SIMULATION OF PARTIAL AREA RESPONSE FROM A SMALL SEMIARID WATERSHED [1]

Leonard J. Lane and Delmer E. Wallace [2]

INTRODUCTION

The research reported here is an attempt to improve understanding of how geomorphic features of small semiarid watersheds affect their hydrologic performance. The surface topography and channel characteristics of watersheds of interest have been formed by surface runoff-erosion processes. Therefore, the intention is to select models where geomorphic features have a high correspondence with similar features in the real watershed. Thus, it may be possible to infer that hydrologic significance of these features in the model suggest similar relations for the real watershed.

PARTIAL AREA RESPONSE

Partial area response is a watershed response when only a portion of the total watershed area is contributing runoff at the outlet or point of interest. This concept is included in a broader one--that of spatial variability of rainfall, infiltration, and thus rainfall excess. In this paper the term partial area response will be used to describe the hydrologic phenomena resulting from the ensemble of spatial variabilities, as reflected in the runoff hydrograph at the watershed outlet.

While the partial area concept evolved in consideration of regions more humid than those studied here (Hewlett, 1961; Dunne and Black, 1970; Patten, 1975; and others), Arteaga and Rantz (1971) successfully applied the theory to a small (0.50 mi^2) semiarid watershed in Arizona. Their analysis on the Queen Creek Tributary involved relating an average loss rate, L_{60}, to an average runoff-producing rainfall rate, P_{60} (both terms in inches per hour). The resulting regression equation, based on 11 events with total rainfall varying from 0.46 to 2.07 in., is.

$$L_{60} = \begin{cases} P_{60}, & P_{60} \leq 0.77 \text{ in/hr} \\ 0.20 + 0.74P_{60}, & P_{60} > 0.77 \text{ in/hr.} \end{cases} \tag{1}$$

Solving for the average runoff rate in inches per hour, R_{60}, results in

$$R_{60} = \begin{cases} 0, & P_{60} \leq 0.77 \text{ in/hr} \\ 0.26P_{60} - 0.20, & P_{60} > 0.77 \text{ in/hr,} \end{cases} \tag{2}$$

which can be written as

$$R_{60} = \begin{cases} 0, & P_{60} \leq 0.77 \text{ in/hr} \\ 0.26(P_{60} - 0.77), & P_{60} > 0.77 \text{ in/hr.} \end{cases} \tag{3}$$

Eq. 3 was interpreted ("simplistically" in their terms) as indicating 1.00 - 0.26 = 0.74 as the proportion of the total area not contributing runoff, and that the remaining 26% of the area has an average loss rate or ϕ-index of 0.77 in/hr. Eq. 1 can be interpreted as representing the change in average loss rate with increasing rainfall intensity. Since it takes an increase in rainfall intensity to bring the "higher infiltration" zones into runoff production activity, the resulting average loss rate increases. This relation would hold (not necessarily linearly) until the rate of change of contributing area with increasing intensity approaches zero. For additional discussion of this relation see Wallace and Lane (1976).

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1. Contribution of the United States Department of Agriculture, Agricultural Research Service, Western Region.

2. The authors are Research Hydrologist and Geologist, respectively, Southwest Watershed Research Center, 442 East Seventh Street, Tucson, Arizona 85705.

Arteaga and Rantz (1971) noted that the contributing area was probably not constant but related to a storm index,

$$SI = \frac{A_m + (A_m + S)}{2} = A_m + S/2, \tag{4}$$

where SI = storm index (in),
A_m = antecedent rainfall (in), and
S = total storm rainfall (in).

Their reasoning for defining SI by Eq. 4 is that the contributing area increases during a storm dependent upon antecedent and current rainfall and that the average contributing area would be related to the average rainfall at the beginning (A_m) and at the end (A_m + S) of the rainfall event. They did not clarify how long before an event antecedent rainfall was summed to obtain A_m. In addition, A_m undoubtedly is not independent of the timing before the day in question. A function fitting the midrange of their data is:

$$a = 0.36\ (SI)^{0.64}, \tag{5}$$

where a is the proportion, $0 \leq a \leq 1.0$, of total watershed area contributing, averaged over the storm period.

Therefore, the partial area concept may be valid for small semiarid watersheds. Experimental data are used to derive equations similar to Eqs. 3 and 5 on a different Arizona watershed. However, before this is done it is necessary to describe the procedures and data used.

In representing watershed topography in a mathematical model, each interchannel (including upland) area is modeled as a plane or a series (cascade) of planes in a logical flow sequence. The equation and, thus, the slope of each plane is derived by least squares fitting using x, y, z-coordinate data from topographic maps. Hobson (1967) used this approach in topographic analysis of land surfaces. The reasoning here is that deviations of watershed elevations from the best fit plane can be analyzed to characterize the goodness-of-fit of the least squares plane to the watershed surface. A topographic map defines a watershed perimeter and channel network. Each point on the perimeter and within the watershed is defined by its coordinates (x, y, z). To each z_i value on the watershed, there is a corresponding estimated value

$$\hat{z}_i = b_1 + b_2 x_i + b_3 y_i, \tag{6}$$

where x_i, y_i = the corresponding horizontal coordinates,
b_1, b_2, b_3 = coefficients of the least squares plane, and
$\hat{z}_i$ = an estimated elevation value corresponding to z_i.

A deviation of the plane from the surface is then $z_i - \hat{z}_i$. If $\bar{z}$ is the arithmetic mean of the observed elevation data, then a geometric goodness-of-fit statistic, R_p^2, was defined as:

$$R_p^2 = \frac{\sum_{i=1}^{n} (z_i - \hat{z}_i)^2 - \sum_{i=1}^{n} (z_i - \bar{z})^2}{\sum_{i=1}^{n} (z_i - \bar{z})^2}, \tag{7}$$

and represents the relative improvement by fitting the plane over using the mean elevation (Lane, 1975; Lane, Woolhiser, and Yevjevich, 1975). This statistic can be used to decide when an irregular natural surface can be modeled as a plane for overland flow simulation. Also, it can be used to decide how many planes in cascade are necessary to model an irregular-slope. Thus, an objective statistical tool is available to decide when a geometric simplification is sufficiently accurate in modeling overland flow.

Gray (1961) defined slope of the main stream, S_c, as the slope of the hypotenuse of a right triangle with the same base length and the same area as that under the observed stream profile. However, Gray defined the length of the main stream, L_c, as the length of the main stream extended to the watershed divide. This definition required modification for the watersheds with extensive upland areas. Therefore, throughout this study, length of the main channel, L_c, will refer to the actual-unextended channel length, e.g., the length of channel to the last definable stream on an aerial photograph. Watershed length, L_b, will always exceed the length of the main channel. Total relief of the main channel is H_c, and the altitude of the equivalent area right triangle is h. With these definitions, the index of concavity, I_c, is

$$I_c = h/H_c \tag{8}$$

as a measure of the overall stream concavity. A value of I_c less than one would indicate an overall concave profile, and a value of I_c greater than one would indicate an overall convex profile. Finally, the index of concavity is proposed as an individual channel goodness-of-fit statistic measuring how well the channel slope is represented by a straight line.

Drainage density (the total length of all identifiable stream channels divided by the watershed area) is an overall measure of the entire drainage system in a watershed. Since drainage density gives the length of channels per unit area, it is a measure of drainage efficiency, but also, the mean length of overland flow is approximately equal to one over twice the drainage density (Horton, 1932). Denote D_d as the drainage density in the watershed (prototype) and d_d as the drainage density in the model (cascade of planes and channels). The ratio $I_d = d_d/D_d$ is the drainage density ratio and is a measure of how well the channel network is modeled with respect to total length.

From a topographic map a watershed perimeter, its channel network, and the interchannel areas of overland flow can be identified. Goodness-of-fit statistics are proposed for fitting a cascade of planes and channels to watershed coordinate data. The geometric goodness-of-fit statistic is a measure of how well a set of planes fits the designated zones of overland flow. The index of concavity is a measure of how well an individual channel is represented by a uniform slope. The drainage density ratio is an overall measure of how well the entire channel network is represented in the mathematical model.

In kinematic wave theory, the momentum equation is approximated by maintaining only those terms expressing bottom slope and friction slope. The resulting simplified depth-discharge equation is:

$$Q = \alpha h^n, \tag{9}$$

where Q = local discharge,

h = local flow depth,

α = coefficient incorporating the slope and roughness, and

n = exponent reflecting the assumed velocity-depth relation and the assumed flow type -- laminar or turbulent.

The continuity equation is:

$$\frac{\partial h}{\partial t} + \frac{\partial (uh)}{\partial x} = q\ (x,t), \tag{10}$$

where h = local flow depth,

u = local velocity,

x = distance in direction of flow,

t = time, and

q = lateral inflow rate.

Eqs. 9 and 10 are the kinematic wave equations (Henderson and Wooding, 1964; Wooding, 1965a, b, and 1966). The kinematic cascade model involves applying Eqs. 9 and 10 to the cascade of planes and channels (Kibler and Woolhiser, 1970). The basic simulation program used here is a finite difference program for the kinematic cascade -- where open channel flow is always turbulent and the Chezy roughness relationship is assumed to apply. Overland flow begins as laminar flow and then there is a transition to turbulent flow if a transitional Reynolds number, R_c, is reached.

The Darcy-Weisbach friction factor, f, for laminar flow is:

$$f = K/R_c, \tag{11}$$

where K = resistance coefficient,

R_c = Reynolds number, and

f = friction factor.

For turbulent flow and the Chezy relationship:

$$f = 8g/C^2, \tag{12}$$

where g = gravity constant, and

C = Chezy coefficient.

The coefficient in Eq. 9 for laminar flow is:

$$\alpha = 8gS/K\nu \tag{13}$$

where α = coefficient,

S = slope, and

ν = kinematic viscosity, and the other variables are as described above.

For turbulent flow, the coefficient is:

$$\alpha = C\sqrt{S} \tag{14}$$

If there is a transition from laminar to turbulent flow, and the friction factor at the transition satisfies Eq. 11 and 12, then it must be that:

$$C = \frac{\sqrt{8gR_c}}{K} \tag{15}$$

The variables are as defined previously. Therefore, K is a resistance coefficient for laminar flow on a plane; given K and R_c, then the turbulent roughness coefficient for overland flow is determined by Eq. 15. Chezy C is the roughness coefficient for turbulent open channel flow. The exponent n in Eq. 9 is 3.0 for laminar flow and 1.5 for turbulent flow.

Values for Chezy C for open channel flow can be obtained directly from handbooks or from values of Manning's n (Barnes, 1967) as in:

$$C = \frac{1.5\ R^{1/6}}{n}$$

where R is hydraulic radius.

Data for laminar flow over natural surfaces were presented by Woolhiser (1974). These same data were presented graphically by Lane (1975). Roughness coefficients from tables in handbooks or from graphs will be called "tabular roughness coefficients" to distinguish them from optimized coefficients obtained from runoff data.

Each observed hydrograph consists of m ordinates or discharge values and the associated times (t_i, q_i) for i = 1, 2, ...m. The simulated or computed hydrograph from the finite difference program consists of m computed ordinates at the corresponding times $(t_i, \hat{q}_i)$. For any particular time, t_i, the error in discharge or runoff rate is $q_i - \hat{q}_i$. If $\bar{q}$ is the mean discharge of the observed data, then a hydrograph goodness-of-fit statistic is R_q^2, where,

$$R_q^2 = \frac{\sum_{i=1}^{m}(q_i - \bar{q})^2 - \sum_{i=1}^{m}(q_i - \hat{q}_i)^2}{\sum_{i=1}^{m}(q_i - \bar{q})^2} \tag{17}$$

is the relative improvement by fitting (optimizing) the computed hydrograph over using the mean discharge. This is the basic goodness-of-fit statistic measuring how well the computed hydrograph matches the observed hydrograph. With R_q a maximum for any given kinematic cascade, the corresponding model parameter values are the optimal values and the best fit hydrograph is the optimal hydrograph.

The modeling procedure is summarized in Fig. 1. The left portion of this figure deals with the topographic analyses described above, and the right portion deals with the hydrologic analysis via the kinematic cascade program. Topographic data are used to derive the geometry of planes and channels and the associated goodness-of-fit statistics: R_p^2, I_c, and I_d.

Observed hydrologic data are used to estimate rainfall excess and to compare with the simulated hydrographs in optimization. Results of the hydrologic analysis are the optimum kinematic cascade model parameters and the hydrograph goodness-of-fit statistic (R_q^2).

EXPERIMENTAL DATA

The Santa Rita Experimental Range is administered by the USDA Forest Service, Rocky Mountain Forest and Range Experiment Station in Tucson, Arizona. The Santa Rita Range is located 30 mi south of Tucson on a broad plain dissected by many shallow ephemeral streams (Martin and Cable, 1975). Average annual rainfall varies from about 10 to near 20 in, depending upon elevation (Martin and Reynolds,

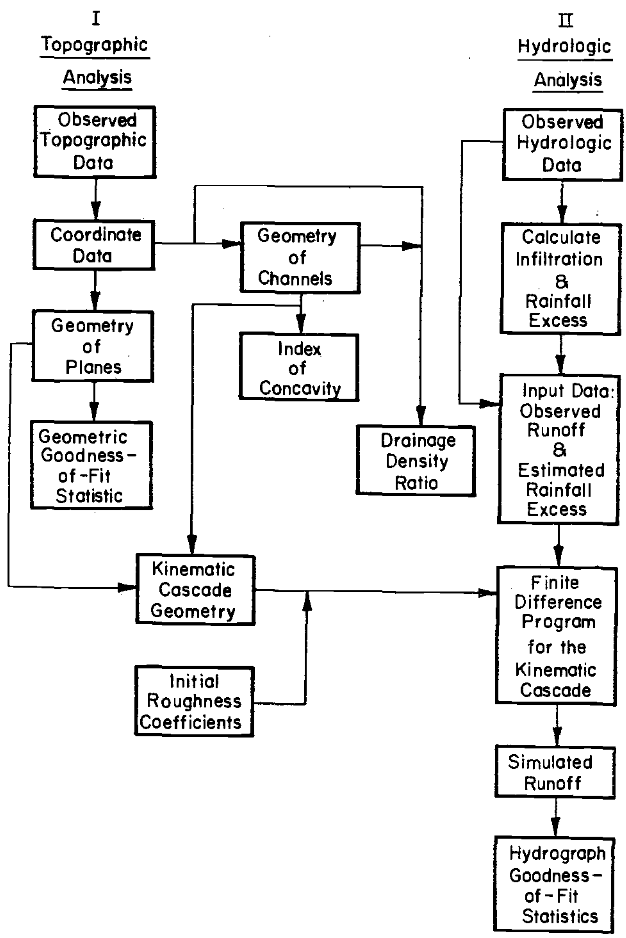

Figure 1. Summary of modeling procedure.

1973). Recently, eight small watersheds were selected for intensive hydrologic study in conjunction with a study of herbaceous vegetation (Martin, Morton, and Renard, 1974). Of these eight watersheds, five were instrumented in time for the 1975 season and the remaining ones will be operating by summer, 1976. In line with the Agricultural Research Service (ARS) national numbering system, the Santa Rita area is designated location 76. Thus, watershed 1 is numbered 76.001.

Green and Sellers (1964) provide a climatic summary for this area and a source for pictures, descriptions, and a history of the region is The Changing Mile by Hastings and Turner (1965).

Watershed 76.001 is a 4.02-acre watershed, which is long and narrow with a width-length ratio of 0.22. The lower one-half of the area has well-defined drainage, but the upper half does not.

During the summer of 1975, 10 rainfall-runoff events were observed and runoff hydrographs obtained for 8 events (Table 1). Two events resulted in multiple peaks hydrographs each of which could be separated into two hydrographs. The first two of the 10 events were not recorded because flume installation was not completed in time to measure the runoff for these dates. Since there were no large events, (column 3, of Table 1) these events represent the rather high-frequency events and not the larger low-frequency events. Rainfall excess was estimated using a simple ϕ-index (which will be explained later). Rates and volumes of runoff were calculated assuming the entire watershed area is contributing runoff uniformly.

Table 1 RAINFALL DEPTH-DURATION DATA AND AVERAGE LOSS RATE FOR 1975 DATA ON WATERSHED 76.001

Runoff Event No.	Date of Event	Total Depth P (in)	Total Duration D (min)	Rainfall Data: Duration of Runoff Producing Rainfall D_p 1/ (min)	Rainfall Data: Average Rate During Runoff Producing Rainfall I_p (in/hr)	φ-index 2/ (in/hr)	5-day Antecedent Moisture Index A_m (in)	Storm Index SI (in)	Proportion of Area Contributing Runoff a From Eq. 21
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
1	07/12/75	0.73	32	8	3.60	2.33	0.14	0.50	0.40
2	07/24/75	0.34	63	3	1.60	1.48	0.04	0.21	0.22
3	07/27/75	0.23	12	2	2.10	1.56	0.06	0.18	0.21
4	08/08/75	0.51	37	3	4.00	2.56	0.00	0.26	0.26
5	08/12/75	1.00	83	15	2.60	1.50	0.18	0.68	0.48
6	09/01/75	0.66	154	6	1.00	0.75	0.05	0.38	0.33
7	09/13/75a	0.24	13	4	2.10	1.53	0.04	0.16	0.19
8	09/13/75b	0.14	22	5	1.20	0.97	0.28	0.35	0.31

1/ Time for which rainfall intensity exceeds the φ-index.

2/ Average loss rate (φ-index) calculated for the entire watershed area.

ANALYSIS AND RESULTS

PERCENT CONTRIBUTING AREA FROM AVERAGE LOSS RATE

Values of the φ-index to match observed runoff volumes were computed for each of the eight storms on Watershed 76.001 in Table 1 . Runoff-producing rainfall is defined as occurring when rainfall intensity, I, exceeds the φ-index (Table 1). For the 8 storms on Watershed 76.001, the equation corresponding to Eq. 1 is

$$\phi = \begin{cases} I, & I \leq 0.76 \text{ in/hr} \\ 0.55 I_p + 0.34, & I_p > .76 \text{ in/hr}, \end{cases} \tag{18}$$

and the equation corresponding to Eq. 3 is

$$\bar{q} = \begin{cases} 0, & I \leq 0.76 \text{ in/hr} \\ 0.45(I - 0.76), & I > 0.76 \text{ in/hr}. \end{cases} \tag{19}$$

About 45% of the watershed was contributing, and the average φ-index for the contributing area is 0.76 in/hr (Fig. 2). These values agree with results from the Queen Creek Watershed. Also, it seems reasonable to assume that a relatively larger percent of the total area would be contributing on the small 4.02 acre Santa Rita watershed (45 vs. 26% for Queen Creek).

Antecedent precipitation index A_m, is computed for the previous 5 days as

$$A_m = \sum_{i=0}^{m=5} P_i (1/2)^i \tag{20}$$

where P_i = depth of rainfall on i'th previous day, (in),

i = number of days previous, and

A_m = antecedent moisture index (in).

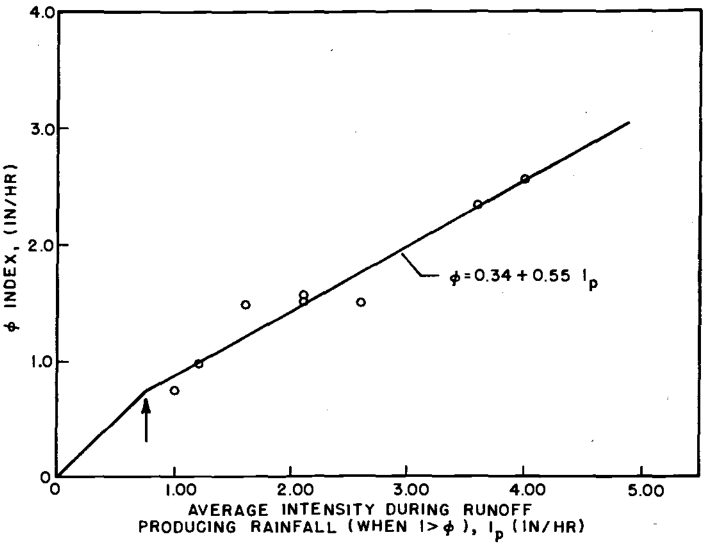

Figure 2. Average loss rate, ϕ-index, vs. average intensity of runoff producing rainfall, I_p, watershed 76.001.

Values of A_m and the storm index, from Eq. 4, are shown in columns 8 and 9 of Table 1.

The coefficient in Eq. 19 for Watershed 76.001 is 0.45 while the coefficient in Eq. 3 for the Queen Creek watershed is 0.26. For this reason, it would seem reasonable to assume the coefficient (0.36) in Eq. 5 will also be different for the smaller (4.02 acre) Watershed 76.001. Therefore, the coefficient in Eq. 5 is multiplied by the ratio 0.45/0.26 to produce:

$$a = 0.62\ (SI)^{0.64} \tag{21}$$

as a simplified equation for the proportion of the total watershed area contributing runoff, a. Values of a for the eight storms on this watershed during 1975 are in column 10 of Table 1. The mean of these values is 0.30 as compared with the coefficient of 0.45 in Eq. 19. Thus, Eq. 21 yields a mean value of the proportion of the area contributing which is 50% less than suggested by Eq. 19. The reasons for this discrepancy are not immediately clear. One possible reason might be that the 1975 data do not contain any large events where total rainfall exceeded 1.00 in. One possible solution might be via the runoff simulation program.

RAINFALL-RUNOFF SIMULATION USING PARTIAL AREA-KINEMATIC CASCADE MODELS

Rainfall excess is estimated using the ϕ-index. With this method, infiltration is constant in time and varies in space through partial area analysis as described earlier. The result will be a preliminary estimate of contributing area. Later analysis will examine similar results with improved rainfall excess estimates to assess the influence of rainfall excess variability.

A simplified model of Watershed 76.001 consists of a cascade of four planes and a single channel. Each of the four watershed subzones is modeled as a plane, and the channel network is modeled by a single channel representing the prototype main channel (Geometry 2B, Fig. 3). This figure also shows the proportion of contributing area for successively more of the watershed area contributing flow at the outlet. The kinematic cascade description parameters are summarized in Table 2. The total length of the watershed is L_b = 1080 ft. Thus, the main channel extends approximately one-half the distance up the watershed. The topographic or geometric goodness-of-fit statistics for this example are also shown in Table 2.

Data for two events on 7/12/75 and 8/8/75 (Table 1) are shown in Figs. 4 and 5. These graphs show the observed and simulated hydrographs for the entire area and for 50% of the area contributing. For the event on 7/12/75 the hydrograph goodness-of-fit statistic is R_q^2 = 0.96 for the entire area and R_q^2 = 0.93 for the partial area response. Corresponding values are 0.54 and 0.88 for the event on 8/8/75. In the first event, both simulated hydrographs match the observed hydrograph, but in the second example the partial area response is a closer fit to the observed hydrograph. These two examples are indicative of the results for the 1975 data. For the entire area response, the mean R_q^2 for the eight storms listed in Table 1 is 0.56 and the ratio of mean fitted to mean observed peak discharge is 0.84. The corresponding R_q^2 is 0.81, and the ratio of peak discharges is 1.02 for the 50%

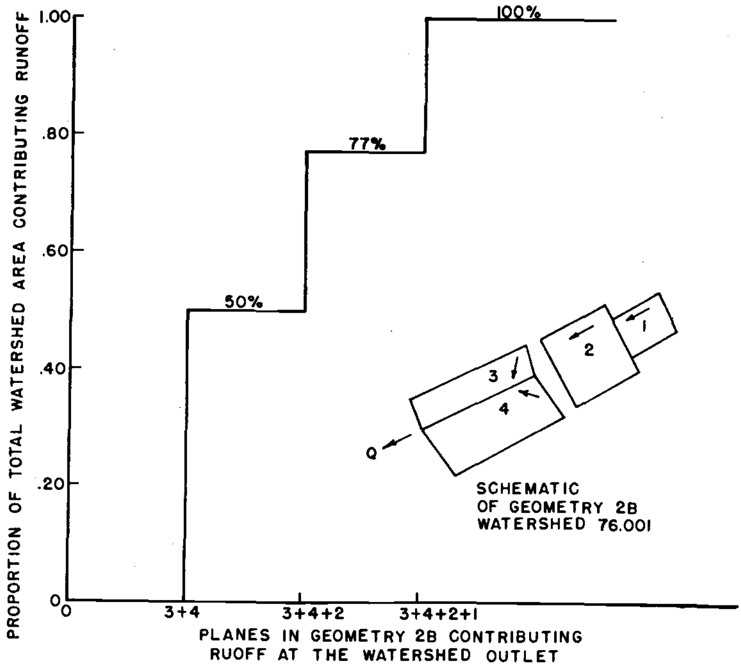

Figure 3. Relation between number of planes and proportion of watershed area contributing runoff.

Table 2. Characteristics of the Simplified Kinematic Cascade Model of Watershed 76.001, Geometry 2B

Element in Cascade	Area ($ft^2 x 10^3$)	Length (ft)	Width (ft)	Slope	Comments
Plane 1	40.9	341.	120.	.034	Uplane zone
Plane 2	46.5	230.	202.	.034	Receives flow from Plane 1. Contributes flow to upstream boundary of main channel
Plane 3	28.0	55.	509.	.081	Lateral inflow to main channel
Plane 4	59.6	117.	509.	.051	Lateral inflow to main channel
Channel 5	----	509.	----	.036	Main channel ends at head cut in mid-watershed

Goodness-of-Fit Statistic	Value for Geometry 2B
R_p^2	0.97
I_c	0.82
I_d	0.31

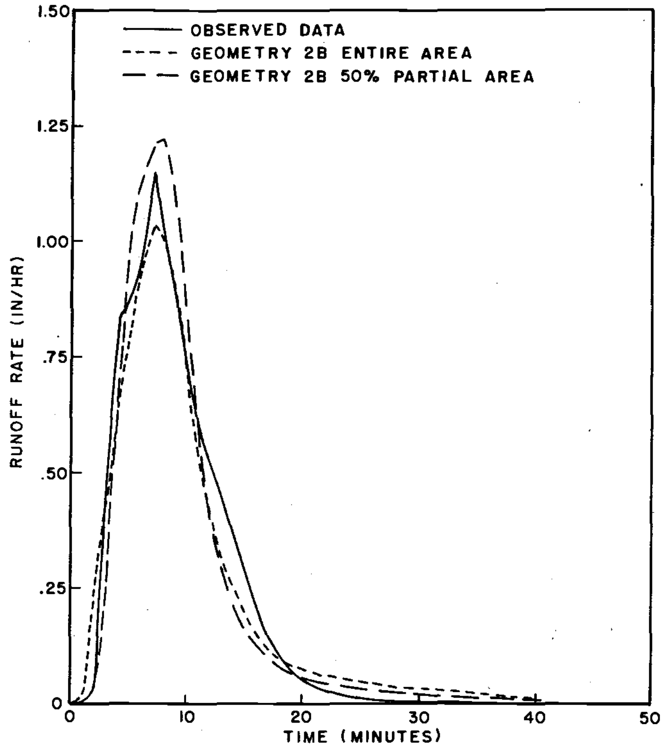

Figure 4. Observed and simulated hydrographs for watershed 76.001, event of 7/12/75. Entire area and partial area responses.

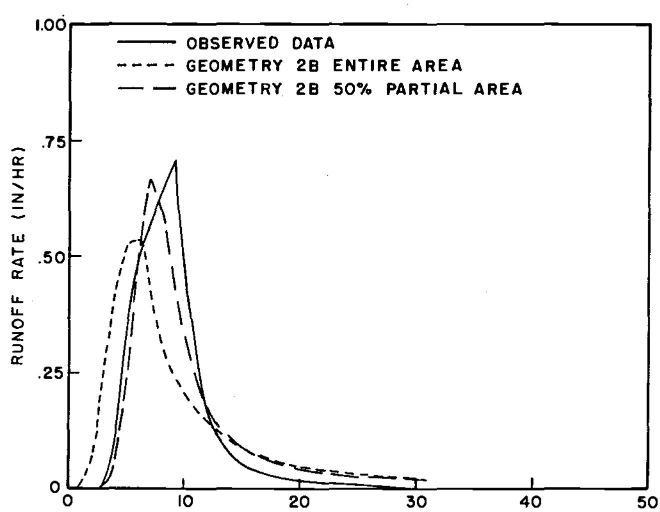

Figure 5. Observed and simulated hydrographs for watershed 76.001, event of 8/8/75. Entire area and partial area responses.

partial area response.

Finally, infiltrometer data from eight plots, two in each zone, suggest a variation in infiltration rates on the order of ratio of 1:2 with zone 2 having the highest infiltration (lowest runoff) and zone 4 having the lowest infiltration (highest runoff). At present, the infiltrometer data can only be given a qualitative interpretation. However, they do support the hypothesis of partial area contribution.

SUMMARY AND OBSERVATIONS

The research reported here is an attempt to improve understanding of how geomorphic features affect hydrologic response, particularly partial area response, on semiarid watersheds. Results from a small watershed in central Arizona relating average percent contributing area with average loss rate suggested a similar relation on the smaller Santa Rita Watershed. This similarity was confirmed by analysis of eight small runoff events.

Geomorphic features (and the resulting goodness-of-fit statistics) are used to divide the watershed into subareas homogeneous with respect to their features and hydrologic response. The kinematic cascade model is used to simulate partial area response. The results from these analyses also suggest a partial rather than entire area response for the 1975 runoff data analyzed.

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