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Variability in discharge, stream power, and particle-size distributions in ephemeral-stream channel systems

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Abstract The interacting factors of climate, geology, vegetation, soils, land use, and transmission losses affect the characteristics of discharge and sediment yield in ephemeral streams in arid and semiarid areas of the southwest USA. Research results are presented which describe and summarize these factors and emphasize the consequences of spatially varying rainfall and transmission losses (infiltration losses to stream bed and banks) on the subsequent spatial variability of peak discharge, stream power, and median particle-sizes of bed sediment in ephemeral-stream channels of the Walnut Gulch Experimental Watershed, Arizona, USA.

INTRODUCTION

Spatial and temporal variability in hydrologic processes and the resulting erosion and sedimentation processes are characteristically high in arid and semiarid regions. High variability results from climatic factors such as infrequent and spotty precipitation (i.e. Sellers, 1964; Osborn, 1983). Variable geologic and geomorphic features, including ephemeral-stream channels (i.e. Leopold & Miller, 1956; Thornes, 1977), and marked variations in soils and soil moisture result in variations in vegetation, land use and management (i.e. Fuller, 1975; Branson *et al.*, 1981).

Insufficient knowledge concerning spatial and temporal variations in hydrologic, erosion, and sedimentation processes and their links with geomorphic features at various scales is limiting our ability to model these processes accurately, and thus, to develop the predictive capability required for land use and management decisions. The purpose of this paper is to report the results of a hydrologic modelling study conducted to emphasize the consequences of spatially varying rainfall and transmission losses (infiltration losses to stream bed and banks) on the subsequent spatial variability of peak discharge, stream power, and median particle-sizes of bed sediment in ephemeral-stream channels of the Walnut Gulch Experimental Watershed, Arizona, USA.

DESCRIPTION OF STUDY SITES AND DATA

The Walnut Gulch Experimental Watershed, operated by the US Department of Agriculture, Agricultural Research Service (USDA-ARS) is illustrated in Fig. 1 and

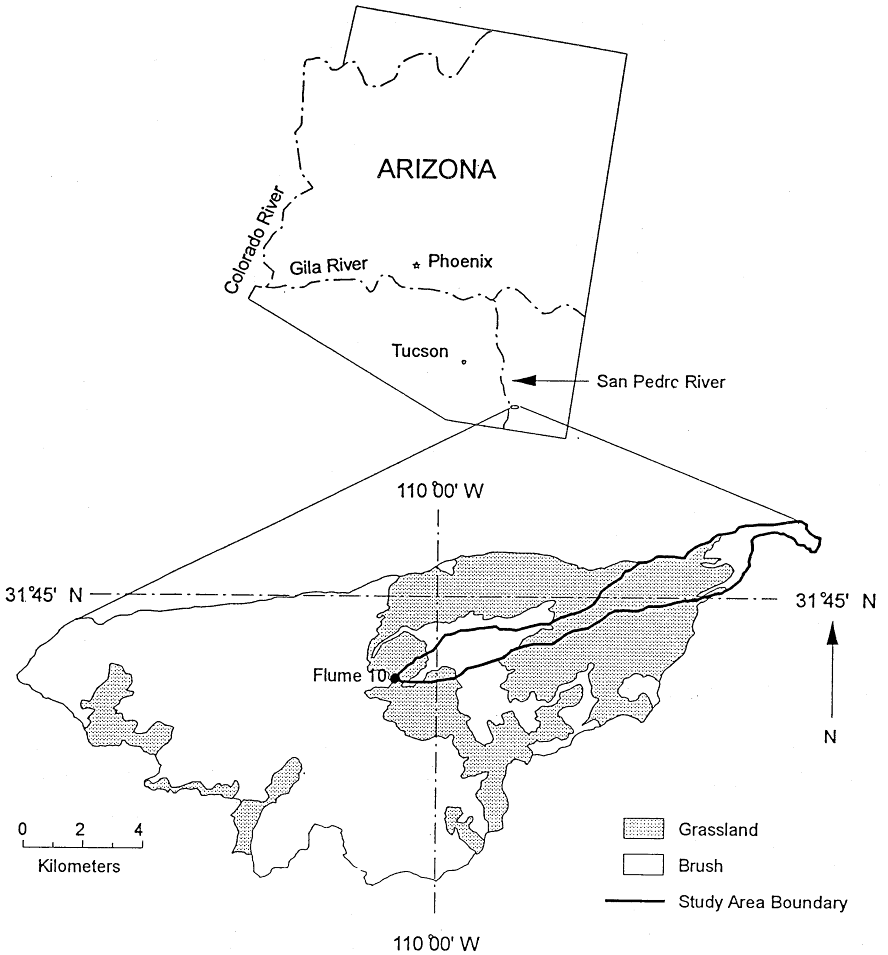

Fig. 1 Location map for the Walnut Gulch Experimental Watershed.

Subwatershed 10 is shown in Fig. 2. Subwatershed 10 drains approximately 10% of the area drained by Walnut Gulch, has relatively more relief, has a higher drainage density, and is significantly more elongated. Detailed descriptions of the Walnut Gulch Experimental Watershed, its database, and observations and research findings are given by Renard (1970) and Renard *et al.* (1993).

Mean annual temperature at Tombstone, Arizona (within the Walnut Gulch Watershed) is 17.6°C, mean annual precipitation is 324 mm, and the climate is

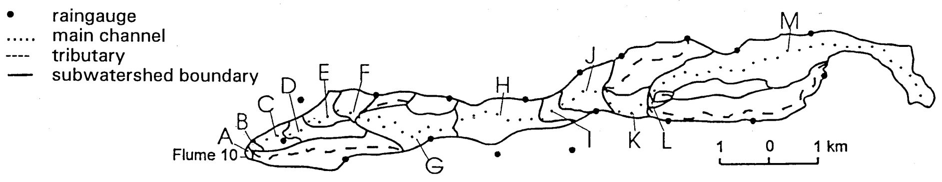

Fig. 2 Subwatershed 10 on Walnut Gulch Experimental Watershed showing channel system and subwatershed discretization for the distributed hydrologic model.

classified as semiarid or steppe. About 70% of the annual precipitation occurs during the summer months from convective thunderstorms of limited areal extent.

Soils on the Walnut Gulch Watershed, like most desert and semidesert soils, are notable for their variations with topographic features and their close relationships with the parent material because of slow rates of soil formation processes in moisture deficient environments. The parent material is dominated by fan deposits, mostly derived from intrusive and volcanic rocks and cemented with calcretes; thus, associated soils are generally well-drained, calcareous, gravelly to cobbly loams. Other important soils developed from igneous, intrusive materials and are typically shallow, cobbly, and fine textured. Finally, soils in flood plains along the ephemeral stream channels are formed of alluvium and vary from sands to loams.

Shrub vegetation, such as creosote bush, acacia, tarbush, and small mesquite trees, dominates (30 to 40% canopy cover) the lower two-thirds of the watershed. The major grass species (10 to 80% canopy cover) on the upper third of the watershed are the gramma grasses, bush muhley, and lovegrass, with some invasion of the shrub species and mesquite (Renard *et al.*, 1993). Land use consists primarily of grazing, recreation, mining and some urbanization.

METHODS AND ANALYSES

Distributed watershed modelling

A calibrated, distributed hydrologic model (Lane, 1982) was used as a tool to compute runoff from rainfall data and to route the runoff in ephemeral-stream channels to compute peak discharge and stream power. Spatial variations in peak discharge due to distributed rainfall, soils, vegetation, and transmission losses are explicitly included in the calculations.

Thiessen weights were determined for the 18 recording raingauges on or near Subwatershed 10 (Fig. 2) and then areal average rainfall was determined for each of the 38 upland and lateral flow areas used to represent the subwatershed. This procedure was repeated for 74 individual runoff producing storms over the 11-year period of record from 1967 to 1977 to fit, or calibrate, the model to observed runoff data measured in the supercritical flume (Fl 10) located at the subwatershed outlet.

This fitting procedure constituted the model calibration with the following results for the 74 runoff events:

$$V_f = 0.42 + 0.89V_o \tag{1}$$

with a value of $R^2 = 0.71$ where V_f is the fitted runoff volume (mm) and V_o is the observed runoff volume (mm). The corresponding equation for peak discharge is:

$$q_f = 0.51 + 0.96q_o \tag{2}$$

with a value of $R^2 = 0.73$ where q_f is the fitted peak discharge (mm h^{-1}) and q_o is the observed peak discharge (mm h^{-1}).

On 9 July 1993 a thunderstorm occurred over the upper portion of Subwatershed 10 and produced runoff at the subwatershed outlet. Runoff curve numbers were adjusted for the dry initial condition until the model estimate matched the runoff peak discharge as measured at the flume. Stream channel cross sections and composite bed material samples were obtained before and after this runoff event at each cross section.

Finally, 60-minute point rainfall amounts for the 2 and 10 year return periods were determined following Osborn (1983) and then adjusted using a depth area relationship (Osborn, 1983) to estimate average rainfall depths over the 16.6 km^2 subwatershed. These subwatershed-average rainfall amounts were used as input to the calibrated, distributed model to produce runoff volume and peak discharge estimates for the 2 and 10 year floods.

Stream power and sediment transport

Stream power per unit length of the stream bed is calculated as:

$$P = \gamma QS \tag{3}$$

where P is stream power in N s^{-1}, γ is the specific weight of water (N m^{-3}), Q is the discharge rate (m^3 s^{-1}), and S is the longitudinal slope of the channel bed. Stream power has been related to total sediment transport (Bagnold, 1960, 1966, 1977). Stream power per unit weight of water, called unit stream power, has been related to total sediment concentration in streams (i.e. Yang & Stall, 1976; Yang & Molinas, 1982). Graf (1983) used stream power per unit length as a surrogate for total sediment transport in ephemeral stream channels.

Earlier, Lane (1955) recognized the role of stream power in stating a qualitative relationship for stable alluvial channels. Lane's equation stated that:

$$G_s d_s \text{ is proportional to } QS \tag{4}$$

where G_s is sediment transport rate (kg s^{-1}), d_s is a characteristic sediment particle size (mm), Q is discharge rate and S is slope of the stream bed, as in equation (3). Without loss of generality, the right hand side of equation (4) can be multiplied by gamma, γ, and both sides of the equation can be divided by d_s (since both γ and d_s are positive quantities) to produce

$$G_s \text{ is proportional to } \gamma QS/d_s = P/d_s \tag{5}$$

which again suggests that stream power might be a useful surrogate for sediment transport rate.

RESULTS AND DISCUSSION

Physical characteristics of the main channel of Subwatershed 10 are summarized in Table 1. Composite bed material samples were collected at 11 cross sections (Table 1). Median particle size varied with distance along the main channel and also with time before and after the runoff event of 9 July 1993. However, there were no statistically significant trends with distance along the main channel and no statistically significant

Table 1 Physical characteristics for the main channel of Watershed 10 as measured in the field and on 1:5000 scale ortho-topographic maps. Channel characteristics used in the distributed hydrologic model to simulate runoff.

Channel reach	Reach length (km)	Distance above Fl 10 at lower end of reach (km)	Average width of reach (m)	Slope at lower end of reach	Median particle size: Before* (mm)	After (mm)
A) 56[†]-x1[‡]	0.18	0	9.1	0.0106	1.48	0.78
B) 50	0.21	0.18	24	0.0098	----	----
C) 47-x3	0.84	0.39	24	0.0089	2.28	0.96
D) 44-x4	0.68	1.22	23	0.0163	1.45	1.71
E) 41-x5	0.9	1.9	17	0.0157	1.72	1.94
F) 38	0.6	2.8	18	0.014	----	----
G) 31-x6	3.19	3.39	12	0.0124	0.95	0.76
H) 28-x7	2.27	6.58	14	0.0111	1.38	2.03
I) 25-x8	0.58	8.85	18	0.0131	1.89	1.31
J) 22-x9	1.06	9.43	20	0.0097	1.41	1.23
K) 16-x11	1.5	10.49	12	0.0105	2.17	0.96
L) 13-x14	0.18	11.99	7.6	0.0127	1.28	0.96
M) 03-x13	7.42	12.16	9.1	0.0114	2.98	1.37
Upper end	----	19.58	----	----	----	----

* Samples taken before and after the first runoff event of the season on 9 July 1993.
[†] Channel reach numbers as represented in the distributed model.
[‡] Denotes cross section numbers on main channel where bed material samples were taken.

differences in median particle sizes before and after the runoff event of 9 July 1993.

Hydrologic variable estimates based on application of the calibrated, distributed hydrologic model are summarized in Table 2. Calculated peak discharge rates along the main channel in Subwatershed 10 for the storm of 9 July 1993, and for the 2 and 10 year floods are shown in Fig. 3(a). Corresponding stream power results are shown in Fig. 3(b).

Excluding the boundary point at the upper end of the main channel, the ratio of maximum to minimum values for the channel characteristics in Table 1 varied by a factor of approximately 2 to 3. The corresponding maximum to minimum ratio for peak discharge of the 9 July 1993 storm is 5.5 and for stream power is 6.4. Ratios for peak discharge of both the 2 and 10 year floods are about 1.6 and ratios for stream power are 2.0. Recall that rainfall input to the model for the storm on 9 July 1993 was distributed over the 38 elements used to model Subwatershed 10 (Fig. 2) while the rainfall input for the 2 and 10 year floods was calculated from a depth area relation and thus was assumed to be uniform over the entire subwatershed. These analyses suggest that the assumption of uniform rainfall input to the hydrologic model significantly underestimated the spatial variability of peak discharge and stream power, and thus by inference, erosion and sediment transport rates.

The results presented in Table 2 are based on modelling results after the model was calibrated using observed runoff data measured at the subwatershed outlet. However, peak discharge and stream power values calculated at interior points remain unvalidated.

Table 2 Hydrologic variable estimates for the main channel of Watershed 10 based on the physical characteristics shown in Table 1 and results of applying the distributed hydrologic model. Calculations are for the storm of 9 July 1993 and for the 2 and 10 year floods.

Channel reach	Distance above Fl 10 at lower end of reach (km)	9 July 1993:		2 year:		10 year:	
		Q[*] ($m^3 s^{-1}$)	P[†] ($N s^{-1}$)	Q ($m^3 s^{-1}$)	P ($N s^{-1}$)	Q ($m^3 s^{-1}$)	P ($N s^{-1}$)
A) 56[‡]-x1[§]	0	4.79	498	14.6	1520	44.5	4620
B) 50	0.18	5.01	480	12.2	1170	37.5	3600
C) 47-x3	0.39	5.44	476	12.6	1100	38.5	3350
D) 44-x4	1.22	7.39	1180	13.9	2220	41.8	6680
E) 41-x5	1.9	8.84	1360	14.4	2220	42.9	6610
F) 38	2.8	10.5	1430	15.3	2100	45.2	6210
G) 31-x6	3.39	11.9	1450	15.1	1830	44.6	5420
H) 28-x7	6.58	18.2	1980	16.9	1840	48.7	5300
I) 25-x8	8.85	23.9	3060	17.1	2200	48.5	6220
J) 22-x9	9.43	26.2	2490	17.5	1670	49.4	4690
K) 16-x11	10.49	24.7	2540	14.6	1510	40.6	4180
L) 13-x14	11.99	15.9	1980	11.0	1370	29.5	3680
M) 03-x13	12.16	13.8	1540	11.0	1230	29.6	3310
Upper end	19.58	0	0	0.0	0	0.0	0

[*] Q is estimated peak discharge using the calibrated, distributed hydrologic model.
[†] P is stream power calculated from the estimated peak discharge.
[‡] Channel reach numbers as represented in the distributed model.
[§] Denotes cross section numbers on main channel where bed material samples were taken.

Adequate study of spatial variability of hydrological processes and sedimentation processes in ephemeral-stream channel systems will require continuous monitoring of discharge, hydraulic variables, and sediment concentration during runoff events, as well as monitoring of physical features of the channel systems between events at a sufficient number of interior points to test the validity of distributed modelling results.

Subwatershed 10 was discretized for modelling purposes as shown in Fig. 2. This resulted in 13 channel reaches along the main channel. The mean reach length is 1.5 km and the range of lengths is 0.18 to 7.42 km. From Fig. 3, it is apparent that at least one additional cross section (and thus subwatershed in the model discretization) is needed between the cross section at 12.16 km above the flume and the main channel headwaters at 19.58 km.

Under the special circumstances of this study, an appropriate distance between monitoring points along the main channel appears to be 1-2 km. For a watershed of this scale (main channel length of about 20 km), 10 to 20 interior measurement points are needed to test the validity of distributed hydrologic models of the complexity used in this study.

Similar studies on other subwatersheds of Walnut Gulch over a range of geomorphic features are needed to generalize these results basinwide. Such generalizations are

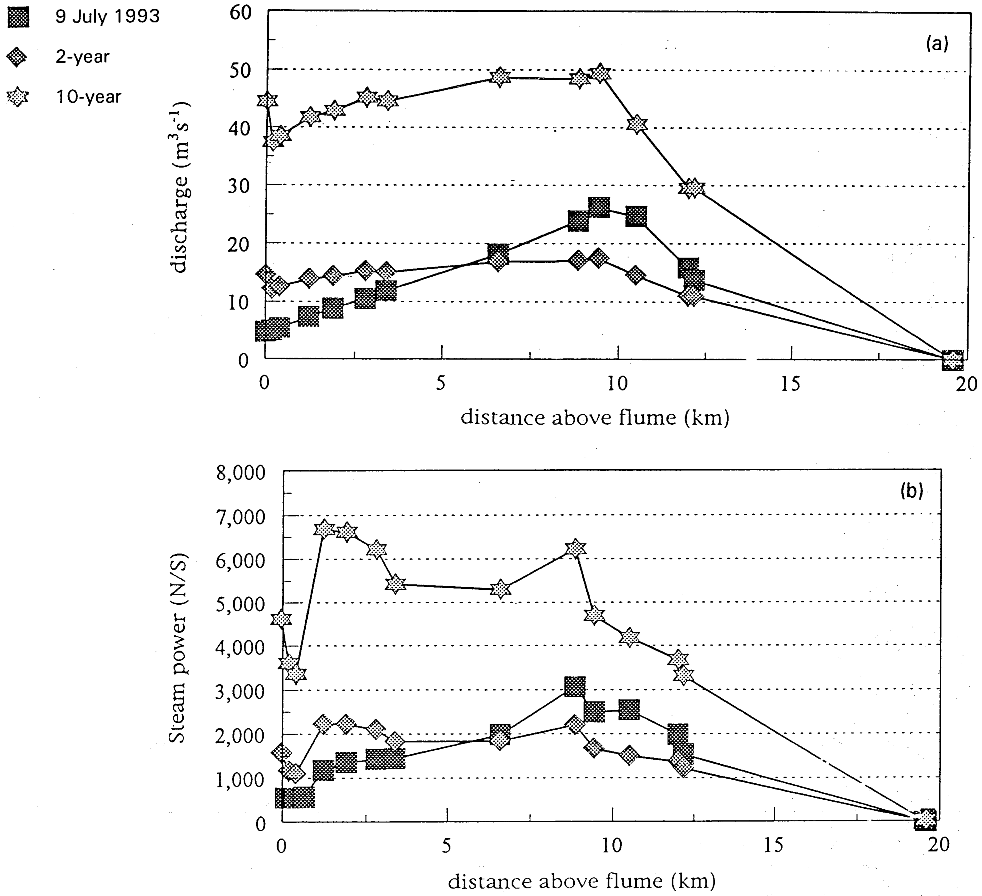

Fig. 3 Variation with distance in the main channel of Subwatershed 10 of (a) peak discharge and (b) stream power.

needed before the impacts of spatial variability in hydrologic and sedimentation processes can be understood, modelled, and predicted.

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