GEOMORPHIC THRESHOLDS AND THEIR INFLUENCE ON SURFACE RUNOFF FROM SMALL SEMIARID WATERSHEDS [1/]

by

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ABSTRACT

The geomorphic threshold concept of landform evolution and its effect on hydrologic performance of drainage systems was investigated on small semiarid watersheds in Southeastern Arizona. Thresholds develop within a geomorphic system with time and can, when exceeded, cause drastic changes in the geomorphic features and in the hydrologic performance of the watershed. The slow continuous evolution of drainage characteristics can be suddenly altered with major readjustment of the landscape taking place. A new state of dynamic equilibrium will then prevail until the drainage system is again subjected to conditions which cause some geomorphic threshold to be exceeded. Areas of potential geomorphic readjustment can be identified from parameters such as channel slope, average land surface slope, drainage density, and mean length of first order streams and these data can be used as components in a calibrated kinematic-cascade model to determine the effects of various degrees of drainage system alteration. The influence on runoff from exceeding various geomorphic thresholds is tested and the resulting hydrologic modifications are simulated and discussed.

INTRODUCTION

THE PROBLEM

Small semiarid watersheds in the Southwestern United States include those where runoff is ephemeral surface flow. Channel systems on these watersheds vary from area to area, may be complex, and change with time, as well as space, in a general landscape evolution. As Heede (1975) states: "Unfortunately, scarcity of data does not provide for the thorough understanding of gully processes that are basic to a definition of gully development stages." Information on cases where there are commensurate hydrologic data are, unfortunately, even more infrequent. Therefore, the need is great for extracting the most geomorphic information from those areas where hydrologic data are available.

The geomorphic threshold concept as described by Schumm (1974) assumes that such geomorphic thresholds are intrinsic and are normally overlooked due to simplifying assumptions and that these thresholds result in complex responses of natural hydrologic systems. Thus, we have the observation that channel systems, particularly gullies, are variable in time at any location as well as variable in space at any time. Our intent here is to utilize Schumm's geomorphic threshold concept in hydrologic analyses of small semiarid watersheds, and to suggest that the identification of these thresholds and the resulting complex hydrologic response is best approached in a two-stage procedure. The first stage, the geomorphic phase, consists of identifying geomorphically similar subareas of a watershed. The second stage, the hydrologic analysis phase, consists of identifying hydrologic response characteristics of the watershed subareas and determining how they combine to produce an overall watershed response (Lane and Wallace, 1976). Our emphasis here is on the geomorphic studies phase.

GEOMORPHIC THRESHOLD CONCEPT

Each of the watersheds we studied is in a unique state of dynamic equilibrium, with varying amounts of physical change needed to cause hydrologic performance change. Primary factors which govern the magnitude of outside influence or force necessary to initiate change are: differences in slope between the lower incised channel network and the upper discontinuous drainage area; ground cover (which includes vegetation, gravel pavement and litter); and complexity of the drainage network.

Numerous variables cause the runoff characteristics of a watershed to undergo change. The impact of urbanization on hydrologic performance is being felt more each year in ever-increasing ways (Graf, 1975). Alteration of runoff characteristics may not always evolve by the generally accepted process of slow, continuous change. Rather, it may occur as cyclic fluctuations, beginning with a period of progressive, continuous change. A failure point or threshold will be reached, at which time a short period of drastic change will take place. The cycle may then repeat itself. Schumm (1974) refers to the crossing point between these periods as the "geomorphic threshold." He describes a geomorphic threshold as a threshold developed within the geomorphic system by changes in the system itself through time. When a geomorphic threshold is exceeded (in our case usually by runoff volume in an amount sufficient to cause the more remote areas of the watersheds to contribute flow to the lower areas) changes in the hydrologic performance of the watershed will occur. Low intensity precipitation would generate runoff in only the lower portion of the watershed with only the major channels contributing to runoff through the watershed outlet. More intense larger volume precipitation would naturally

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produce flow in more of the channels and more collective area (the areas of lesser slope and denser vegetation). Finally, an event would occur in which the magnitude would cause the whole watershed area to contribute to runoff at the outlet, with the upper discontinuous drainage area contributing to the lower drainage network.

THE PROCEDURE

The procedure is to identify, from topographic maps and field observations, those geomorphic features which can be used to partition a watershed into geomorphically homogeneous subzones. Head-cuts, extent of incised drainages, and slope changes of the channel beds are the main features used to determine homogeneity. Though the zones will not be homogeneous in all features, they will be homogeneous in those characteristics which are primary in determining the complexity of responses. Another partitioning criterion important in subsequent modeling efforts is the physical arrangement of subzones with respect to the distance from the watershed outlet. Geomorphic characteristics within each subarea influence that area's hydrologic response. When rainfall depth and intensity exceed critical amounts, geomorphic thresholds are exceeded resulting in complex hydrologic response, in varying degrees, from the entire watershed area.

Partial area response is the watershed's response to a precipitation episode when the ensemble of spatial variabilities of precipitation, infiltration, etc. causes only a portion of the total watershed area to produce runoff at the watershed outlet. With the understanding that geomorphic and other features of the watershed subzones in part determine if the zones are runoff source areas, partial area response can be considered as a hydrologic manifestation of geomorphic thresholds.

Partial area response is examined by considering the relationship between average loss rate (average infiltration rate over the entire watershed for the duration of the rainfall event) and the average intensity of the runoff-producing rainfall. If infiltration is assumed to vary over the watershed, and if for a given level of rainfall intensity only a portion of the total watershed area is contributing runoff, then we should observe a relationship between average loss rate and average rate of runoff-producing rainfall because as rainfall intensity increases, additional areas of the watershed with given infiltration capacity begin to yield runoff. The result is an increase in the average infiltration rate over the areas producing runoff.

Since the watersheds are being partitioned into zones, a rainfall-runoff simulation model constructed of components corresponding to the zones should prove useful in determining how the hydrologic responses of the zones combine to produce the overall watershed response. Such a model is the kinematic cascade model (Kibler and Woolhiser, 1970) calibrated to watershed topography using the goodness-of-fit procedure described by Lane, Woolhiser, and Yevjevich (1975). We used the results of a simplified simulation study using this model to suggest a procedure for predicting the hydrologic effects of gully advance on a small watershed.

DATA AND ANALYSES

EXPERIMENTAL WATERSHEDS

Experimental data used here are: a 6 x 12 ft (0.00165 ac) runoff plot on the Walnut Gulch Experimental Watershed near Tombstone, Arizona; two small watersheds (4.02 ac and 4.26 ac) on the Santa Rita Experimental Range south of Tucson, Arizona; and a 326-ac watershed near Apache Junction, Arizona. A general description of the Walnut Gulch Watershed is given by Renard (1970). For a general reference on the Santa Rita Experimental Range see Martin and Cable (1975). Details of the Queen Creek Watershed are given by Arteaga and Rantz (1973).

RELATION BETWEEN GEOMORPHIC FEATURES AND HYDROLOGIC RESPONSE

As an example of the influence of geomorphic features on watershed response, Watershed 76.001 on the Santa Rita Experimental Range is examined in detail. Watershed 76.001 is a 4.02-ac (1.62 ha) watershed with incised drainage on the lower portion of its area and an upland area with poorly defined drainage. For this watershed, and the calibrated kinematic cascade model discussed later, we divided the watershed into four zones with a single, main channel (Figure 1).

For the four subzones of Watershed 76.001, we quantitavely measured different intra-watershed subzones, including land slope, drainage density, and topographic roughness (Table 1).

Zone #1, the uppermost zone of watershed 76.001, is characterized by flat slopes (approximately 3% slope). Channels are shallow, discontinuous, very short, and extremely crenulated, as compared with the other areas. Runoff is ephemeral. For low-intensity, low-volume precipitation events, the zone will produce intermittent, non-uniform overland flow (if any flow at all). For higher intensity, larger volume events, overland flow will be produced. Thus, the zone can be considered a nearly flat plane, with a surface texture of varying roughness and no discernable drainage pattern.

Zone #2 is a transition or intermediate zone, with some characteristics of Zones #1, #3, and #4. The lower boundary of this zone is well defined by head cuts or nick points of the incised drainage. Both channel and ground surface slopes are less than those of Zones #3 and #4. Drainage in this zone consists of subdued channels that are continuations of the incised channels of Zones #3 and #4. The

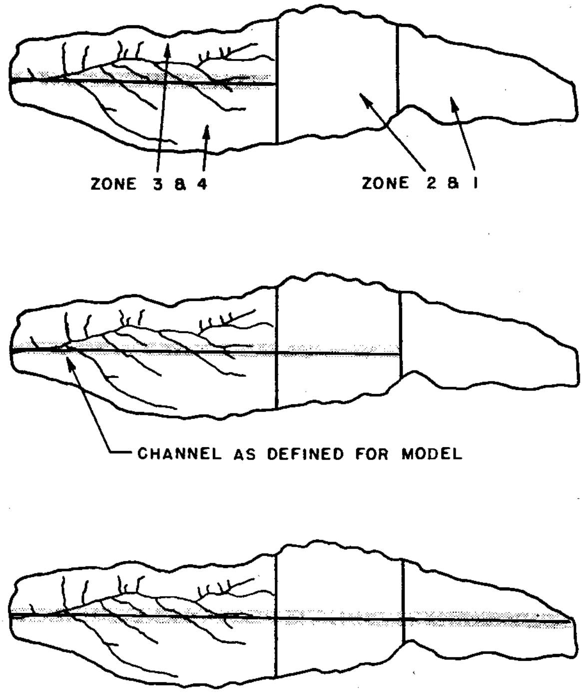

FIGURE 1. Map of Watershed 76.001 illustrating the four zones of the watershed and channel lengths used for modeling purposes.

Table 1

CHARACTERISTICS OF ZONES IN WATERSHED 76.001

Zone	Area (acres)	Slope of Best Fit Plane	Geometric G-O-F Statistic 1/ R_p^2	Drainage Density 2/ Dd (ft/Ft^2)	Mean Length of 1st Order Channels (Ft.) (M)
.1	0.939	.0343	.998	---	---
2	1.067	.0343	.998	---	---
3	0.643	.0811	.929	0.0114	26. (7.92m)
4	1,367	.0521	.936	0.0132	85. (25.91m)
TOTAL 4.02 acres					

1/ R_p^2 is a measure of how well the observed elevation data are fit by a plane. A value of 1.0 indicates a perfect fit.

2/ Total length of all channels in a watershed divided by watershed area.

Zone #2 channels are shallower than incised channels, and contain a considerably smaller volume of sand and gravel. The sand bottoms of these channels average 0.55 ft (0.16m) wide and 0.1 to 0.2 ft (0.03m to 0.06m) deep. They contain a lesser volume of alluvium available for flow abstraction than the channels of Zones #3 and #4. Consequently, the Zone is not as affected by antecedent moisture in the channels as are Zones #3 and #4, with larger channels.

Zones #3 and #4--contain the steepest slopes, most deeply incised channels, and the greatest volume of channel alluvium. The upper boundary of these zones ends at the head cuts of the incised channels. There drainage density is greater than in any of the other Zones. Reaction time of these areas to precipitation varies with variations in antecedent moisture and, especially controls within the larger channels caused by tree roots, large boulders, bank caving, etc. However, variation of reaction to precipitation intensity and volume is generally less than the two other Zones. Zones #3 and #4 are characterized by lower, more often exceeded thresholds concerning the start of overland flow and upslope movement of gullies.

AVERAGE LOSS RATE VS. AVERAGE INTENSITY OF RUNOFF-PRODUCING RAINFALL

If ϕ is defined as the average loss rate (in/hr) then runoff-producing rainfall is that portion of the rainfall when intensity exceeds average loss rate ϕ.

As we discussed earlier, Arteage and Rantz (1973) related average loss rate, ϕ, to average density, I_p, as

$$\phi = \begin{cases} I & I < I_c \\ a + bI_p, & I_p \geq I_c \end{cases} \quad (1)$$

where:

ϕ = average loss rate,

I = rainfall intensity,

I_c = threshold intensity below which there will be no runoff,

I_p = average intensity of runoff-producing rainfall,

a = intercept, and

b = slope of regression line.

The average runoff rate, $\bar{q}$, may be expressed as

$$\bar{q} = I_p - \phi$$

Substitution into Eq. 1 yields

$$\bar{q} = \begin{cases} 0.0 & I < I_c \\ (1-b)I_p - a, & I_p \geq I_c. \end{cases} \quad (3)$$

When the runoff rate is 0, $I_c = a/(1-b)$ so that

$$\bar{q} = \begin{cases} 0 & , I < I_c \\ (1-b)\ (I_p - I_c), & I_p \geq I_c \end{cases} \quad (4)$$

is an alternate form of the equation for the average loss rate. Arteaga and Rantz (1973) interpreted Eq. 4 as indicating that (1-b) is the proportion of the total area contributing runoff and that the average loss rate for the area contributing runoff is I_c.

If partial area response (indicated by $b > 0$ and thus $(1-b) < 1$) is a manifestation of geomorphic thresholds, then the percentage of watershed area contributing runoff should be related to geomorphic features. We assumed that geomorphic thresholds were related to watershed area. Under this assumption (1-b) and I_c should be related to watershed area. As expected, since thunderstorm rainfall of the type common on watersheds examined here is of limited areal extent, and as watershed area increases, some areas are more remote from the outlet, then the proportion of watershed area contributing runoff (1-b) would decrease as watershed area increases. However, the situation for the threshold intensity, I_c, is not as obvious. In these watersheds channel network and volume of alluvium contained therein increase as watershed area increases. Therefore, we might expect I_c to increase with increasing watershed area.

Data from the 6- x 12-ft runoff plot and three other watersheds are shown in Table 2. The runoff plot has no channels and would be expected to have nearly 100% of the area contributing. As shown in

Table 2

RELATION BETWEEN PROPORTION OF CONTRIBUTING AREA, THRESHOLD INTENSITY, AND WATERSHED AREA

Watershed	Area (acres) (ha)	Number of Storms	Proportion of area contributing runoff (1 - b)	Threshold Intensity I_c (in/hr)
Walnut Gulch Runoff Plot 63.333	0.00165 (0.006 ha)	8	0.78	0.47
Watershed 76.001	4.02 (1.63 ha)	8	0.45	0.76
Watershed 76.002	4.26 (1.72 ha)	6	0.34	0.85
Queen Creek Watershed	326 (131.98 ha)	11	0.26	0.77

Table 2, the coefficient in Eq. 4 suggests that about 78% of the area actually was contributing. Contributing values are 45% and 34% for the Santa Rita watersheds and 26% for the larger Queen Creek Watershed. Apparently (1-b) decreases as watershed area increases, but the values of (1-b) are only approximate when using small samples. For example, the percentage of contributing area for watershed 76.002 should be nearly equal to the value for 76.001. The threshold intensity to begin producing runoff, I_c, may vary with area as shown in Table 2. However, both the threshold and the proportion of contributing area would also vary with precipitation characteristics, antecedent moisture, time of season, etc. so that trends with area should be considered qualitative. More quantitative determination cannot be made until alternative analysis techniques are developed (see the following section, and Lane and Wallace, 1976) and the results of a tracer experiment being designed at the Southwest Watershed Research Center are available.

A PARTICULAR SIMULATION MODEL

If watershed topography and channel network are modeled as a cascade of planes and channels in a logical flow sequence, and the kinematic wave equations for overland flow and open channel flow are solved for each element in the cascade, then the resulting mathematical model is a kinematic cascade model (Kibler and Woolhiser, 1970). Such a model is compatible with the approach of partitioning the watershed into geomorphically homogeneous zones.

A simplified model of Watershed 76.001 consists of a cascade of four zones, each of which is modeled as a plane and a single channel which is modeled by a single channel representing the prototype main channel. The kinematic cascade parameters for each plane are summarized in Table 3. The total length of the watershed, L_b, is 1080 ft (329m). The main channel extends approximately one half the distance up the watershed.

A rainfall-runoff event on August 12, 1975, was used to calibrate the simplified cascade model to Watershed 76.001. The observed and fitted hydrographs for this event are shown in Figure 2. For the purpose here, rainfall excess was assumed uniform over the 4-ac (1.63 ha) watershed. There is a difference in hydrograph time to peak, but the hydrograph shapes and peak discharges appear similar. Again, the model was calibrated by fitting this hydrograph.

A statistical procedure for fitting cascades of planes and channels to topographic data was described by Lane, Woolhiser, and Yevjevich (1975). Such a procedure was used for Watershed 76.001 as described by Lane and Wallace (1976). This calibrated model was subsequently used to simulate rainfall-runoff processes resulting from channel changes in this watershed.

SIMULATION OF GULLY ADVANCE

As a first approximation of the hydrologic effects of gully advance on small watersheds (as reflected in the surface runoff hydrograph at the watershed outlet) we used the calibrated kinematic

Table 3

CHARACTERISTICS OF THE SIMPLIFIED KINEMATIC CASCADE MODEL OF WATERSHED 76.001

ELEMENT IN CASCADE	AREA	LENGTH	WIDTH	SLOPE	COMMENTS
	(acres)	(ft)	(ft)		
Plane 1	0.939 (0.372 ha)	341 (104 m)	120 (366 m)	.034	Upland zone
Plane 2	1.067 (0.432 ha)	230 (70.1 m)	202 (61.6 m)	.034	Receives flow from Plane 1. Contributes flow to upstream boundary of main channel.
Plane 3	0.643 (0.260 ha)	55 (16.8 m)	509 (155.2 m)	.081	Lateral inflow to main channel
Plane 4	1.368 (0.554 ha)	117 (35.7 m)	509 (155.2 m)	.051	Lateral inflow to main channel
Channel 5	---	509 (155 m)	---	.036	Main channel ends at head cut in mid-watershed

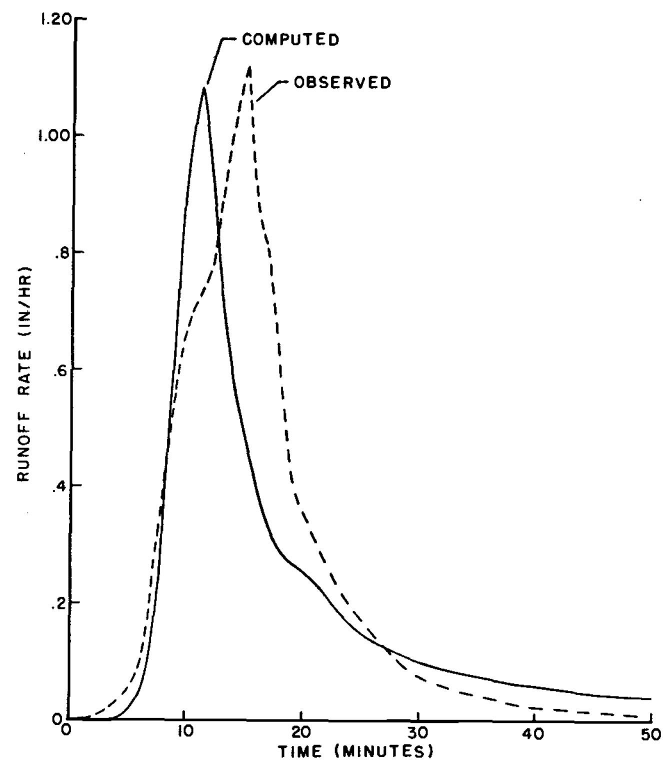

FIGURE 2. Observed and computed hydrographs for the event of August 12, 1975, Watershed 76.001.

cascade model to simulate runoff. Rainfall excess was assumed uniform over the watershed at a constant rate of 2.00 in/hr for 10 min (although we would expect it to change with increasing channel length). For illustrative purposes, the main channel is assumed to be 50%, 100%, 150%, and 200% of its present length. Although it is an oversimplification, we assumed all other watershed features were constant (i.e. only the main channel length changes). The resulting runoff hydrographs are shown in Figure 3.

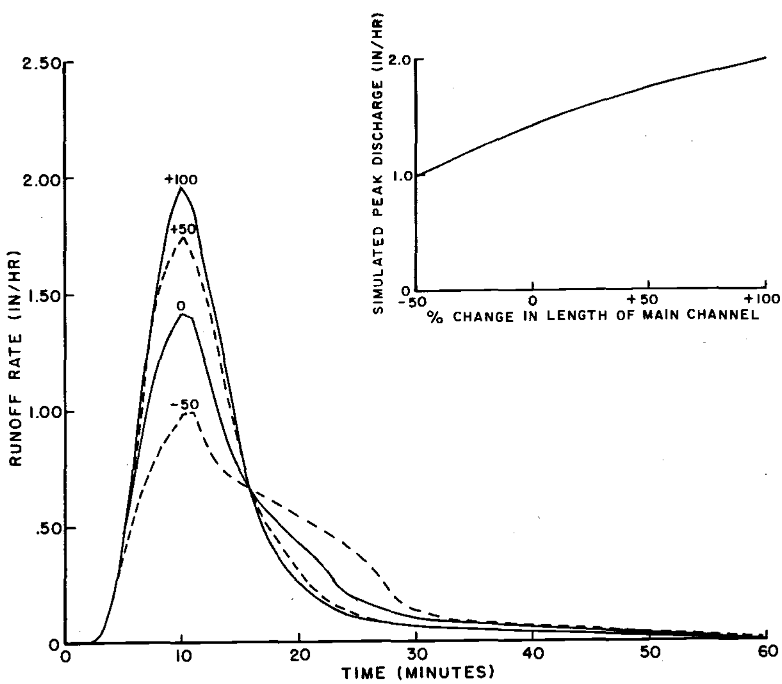

Figure 3. Simulated hydrographs for Watershed 76.001, uniform rainfall excess. Simulation of gully advance of 50%, 100%, 150%, and 200% of the present length of the main channel.

The effects of gully advance include an increase in peak discharge, a faster rise to the peak, and a steeper recession from the peak discharge. The graph in the upper portion of this figure represents the change in peak discharge with gully advance. Due to the simplifications in this example, these results are only a qualitative estimate of the influence of gully advance on the surface runoff hydrograph, but they do allow us to form a working hypothesis for more comprehensive research into the hydrologic import of gully advance on small semiarid watersheds.

OBSERVATIONS AND SUMMARY

RELATION BETWEEN PARTIAL AREA RESPONSE AND SEDIMENT PRODUCTION

Rainfall-runoff simulation results and average loss rate vs. rainfall intensity analyses on small, semiarid watersheds in Arizona suggest that runoff source area variability results in storm runoff hydrographs that are a function of partial area responses (Arteaga and Rantz, 1971, Lane and Wallace, 1975, and Lane and Wallace, 1976). If the watershed is assumed to contribute uniformly over the entire area, while in fact about half the area is contributing runoff, then runoff rates assumed over the entire area may be in error by a factor of two. The resulting errors in estimating runoff rates would then carry over into estimated values for mean shear stress and erosion rates. Hence, the desire to identify, a priori from geomorphic characteristics, those areas of a watershed which will produce runoff from a given size storm under specified antecedent conditions.

PARTIAL AREA RESPONSE OF SMALL SEMIARID WATERSHEDS

Based on the analyses cited earlier and on those conducted here, the assumption of partial area responses for the watersheds in question is warranted. Moreover, it seems reasonable to assume that partial area response is a hydrologic manifestation of an ensemble of geomorphic differences and thresholds producing a complex hydrologic response. A procedure has been introduced for delineation of watershed zones based upon geomorphic features. These zones are compatible with a particular rainfall-runoff simulation model. Such a model can be used to simulate processes such as gully advance on small semiarid watersheds. Such simulation results, while based on model assumptions and limited by available data, do provide working hypotheses on the hydrologic consequences of some geomorphic processes.

REFERENCES

Arteaga, F. E., and Rantz, S. E. 1971.
Application of the source-area concept of storm runoff to a small Arizona watershed. Jour. Research U. S. Geol. Survey, Vol. 1, No. 4, pp. 493-498.

Graf, W. L. 1975.
The impact of suburbanization on fluvial geomorphology. Water Resources Research, Vol, II, No. 5, pp. 690-692.

Heede, B. H. 1975.
Stages of development of gullies in the west. ARS-S-40, pp. 155-161.

Kibler, D. F., and Woolhiser, D. A. 1970.
The kinematic cascade as a hydrologic model. Hydrology Paper No. 39, Colorado State University, Ft. Collins, CO, 27 pages.

Lane, L. J., and Wallace, D. E. 1975.
A basic study of the influence of geomorphic features on watershed flow systems. Part II of File Report No. 1 Geomorphic and Hydrologic Studies, Southwest Watershed Research Center, Tucson, Arizona. 56 pages.

Lane, L. J., and Wallace, D. E. 1976.
Simulation of partial area response from a small semiarid watershed. Proc. 1976 Joint Meetings of Arizona Sec. A.W.R.A. and Hydrology Section, Arizona Academy of Science, Tucson, Arizona, April 28 - May 1, 1976.

Lane, L. J., Woolhiser, D. A., and Yevjevich, V. 1975.
Influence of simplifications in watershed geometry in simulation of surface runoff. CSU Hydrology Paper No. 81, Colorado State Univ., Ft. Collins, CO, 50 pages.

Martin, S. C. and Cable, D. R. 1975.
Highlights of Research on the Santa Rita Experimental Range. In Arid Shrublands, Proc. Third Workshop of the US/Australia Rangeland Panel, Tucson, Az. 1973, pp. 51-57.

Renard, K. G. 1970.
The hydrology of semiarid rangeland watersheds. U. S. Department of Agriculture Publication ARS 41-162, 26 pages.

Schumm, S. A. 1974.
Geomorphic Thresholds and Complex Response of Drainage Systems. Ch. 13 in Fluvial Geomorphology, Proc. Fourth Annual Geomorphology Symp., SUNY-Binghamton, NY, pp. 229-310.