hydraulic radius (R_h) corresponding to maximum discharge at Flume 11. The total time of flow (T_b) was found to increase with the volume of outflow

$$T_b = 144 + 2.75\ V_8 . \tag{6}$$

The time to the centroid of the outflow hydrograph was found to be correlated to the total time of flow and to the outflow volume. Using Eq. (6), the relationship obtained could be reduced to:

$$T_c = 27.5 + 0.07\ V_8 . \tag{7}$$

The coefficients of determination for the two relationships expressed by Eqs. (6) and (7) were $R^2 = 0.58$ and $R^2 = 0.63$, respectively.

The relationship obtained for the time to peak of the outflow hydrograph was

$$T_p = 15.8 - 0.02\ V_8 - 10.2\ R_h^{\frac{1}{2}} \tag{8}$$

but the coefficient of determination in this case had the low value of $R^2 = 0.26$.

The best prediction equation for the time of travel between the beginning of runoff at Flumes 11 and 8 (T_t) was obtained by a linear regression on the

TABLE 2

Comparison of predicted and actual outflow hydrograph parameters at Flume 8.

Event No.	V_8 (acre-feet)		Q_{p8} (cfs)		T_{b8} (min)		T_{p8} (min)		T_{c8} (min)		T_t (min)	
	Actual	Predicted	Actual	Predicted	Actual	Predicted	Actual	Predicted	Actual	Predicted	Actual	Predicted
1	1.28	1.25	14.2	42.9	172	147	11	6	44.2	27.5	86	73
2	0.09	0.00	1.9	11.3	101	144	3	5	24.5	27.5	144	79
3	22.31	22.89	463.4	785.0	234	207	15	8	33.0	29.2	59	58
4	3.45	3.92	142.0	134.0	146	155	11	7	23.0	27.8	63	68
5	46.49	77.79	1914.0	2669.0	226	358	6	12	20.6	33.2	49	42
6	0.16	00.00	7.3	0.0	169	144	3	2	28.8	27.6	116	97
7	3.95	2.02	75.9	69.3	168	150	3	5	37.9	27.8	74	79
8	27.59	25.24	539.8	866.0	283	213	10	8	48.5	29.3	49	52
9	0.00	0.00	0.0	0.0	–	–	–	–	–	–	–	–
10	0.00	0.08	0.0	2.7	–	–	–	–	–	–	–	–
11	3.08	4.73	97.3	162.0	122	157	3	6	21.8	27.9	76	72
12	0.60	0.00	17.5	0.0	116	144	1	4	17.8	27.4	34	81
13	1.89	2.84	63.7	94.0	172	152	2	6	22.2	27.8	68	69
14	12.85	15.17	429.5	520.0	164	186	6	9	21.9	28.7	44	52

logarithmic transformation of the variables

$$T_t = 73.0\, R_h^{-0.56}. \tag{9}$$

The value of the coefficient of determination was again low at $R^2 = 0.33$. All values of time elements in Eqs. (6) to (9) are given in minutes, the volume V_8 is given in acre-feet and the maximum hydraulic radius at Flume 11, R_h, in feet. A comparison between the observed values of the various parameters and those predicted by the set of equations described above is given in Table 2.

The model chosen to represent the antecedent moisture was an exponential decay model, given by Eq. (10).

$$V_{av} = \sum V_t (t)^k \tag{10}$$

where t is the time in days prior to the event, V_t is the volume of inflow on day t in acre-feet, and k is a constant ranging from 0.5 to 0.9.

An attempt was made to relate V_{av} as determined by Eq. (10) to the transmission losses, or equivalently, the downstream volume V_8, in two ways. The first involved V_{av}, and the second involved V_{av}^b where b was an exponent determined by the regression equations. However, neither the linear nor transformed variable was significant, as determined by the F-ratio, in the regression equation developed for the transmission losses. In fact, no significant relationships were found between the antecedent moisture variable V_{av} and any of the parameters of the outflow hydrographs.

The relationships represented by Eqs. (1) to (9) constitute the transfer function that gives the output of the system defined herein for any given input. It appears that of all parameters of the input hydrograph, only the volume of runoff and the peak discharge have significant influence on the output. The peak discharge does not appear in the equations directly. It is represented, however, by the value of the hydraulic radius corresponding to the peak discharge.

Prediction of the outflow hydrograph

The three-parameter gamma distribution used to represent the outflow hydrograph is usually written in the following form:

$$f(t) = \frac{b^a}{\Gamma(a)} (t - c)^{a-1} e^{-(t-c)b} \tag{11}$$

where a, b, c are parameters of the distribution. The equation is identical with that representing the N-reservoirs model instantaneous unit

hydrograph[11]).

$$q(t) = \frac{1}{k\Gamma(N)}\left(\frac{t}{k}\right)^{N-1} e^{-(t/k)} \tag{12}$$

where $N=a$ is the number of reservoirs, $K=1/b$ is the time constant of each reservoir, and $c=t_0$ is the origin of the time scale for the equation.

The relevant properties of the gamma distribution are given by the following equations, which are given here without derivation.

The mode of the distribution is given by

$$t_m = c + (a-1)/b. \tag{13}$$

The mean of the distribution is given by

$$\bar{t} = c + a/b. \tag{14}$$

The maximum ordinate of the distribution is given by

$$f_m = \frac{(a-1)^{a-1} e^{-(a-1)}}{k\Gamma(a)}. \tag{15}$$

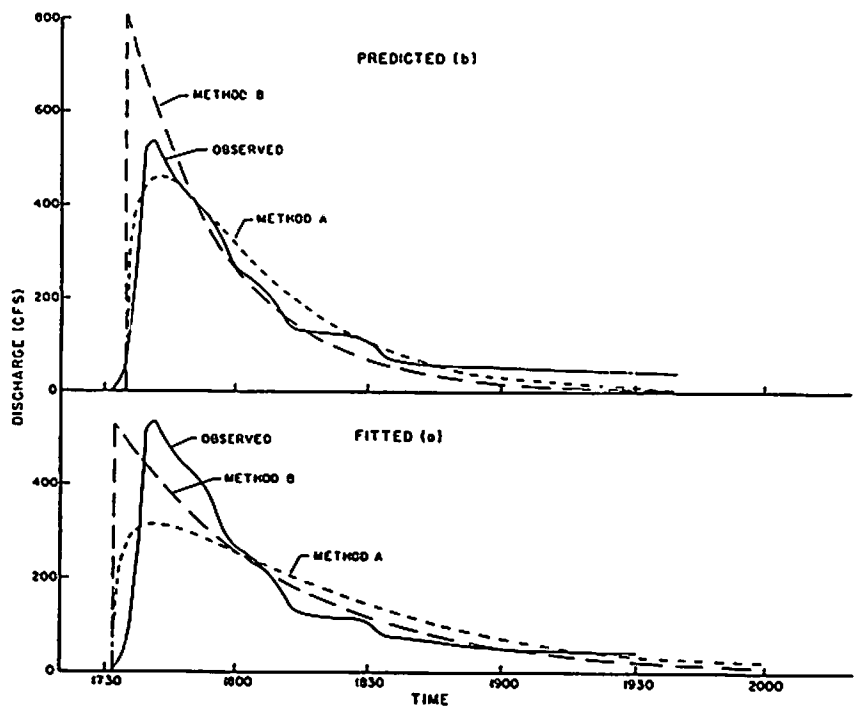

Fig. 7. Outflow hydrographs for event No. 8, July 30, 1966.

The interval between the mode and the mean is given by

$$\bar{t} - t_m = 1/b. \tag{16}$$

The first requirement to be satisfied by the curve adopted is that the area under the curve be equal to the volume of runoff. Since the area represented by the distribution curve is unity (dimensionless), the above requirement is satisfied if the variable represented is taken in the form:

$$f = Q/V \tag{17}$$

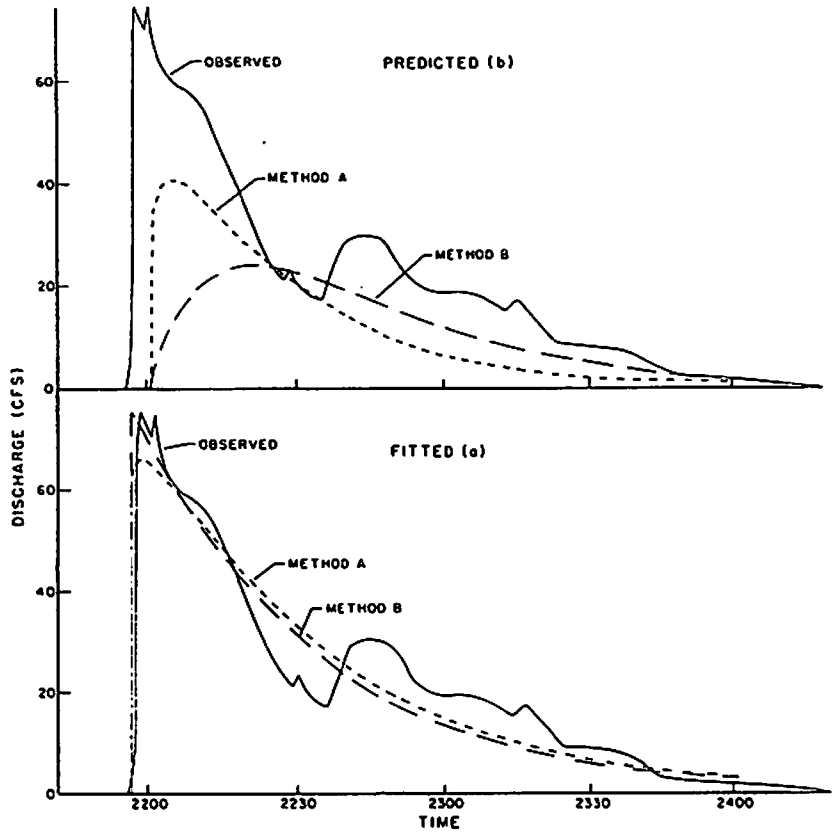

Fig. 8. Outflow hydrographs for event No. 7, Sept. 2, 1965.

where Q is the discharge and V is the total volume of runoff in the event.

In the two methods of curve fitting described above, the value of the parameter c was taken to be equal to the time of start t_0 of the observed hydrographs. For the evaluation of the other two parameters, the first method (Method A) used the simultaneous solution of Eqs. (13) and (14), while the second method (Method B) used Eqs. (15) and (16). Equation (15)

was solved for the value of a, indirectly, by constructing a table of f_m as a function of the parameter a. Values of $\Gamma(a)$ were taken from Abramowitz and Stegun[12]). To solve these equations, values of $t_m = T_p$, $\bar{t} = T_c$ and $f_m = Q_p/V$ were taken from the hydrographs to be represented by the gamma distribution.

The values of the parameters obtained by the two methods are given in Table 3. A comparison of some of the actual and predicted hydrographs is given in Figs. 7 to 9. Figure 7 shows the predicted hydrograph for the event

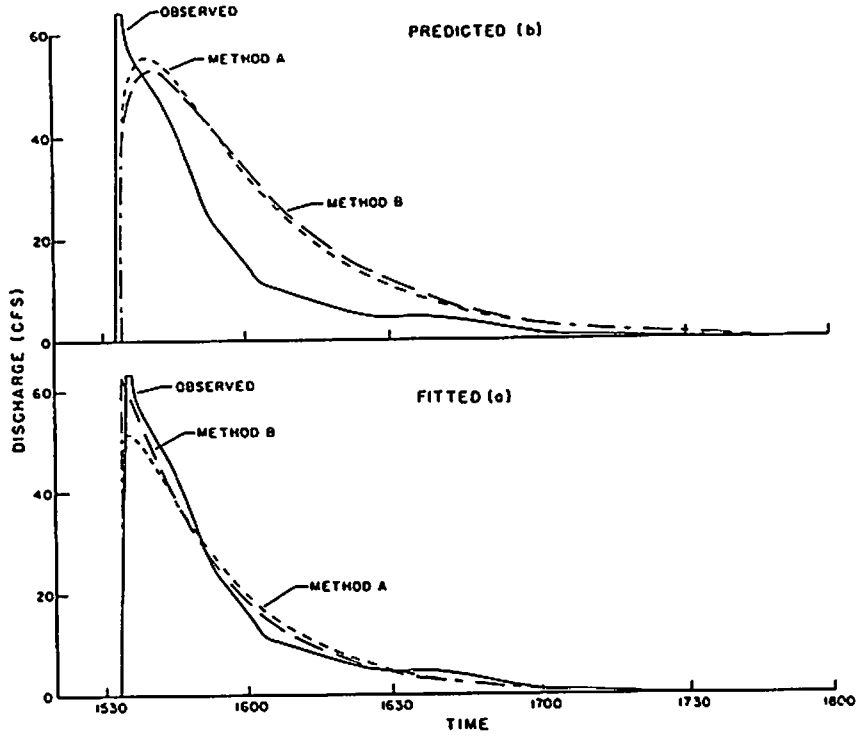

Fig. 9. Outflow hydrographs for event No. 13, August 2, 1968.

of July 30, 1966, illustrated in Figs. 4 and 5. Figures 8 and 9 were chosen to show a case of a bad prediction and a case of a good prediction, respectively. The comparisons were carried out in two stages. First (Figs. 7a, 8a, 9a), the observed outflow hydrographs were compared with the curves obtained by using the parameters derived from the measured outflow hydrographs, that is, distribution curves were fitted to the observed hydrographs. In the second stage (Figs. 7b, 8b, 9b), the observed hydrographs were compared with curves obtained by using parameters predicted from the inflow hydrographs using the relationships derived in the previous section (Eqs. (1) to (9)).

TABLE 3

Parameters for description of outflow hydrographs.

Event No.	Parameters derived from outflow hydrograph				Parameters predicted from inflow hydrograph			
	Method A		Method B		Method A		Method B	
	a	*b*	*a*	*b*	*a*	*b*	*a*	*b*
1	1.331	0.0301	1.445	0.0301	1.279	0.0466	1.002	0.0466
2	1.139	0.0465	1.228	0.0465	** –	–	–	–
3	1.835	0.0556	1.423	0.0556	1.3775	0.0471	1.008	0.0471
4	1.920	0.0836	1.169	0.0836	1.3357	0.0479	1.181	0.0479
5	1.412	0.0686	1.058	0.0686	1.5665	0.0472	1.001	0.0472
6	1.116	0.0388	1.004	0.0388	** –	–	–	–
7	1.086	0.0286	1.019	0.0286	1.2195	0.0439	1.951	0.0439
8	1.260	0.0267	1.001	0.0267	1.3762	0.0470	1.006	0.0470
9	* –	–	–	–	** –	–	–	–
10	* –	–	–	–	1.3420	0.0487	1.009	0.0487
11	1.159	0.0531	1.061	0.0531	1.2744	0.0457	1.099	0.0457
12	1.060	0.0595	1.168	0.0595	** –	–	–	–
13	1.099	0.0496	1.014	0.0496	1.2756	0.0459	1.322	0.0459
14	1.376	0.0627	1.117	0.0627	1.4575	0.0508	1.041	0.0508

* measured outflow volume was zero ** predicted volume was zero

In the first comparison, those hydrographs fitted using Method B gave a better fit to the observed hydrographs than did those fitted using Method A. However, in the second comparison, those hydrographs predicted using Method A gave a better fit than did those predicted using Method B. In the second comparison, Method A tended to underestimate the peak rate, while Method B tended to overestimate the peak rate. The goodness of fit was judged subjectively by visual inspection in all cases.

Discussion of results

The main result of the work reported herein is expressed by the relationships found between the volume and peak discharge of the outflow hydrograph and the volume of the inflow hydrograph for the channel reach considered. Previous papers in which the problem of transmission losses was considered[2,13]) suggested a relationship between the transmission losses and the peak discharge at the upstream station, but the equations offered in the present paper are considered to be better. There is actually no conflict between the two methods since there is a high degree of correlation between the peak discharge and the volume of the hydrograph at any of the runoff-measuring stations in the Walnut Gulch watershed. The present method indicates that the losses are related to the flows throughout the time of passage of the flood wave and not to a single value of the peak discharge.

The representation of the outflow hydrographs by a gamma distribution was found to be justified by the results obtained. The values of the parameter a, which influences the shape of hydrograph, were found to be between 1 and 2, indicating short times to peak and relatively high peaks. The two methods used to fit the gamma distribution to the outflow hydrographs were about equal in their ability to give a good representation of the hydrograph, although one method (B) appeared to be better for fitting actual hydrographs, while the other method (A) gave better results with the predicted hydrographs. No recommendation is made at this stage regarding the preference of Method A or Method B. The poor fit in Fig. 8 can be explained by the fact that the observed hydrograph in this case is double-peaked as a result of two periods of high-intensity precipitation following each other rather closely.

Conclusions

1. A method has been developed for predicting the outflow hydrographs for a given reach of an ephemeral stream in the Walnut Gulch watershed, which is typical of watersheds in southeast Arizona. The system proposed for representing the given reach gives fairly good estimates of the parameters

describing the outflow hydrograph, and the same shape of the hydrograph can be obtained by fitting a gamma distribution with parameters derived from the predicted parameters of the outflow hydrograph.

2. The transmission losses, and hence the outflow volume, were found to be correlated significantly only to the volume of the inflow hydrograph. Other parameters considered, including antecedent channel moisture indices, apparently do not have any significant contribution to the prediction of the losses or outflow volume.

3. The two methods described in the paper for fitting the gamma distribution to outflow hydrographs appear in the present work to be equivalent, without preference for either. The two methods involved equating the mean and mode of the observed and theoretical distributions and equating the maximum and the difference between the mean and mode of the observed and theoretical distributions.

4. The regression equations and the gamma distribution used give better results in cases of single-peaked hydrographs. Double-peaked hydrographs could possibly be treated by separating them into two individual hydrographs and superimposing the results.

5. The prediction equation for transmission losses was related only to events with the flow contained within the banks of the stream channel. The single flow event where water spilled into the flood plain was excluded from the data used to develop the regression equations. Using the regression equation to predict losses for this case considerably underestimated the losses. Were more storm events available for the out-of-bank flow conditions, prediction equations for the transmission losses could be presented for both flow conditions.

6. A desirable extension of the work reported is to obtain similar regression equations for other streams of the Southwest. Comparison of the coefficients in these regression equations with the physical characteristics of the streams considered could lead to a regional description of transmission losses in terms of the system proposed to represent the streams. In the absence of this regional description, the results presented in this paper may serve as a guide for estimating transmission losses in other ephemeral streams.

Notations

a, b, c	Parameters of the gamma distribution
f_m	Maximum ordinate of gamma distribution
L	Transmission loss volume, acre-feet
Q_p	Peak rate of runoff, cubic feet per second
R	Simple correlation coefficient

R^2 Coefficient of determination
R_h Hydraulic radius of maximum flow at Flume 11, feet
T_b Duration of runoff hydrograph, minutes
T_c Time to centroid of hydrograph, minutes
T_p Time to hydrograph peak, minutes
T_t Time of travel of wave front, minutes
$\bar{t}$ Mean of gamma distribution
t_m Mode of gamma distribution
t_0 Time of start of runoff hydrograph
V Volume of runoff, acre-feet
V_{av} Antecedent moisture index

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