Storm-Cell Properties Influencing Runoff from Small Watersheds

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In much of the western United States, runoff from small watersheds is dominated by occasional short-duration, extremely variable, high-intensity thunderstorm rainfall. These runoff-producing events are important in highway-culvert and small-bridge design, erosion and sedimentation studies, evaluations of range management and renovation programs, and studies on urbanizing watersheds. A kinematic-cascade model (KINEROS) was adapted in this study for use on a small rangeland watershed to determine the influences of thunderstorm rainfall variability in time and space on peak discharge and runoff volume. Model parameters were developed with existing rainfall and runoff data, and the hydrographs were generated from simulated rainfall distributions. The study showed that for small rangeland watersheds (less than 1 mile^2), spatial and temporal rainfall distributions exert approximately equal influences on peak discharge and the influences tend to be additive. Further studies on the interrelationship between rainfall variability and watershed size are indicated, because where the storm is centered becomes increasingly important with increasing watershed size.

In much of the western United States, and particularly in the Southwest, runoff from small watersheds is dominated by occasional short-duration, extremely variable, high-intensity thunderstorm rains (1,2). These runoff-producing events are important in highway-culvert and small-bridge design, erosion and sedimentation studies, evaluations of range management and renovation programs, and studies on urbanizing watersheds, but expected peak discharges and runoff volumes for such events are difficult to estimate accurately. In this paper, a kinematic-cascade model (KINEROS) was adapted for use on a small (560-acre) rangeland subwatershed to investigate the influence of thunderstorm rainfall variability in time and space on peak discharge and runoff volume. The model parameters were developed with existing rainfall and runoff data, and hydrographs were generated from simulated rainfall distributions. The influence of temporal and spatial variability was examined through comparison of the generated peak discharges and runoff volumes.

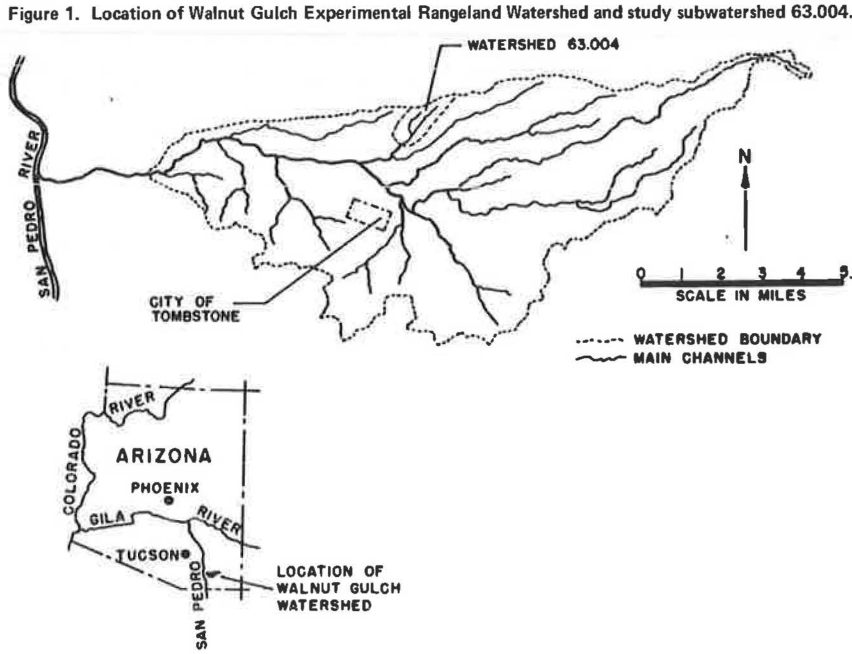
WATERSHED DESCRIPTION

The Walnut Gulch Experimental Rangeland Watershed, operated by the Agricultural Research Service (ARS) of the U.S. Department of Agriculture (USDA), is located near Tombstone in southeastern Arizona (Figure 1). The lower two-thirds of the 58-mile^2 watershed is primarily brush covered (whitethorn, creosote bush, tar bush, and burroweed); the upper one-third is primarily grass covered (grama grasses). Tombstone is centrally located on the watershed. The 560-acre study subwatershed (63.004) lies north of Tombstone on the Walnut Gulch watershed boundary (Figure 1). Slopes of the study subwatershed vary up to 14 percent; the average is 9 percent. The subwatershed is drained by well-defined sand-bottomed channels in the lower portion and broad swales with poorly defined shallow meandering channels in the upper portion. Headcuts separate the sand-bottomed channels and swales on the two major branches of the drainage system. The subwatershed is brush covered, and the soils are primarily gravelly and silty loams.

RAINFALL-RUNOFF MODELING

Many different mathematical models have been used to estimate drainage runoff peaks or volumes or both for small watersheds (3,4), but few models are sensitive enough to separate the influences on runoff of rainfall variability and critical watershed characteristics. In some cases, such definition is not needed, and the model can be quite simple (the ra-

Figure 1. Location of Walnut Gulch Experimental Rangeland Watershed and study subwatershed 63.004.



tional formula, for example). Nevertheless, to identify the significant thunderstorm-cell rainfall properties that influence runoff, critical watershed characteristics must be modeled so that their effect can be eliminated when rainfall is varied. It must be possible to isolate the watershed influences on runoff so that variations in runoff can be attributed directly to the rainfall input to the system. In the past, efforts to model the influences of rainfall variability on watershed runoff have been handicapped by the lack of a sensitive (and uncomplicated) rainfall-runoff model.

Several rainfall-runoff models were suggested for this study, and from these a kinematic-cascade model (KINEROS) (5-8) was chosen because it was versatile and sensitive to both rainfall and watershed characteristics.

Model Description

KINEROS is a well-tested nonlinear, deterministic, distributed-parameter model (6). Inputs are (a) the hyetograph of actual or simulated rainfall, (b) the watershed surface geometry and topography, (c) parameters for surface roughness, (d) infiltration parameters, and (e) the channel networks, including slope, cross-sectional area, cross-sectional shape, and hydraulic roughness. The model also includes a subroutine for erosion, which was not used in this study. A more detailed description of the model is given elsewhere (8). For this study, a subroutine was added to account for channel abstractions.

The watershed was segmented into a series of 21 representative rectangular planes and 9 trapezoidal channel segments (Figures 2 and 3). Because all planes of the watershed were pervious, with relatively homogeneous soils and cover, the same infiltration and roughness characteristics were used throughout. Surface geometries were determined separately for each plane and channel reach (Figure 3). The numbers indicate the order in which each plane was entered into the program. Runoff from the uppermost plane along a slope can be calculated independently of that for all other planes. Because the runoff from the upper plane provides the upper boundary condition for lower planes, sequential calculation is required for complex slopes such as planes 27 and 28 in Figure 3. Flows were routed through each channel segment by using the kinematic approximation to the equations of unsteady, gradually varied flow.

Variables such as infiltration and surface roughness were adjusted based on comparisons of hydrograph simulations and actual runoff hydrographs. Particular attention was paid to surface rock cover (erosion pavement) and roughness, the initial water-holding capacity of the soils, and initial and final infiltration rates. Once the model had been adjusted, it was used to generate a series of hydrographs from simulated rainfall inputs.

Rainfall Input

The storm-cell properties that would be expected to influence runoff are the rainfall amount and duration and the rainfall variability in time and space. These properties were examined through a series of selected inputs.

Several investigators (2,9) reported strong correlations for small watersheds between peak discharge and maximum rainfall for 30 min. On the other hand, 60-min rainfall is a more common unit used in modeling of rainfall and runoff, so both 30- and 60-min rainfall durations were used in the simulations. Also, commonly used 2-, 5-, 10-, and 100-yr expected rainfall amounts (0.9, 1.2, 1.5, and 2.3 in. for 30-min durations, and 1.2, 1.5, 1.9, and 2.9 in. for 60-min durations) were selected (1).

Temporal and spatial rainfall variabilities were considered next. Maximum intensities were concentrated early and late in the event given for each of the expected 30- and 60-min amounts (Table 1). Early events are characterized by concentration of two-thirds of the rainfall in the first one-third of the storm; in late events, two-thirds of the rainfall was concentrated in the last one-third of the

Figure 2. Detailed map of subwatershed 63.004, Walnut Gulch.

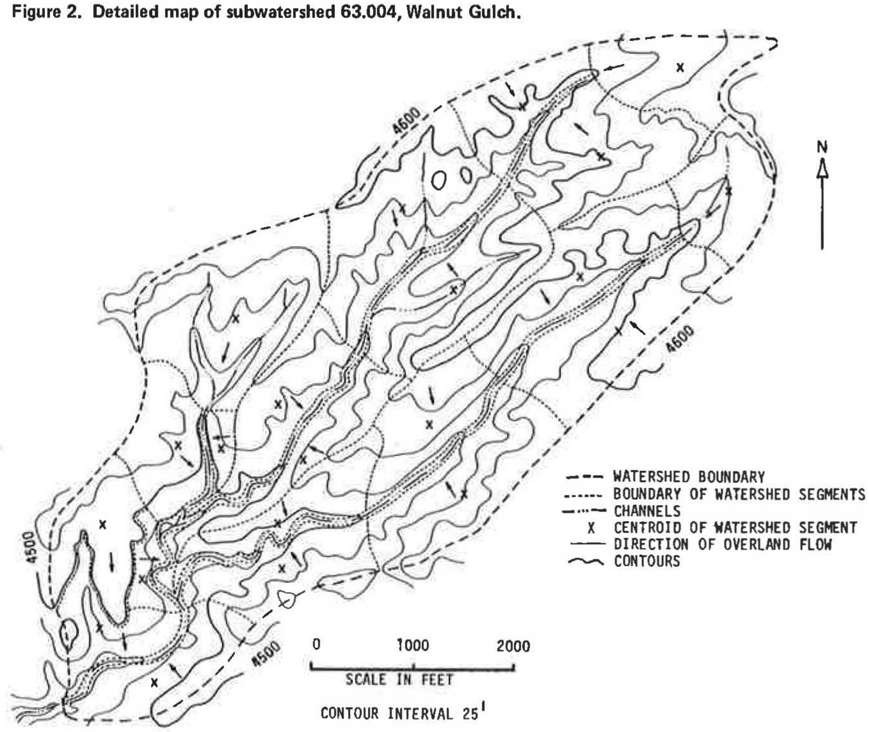


Figure 3. Schematic representation of planes and channels of subwatershed 63.004 for KINEROS.

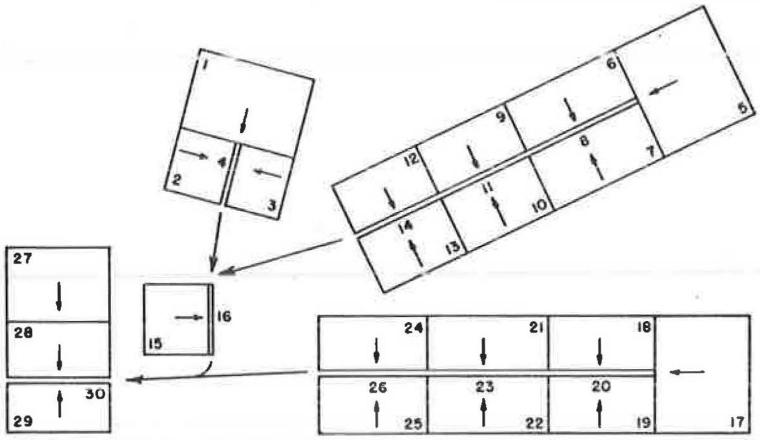
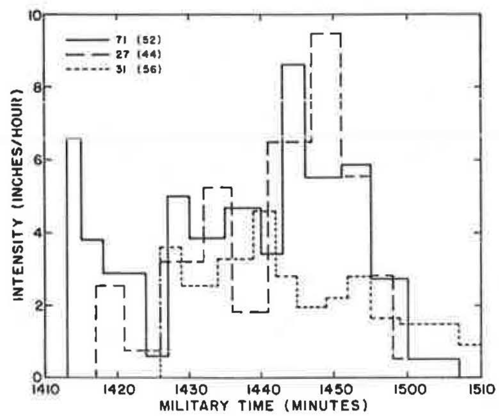


Table 1. Simulated early maximum rainfall intensities for selected frequencies for rainfall and runoff modeling, subwatershed 63.004, Walnut Gulch.

Duration of Storm	Portion of Storm (min)	Rainfall (in./hr) by Frequency (yr) 2	5	10	100
30 min	0-3	2.3	3.0	4.0	6.0
	3-6	3.1	4.2	5.2	8.0
	6-9	3.1	4.2	5.2	8.0
	9-12	2.3	3.0	4.0	6.0
	12-15	2.3	3.0	4.0	6.0
	15-18	2.0	2.6	3.2	5.0
	18-21	1.7	2.0	2.6	4.0
	21-24	0.8	1.0	1.3	2.0
	24-27	0.5	0.6	0.8	1.2
	27-30	0.2	0.3	0.4	0.6
60 min	0-6	2.5	3.0	4.0	6.0
	6-12	3.3	4.2	5.2	8.0
	12-18	2.5	3.0	4.0	6.0
	18-24	1.7	2.0	2.6	4.0
	24-30	0.8	1.0	1.3	2.0
	30-36	0.5	0.6	0.8	1.2
	36-46	0.2	0.3	0.4	0.6
	46-48	0.2	0.3	0.4	0.6
	48-54	0.1	0.2	0.2	0.3
	54-60	0.1	0.2	0.2	0.3

Note: Late storms are mirror images of early storms.

Figure 4. Maximum recorded 60-min point rainfall on Walnut Gulch (1956-1982) for adjacent gages superimposed on subwatershed 63.004.



storm. Spatial variability was modeled by centering each of the simulated events at three locations on the subwatershed--near the outlet, in the middle, and at the head of the subwatershed. Point-to-point reductions in rainfall amounts were based on earlier evaluations of Walnut Gulch rainfall data (10), and rainfall volume varied with storm location.

Finally, as a test of the effect of spatial variability on runoff, the event with the maximum observed rainfall in 25 yr of record on Walnut Gulch was centered on the study subwatershed at three different locations (Figure 4 and Table 2).

Model Output

Hydrographs were generated from spatially varied rainfall for all 30- and 60-min simulated events. Peaks and volumes were compared (Tables 3 and 4). Storms that were spatially centered on the subwatershed produced significantly greater peaks than those centered near the outlet or at the head of the watershed (Figure 5). For events of all frequencies, rainfall centered near the subwatershed outlet produced slightly greater peaks than that centered at the head of the subwatershed (Figure 6). All 30- and 60-min events were similar in that peak discharges were greater when rainfall was centered on the subwatershed rather than centered either near the outlet or at the head of the subwatershed. All 30- and 60-min simulations in which maximum rainfall was concentrated late in the event produced greater peak discharges than those with rainfall concentrated early in the event (Figure 7), primarily because the maximum intensities were recorded on a saturated subwatershed.

Runoff volumes were significantly higher for those events centered on the subwatershed, whereas runoff volume from the late events was only slightly greater than that from the early events (Figures 8 and 9).

The maximum recorded peak discharge from the subwatershed has been 1,250 ft^3/sec. Although there were insufficient data from the subwatershed to plot a peak-discharge frequency curve, the estimated Q_{100} based on the 25-yr record at other Walnut Gulch stations would be 1,660 ft^3/sec (11). The simulated 60-min, 100-yr event with maximum rainfall centered on the subwatershed, and occurring late in the event, produced a peak discharge of 1,900 ft^3/sec--400 ft^3/sec higher than a similar simulated event with maximum rainfall concentrated early in the event (Figure 5 and Table 3). Interestingly, the record Walnut Gulch storm when superimposed in time near the outlet, in the center, and at the head of the subwatershed, was so oriented in time and space that it produced peak discharges varying from only 1,814 to 1,871 ft^3/sec (Figure 10). Peak

Table 2. Maximum-rainfall event superimposed on subwatershed 63.004 with maximum point rainfall centered at rain gages 27, 71, and 31.

Military Time	Rainfall (in.) by Rain Gage (RG)								
	Centered at RG 27			Centered at RG 71			Centered at RG 31[a]		
	27	71	31	27	71	31	27	71	31
1413	0	0	0	0	0	0	0	0	0
1415	0.22	0	0	0	0.22	0	0	0	0.22
1416	-	0	0	0	-	0	0	0	-
1417	-	0	-	0	-	0	-	0	-
1418	0.41	-	0.08	-	0.41	0	0.08	-	0.41
1421	-	0.17	-	0.17	-	0	-	0.17	-
1423	-	-	0.15	-	-	0	0.15	-	-
1424	0.70	-	-	-	0.70	0	-	-	0.70
1426	-	0.23	0.19	0.23	-	0	0.19	0.23	-
1427	0.73	-	-	-	0.73	-	-	-	0.73
1429	-	-	-	-	-	0.18	-	-	-
1430	0.98	-	-	-	0.98	-	-	-	0.98
1431	-	-	0.23	-	-	-	0.23	-	-
1432	-	0.55	-	0.55	-	-	-	0.55	-
1434	-	-	-	-	-	0.39	-	-	-
1435	1.30	-	0.25	-	1.30	-	0.25	-	1.30
1436	-	0.90	-	0.90	-	-	-	0.90	-
1439	-	-	-	-	-	0.66	-	-	-
1440	1.69	-	0.58	-	1.69	-	0.58	-	1.69
1441	-	1.05	-	1.05	-	-	-	1.05	-
1442	-	-	-	-	-	0.89	-	-	-
1443	1.86	-	-	-	1.86	-	-	-	1.86
1445	-	-	1.01	-	-	1.03	1.01	-	-
1446	2.29	-	-	-	2.29	-	-	-	2.29
1447	-	1.70	-	1.70	-	-	-	1.70	-
1449	-	-	-	-	-	1.16	-	-	-
1450	-	-	1.29	-	-	-	1.29	-	-
1451	2.73	2.33	-	2.33	2.73	-	-	2.33	2.73
1452	-	-	-	-	-	1.27	-	-	-
1455	3.12	2.70	1.47	2.70	3.12	1.41	1.47	2.70	3.12
1458	-	2.84	1.51	2.84	-	-	1.51	2.84	-
1459	-	-	-	-	-	1.52	-	-	-
1500	3.35	-	-	-	3.35	-	-	-	3.35
1501	-	-	1.54	-	-	-	1.54	-	-
1504	-	2.89	1.57	2.89	-	-	1.57	2.89	-
1507	3.41		-		3.41	1.72	-		3.41
1511			-			1.78	-		
1512			1.60			-	1.60		
1515						1.86			

[a]The same as storm centered on RG 27, but amounts at RG 27 and RG 31 are reversed.

Table 3. Peak discharge from simulated rainfall on subwatershed 63.004, Walnut Gulch.

Type of Storm	Location of Event on Subwatershed	Peak Discharge (ft^3/sec) by Frequency (yr)			
		2	5	10	100
30-min					
Early	Outlet	2	125	201	692
	Middle	1	147	261	1,021
	Head	0	90	169	743
Late	Outlet	16	159	243	858
	Middle	16	174	304	1,185
	Head	3	114	207	883
60-min					
Early	Outlet	70	237	361	1,188
	Middle	78	304	499	1,492
	Head	37	207	355	1,248
Late	Outlet	137	339	544	1,536
	Middle	154	445	703	1,896
	Head	92	315	526	1,591

Table 4. Runoff volume from simulated rainfall on subwatershed 63.004, Walnut Gulch.

Type of Storm	Location of Event on Subwatershed	Runoff Volume (in.) by Frequency (yr)			
		2	5	10	100
30-min					
Early	Outlet	<0.01	0.08	0.15	0.57
	Middle	<0.01	0.13	0.22	0.79
	Head	0.00	0.07	0.14	0.54
Late	Outlet	0.02	0.10	0.16	0.60
	Middle	0.01	0.14	0.24	0.79
	Head	<0.01	0.09	0.15	0.57
60-min					
Early	Outlet	0.04	0.18	0.30	0.99
	Middle	0.07	0.25	0.40	1.19
	Head	0.03	0.17	0.28	0.97
Late	Outlet	0.08	0.25	0.39	1.06
	Middle	0.13	0.33	0.50	1.26
	Head	0.07	0.24	0.38	1.04

discharges of 1,800 to 1,900 ft^3/sec from centered 60-min, 100-yr late-occurring simulated rainfall and from the maximum observed Walnut Gulch rainfall seemed reasonable.

To investigate the effect of spatial variability of rainfall on runoff, average rainfall depths were assumed over the subwatershed for each storm duration and frequency; temporal variability was retained. Hydrographs were generated from the full range of 30- and 60-min simulated rainfall amounts and compared with similar peaks based on spatially and temporally varied rainfall (Tables 3 and 5). The differences were meaningful for the 10-yr events but relatively small for the 100-yr events (generally about 10 percent smaller). Runoff volumes were also less for the spatially uniform rainfall (Tables 4 and 6).

To determine the influence of a constant rainfall rate versus a variable one, hydrographs were generated from simulated spatially varied, constantrate, 30- and 60-min events (Tables 7 and 8). When peak discharges for the 30-min events were compared,

Figure 5. Hydrographs from simulated 60-min, 10- and 100-yr storms centered at three locations with rainfall intensities occurring early and late in the event.

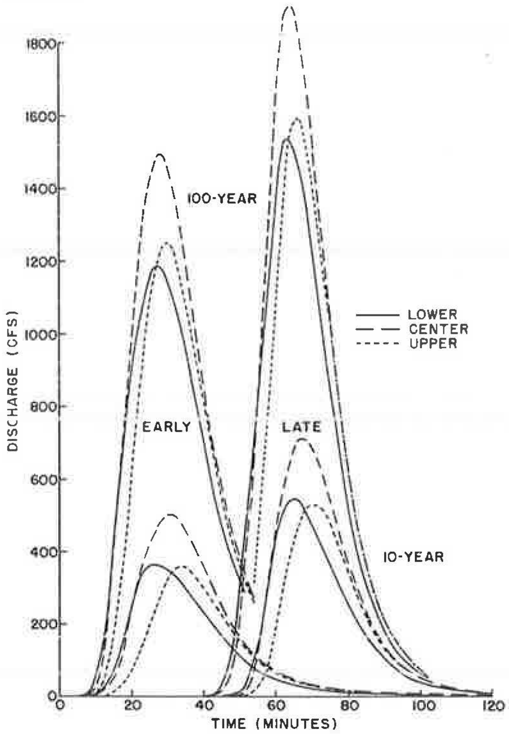


Figure 6. Peak discharge from simulated storms that were centered versus those that were not centered on the subwatershed.

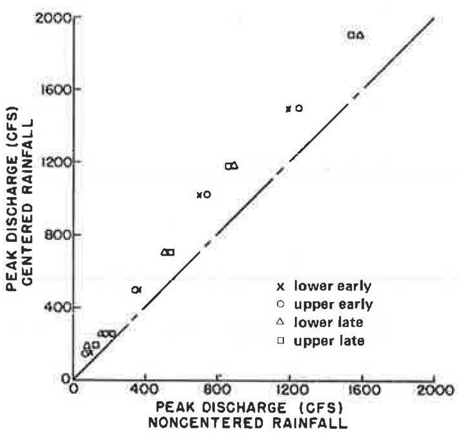


Figure 7. Peak discharge from simulated storms with maximum intensities concentrated early and late in the event.

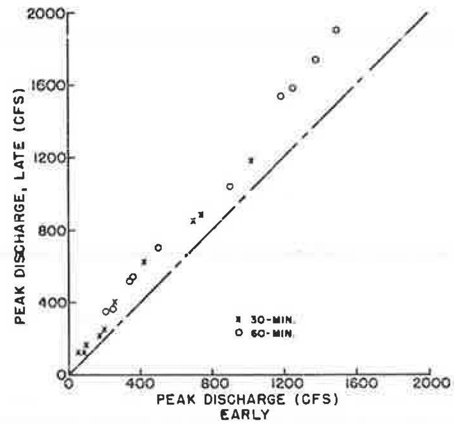


Figure 8. Runoff volume from simulated storms that were centered versus those that were not centered on the subwatershed.

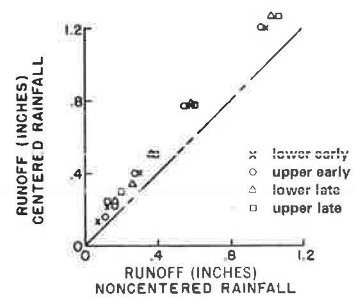
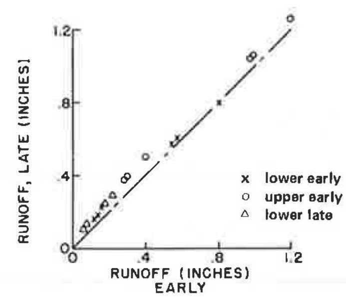


Figure 9. Runoff volume from simulated storms with intensities concentrated early and late in the event.



those generated from constant inputs were considerably lower than those generated from time-variable inputs (Tables 5 and 7). When rainfall was spread uniformly over a 60-min period, the differences between constant and varied time inputs were much more striking (Tables 5 and 7). Simulated peaks were reduced by more than 50 percent for events of all frequencies with 60-min constant rainfall rates.

EVALUATION

Quantitative differences in hydrograph peaks and volumes generated from spatially and temporally varied rainfall patterns were apparent when runoff peaks and volumes were compared. There was a strong linear relationship between storms centered on the subwatershed and those centered near the outlet or at the head of the subwatershed for peak discharges up to 800 ft^3/sec and runoff volumes up to 0.6 in. (Figures 6 and 8). Peak discharges and volumes were 35 to 40 percent higher for events centered on the subwatershed. Rainfall volumes were 10 to 15 percent greater for the events centered on the subwatershed, so higher peaks and volumes were not due entirely to more rainfall. Above 800 ft^3/sec and 0.6 in., events centered on the subwatershed produced constant increases in peak discharge of 300 ft^3/sec and runoff volume of 0.22 in. The relationships were as follows:

$$Q_{Pc} = 1.375Q_{Pnc} \; (0 < Q_{Pnc} < 800) \quad (1)$$

$$Q_{Pc} = Q_{Pnc} + 300 \; (Q_{Pnc} > 800) \quad (2)$$

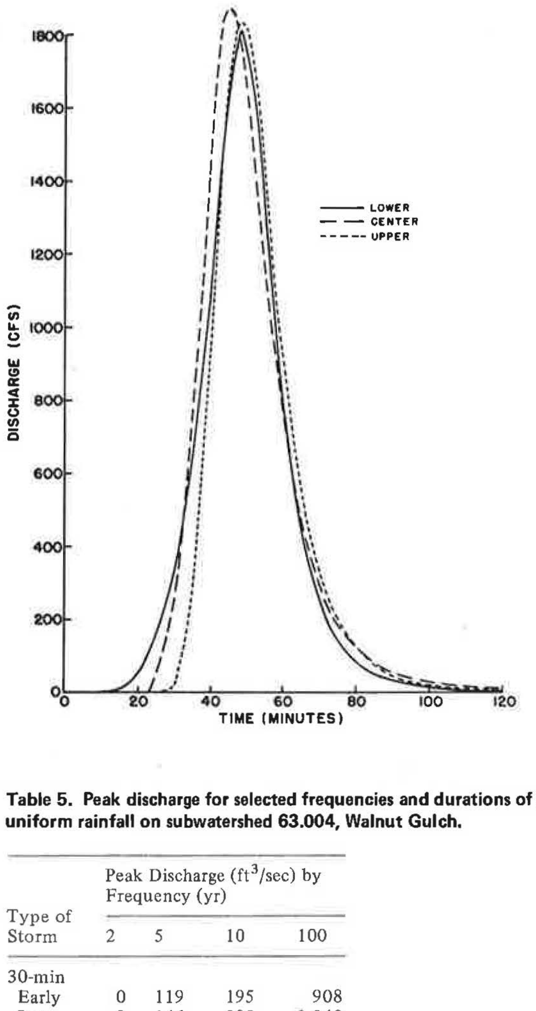
$$Q_c = 1.375Q_{nc} \; (0 < Q_{nc} < 0.6) \quad (3)$$

$$Q_c = Q_{nc} + 0.22 \; (Q_c > 0.6) \quad (4)$$

where

Q_{Pc} = peak discharge from simulated rainfall centered on subwatershed,
Q_{Pnc} = peak discharge from simulated rainfall not centered on subwatershed,
Q_c = runoff volume from simulated rainfall centered on subwatershed, and
Q_{nc} = runoff volume from simulated rainfall not centered on subwatershed.

Figure 10. Hydrographs from the maximum observed Walnut Gulch storm superimposed at three locations on subwatershed 63.004.



There were also good linear correlations for both peak discharge and runoff volume for the full range of values given by

$$Q_{Pc} = 1.25Q_{Pnc} \quad (5)$$

$$Q_c = 1.25\ Q_{nc} \quad (6)$$

Either Equations 1 and 2 together or Equation 5 alone would give an acceptable estimate of peak discharge for this small watershed, but the suggestion of a limit to the linear relationship could become important with increasing watershed size. Extrapolation of Equation 5 could possibly lead to costly overestimates for peak discharges from larger watersheds.

There was also a strong linear relationship between peak discharges when maximum rainfall intensities occurred early or late in the event (Figure 8). The relationship was as follows:

$$Q_{Pl} = 1.25Q_{Pe} \quad (7)$$

where Q_{Pl} is the peak discharge from maximum intensities occurring late in the event, and Q_{Pe} is the peak discharge from maximum intensities occurring early in the event. Again, however, there was a suggestion that there may be a limit on the linear relationship, which could lead to overestimates for larger watersheds. Because rainfall amounts were the same for each selected storm event, runoff volumes were only slightly greater for the late-occurring events (Figure 9).

The influences of temporal and spatial rainfall variability on peak discharge tended to be additive. The 60-min, 100-yr, late-occurring, centered peak discharge was 60 percent higher than the 60-min, 100-yr, early-occurring, noncentered peak discharge. The maximum peak discharges for the lower-frequency events were up to 100 percent higher than the minimums for storm units of the same frequency. Obviously, both storm location and temporal variability of rainfall can significantly affect peak discharge.

Assuming spatially uniform rainfall on the 560-

Table 5. Peak discharge for selected frequencies and durations of spatially uniform rainfall on subwatershed 63.004, Walnut Gulch.

Type of Storm	Peak Discharge (ft³/sec) by Frequency (yr) 2	5	10	100
30-min				
Early	0	119	195	908
Late	2	146	293	1,040
60-min				
Early	24	257	422	1,380
Late	78	363	626	1,745

Table 6. Runoff volume for selected frequencies and durations of spatially uniform rainfall on subwatershed 63.004, Walnut Gulch.

Type of Storm	Runoff Volume (in.) by Frequency (yr) 2	5	10	100
30-min				
Early	0	0.11	0.16	0.71
Late	<0.01	0.13	0.21	0.72
60-min				
Early	0.02	0.22	0.35	1.12
Late	0.07	0.29	0.46	1.19

Table 7. Peak discharge for selected frequencies and durations of constant rainfall rates on subwatershed 63.004, Walnut Gulch.

Type of Storm	Location of Event on Subwatershed	Peak Discharge (ft³/sec) by Frequency (yr) 2	5	10	100
30-min	Outlet	0	20	153	677
	Middle	0	20	200	980
	Head	0	3	123	714
60-min	Outlet	0	3	108	622
	Middle	0	0	163	795
	Head	0	0	90	640

Table 8. Runoff volume for selected frequencies and durations of constant rainfall rates on subwatershed 63.004, Walnut Gulch.

Type of Storm	Location of Event on Subwatershed	Runoff Volume (in.) by Frequency (yr) 2	5	10	100
30-min	Outlet	0	0.01	0.10	0.52
	Middle	0	0.02	0.16	0.72
	Head	0	<0.01	0.09	0.50
60-min	Outlet	0	<0.01	0.08	0.66
	Middle	0	0	0.14	0.86
	Head	0	0	0.07	0.63

acre subwatershed reduces peak discharges by only about 10 percent. For larger watersheds and therefore decreasing rainfall averages, however, assuming spatially uniform rainfall could lead to significant underestimates of peak discharge, especially when runoff-producing rainfall does not cover the entire watershed.

As long as assumed rainfall durations are kept relatively short, assuming a constant rainfall rate does not greatly decrease generated peak discharges. However, for durations longer than about 30 min, assuming a constant rainfall rate can lead to greatly underestimating peak discharge. For example, for a duration of 60 min, assuming a constant rainfall rate would reduce the simulated peak discharge by more than 50 percent.

Rainfall versus runoff relationships for simulated storms that were centered and not centered and maximum intensities concentrated early and late in the event are shown in Tables 9-11. Both linear regression and exponential curves were fitted for the four sets of events (Figures 11-14). The exponential curves were only a slight improvement over linear regression. Nevertheless, the differences could be significant at runoff thresholds or for large events. The expressions for combined data were as follows:

$$Q = -0.622 + 0.654P \quad (SEE = 0.070) \tag{8}$$

$$Q = 0.236P^{1.82} - 0.180 \quad (SEE = 0.047) \tag{9}$$

where Q is the storm runoff in inches and P is the storm rainfall in inches. There was slightly more runoff from equal amounts of rainfall for centered events as opposed to those that were not centered. The differences were not significant. There was an average increase of 0.07 in. in runoff volumes from equal amounts of late-occurring, maximum-rainfall intensities as opposed to early concentrations of rainfall. In many situations, the increase would be important.

Relationships between frequency and peak discharge for each classification tend to plot as straight lines on log-normal paper for 5- to 100-yr expected rainfall amounts (Figures 15 and 16). Because the 5-, 10-, and 100-yr events plotted as straight lines, it was assumed that storms for any frequency greater than 5 yr would plot on the same lines. The influence of within-storm variations is clearly evident and well defined for 5- to 100-yr

Table 9. Rainfall and runoff for simulated early and late 2-, 5-, 10-, and 100-yr storms by location on subwatershed 63.004, Walnut Gulch.

Frequency and Type of Storm	Location of Event on Subwatershed	Duration of Storm: 30 min P (in.)	30 min Q (in.)	60 min P (in.)	60 min Q (in.)
2 yr, early	Outlet	0.77	<0.01	1.10	0.04
	Middle	0.84	<0.01	1.19	0.07
	Head	0.77	0	1.09	0.03
2 yr, late	Outlet	0.77	0.02	1.10	0.08
	Middle	0.84	0.01	1.19	0.13
	Head	0.77	<0.01	1.09	0.07
5 yr, early	Outlet	1.03	0.08	1.36	0.18
	Middle	1.12	0.13	1.49	0.25
	Head	1.02	0.07	1.35	0.17
5 yr, late	Outlet	1.03	0.10	1.36	0.25
	Middle	1.12	0.14	1.49	0.33
	Head	1.02	0.09	1.35	0.24
10 yr, early	Outlet	1.25	0.15	1.60	0.30
	Middle	1.36	0.22	1.75	0.40
	Head	1.24	0.14	1.59	0.28
10 yr, late	Outlet	1.25	0.16	1.60	0.39
	Middle	1.36	0.24	1.75	0.50
	Head	1.24	0.16	1.59	0.38
100 yr, early	Outlet	1.80	0.57	2.46	0.97
	Middle	2.05	0.78	2.69	1.19
	Head	1.79	0.54	2.43	0.97
100 yr, late	Outlet	1.80	0.60	2.46	1.06
	Middle	2.05	0.79	2.69	1.26
	Head	1.78	0.57	2.43	1.04

Note: P = storm rainfall; Q = storm runoff.

Table 10. Rainfall and runoff for simulated early and late 2-, 5-, 10-, and 100-yr storms with spatially uniform rainfall.

Frequency and Type of Storm	30-min Storm P (in.)	30-min Storm Q (in.)	60-min Storm P (in.)	60-min Storm Q (in.)
2 yr				
Early	0.78	0	1.09	0.02
Late	0.78	<0.01	1.09	0.07
5 yr				
Early	1.09	0.11	1.42	0.22
Late	1.09	0.13	1.42	0.29
10 yr				
Early	1.28	0.16	1.70	0.35
Late	1.28	0.21	1.70	0.46
100 yr				
Early	1.95	0.71	2.62	1.12
Late	1.95	0.72	2.59	1.19

Note: P = storm rainfall; Q = storm runoff.

Table 11. Rainfall and runoff for simulated early and late 2-, 5-, 10-, and 100-yr storms with constant rainfall.

Frequency of Storm	Location of Event on Subwatershed	30-min Storm P (in.)	30-min Storm Q (in.)	60-min Storm P (in.)	60-min Storm Q (in.)
2 yr	Outlet	0.70	0	1.00	0
	Middle	0.80	0	1.10	0
	Head	0.70	0	1.00	0
5 yr	Outlet	1.00	0.01	1.23	<0.01
	Middle	1.10	0.02	1.35	0
	Head	1.00	<0.01	1.22	0
10 yr	Outlet	1.26	0.10	1.61	0.08
	Middle	1.37	0.16	1.75	0.14
	Head	1.24	0.09	1.59	0.07
100 yr	Outlet	1.81	0.52	2.41	0.66
	Middle	2.05	0.72	2.64	0.86
	Head	1.79	0.50	2.38	0.63

Note: P = storm rainfall; Q = storm runoff.

Figure 11. Rainfall versus runoff for simulated centered 2-, 5-, 10-, and 100-yr storms.

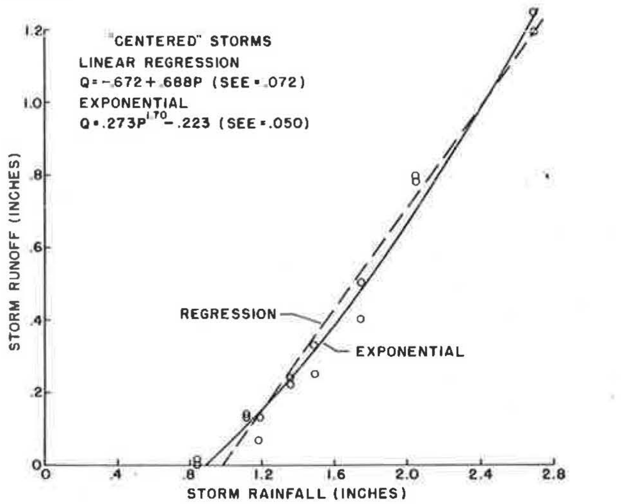


Figure 12. Rainfall versus runoff for simulated 2-, 5-, 10-, and 100-yr storms that were not centered.

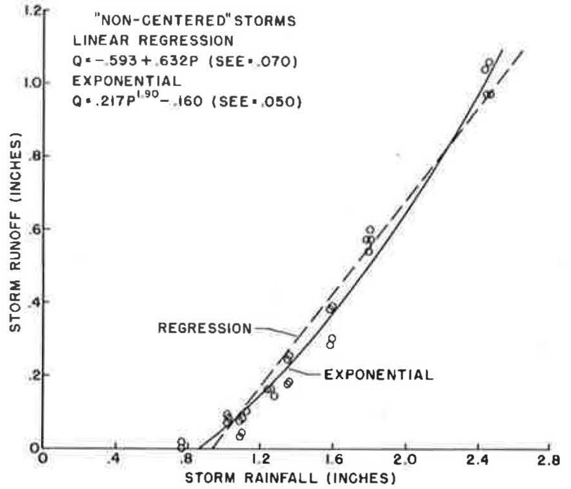


Figure 13. Rainfall versus runoff for simulated early 2-, 5-, 10-, and 100-yr storms.

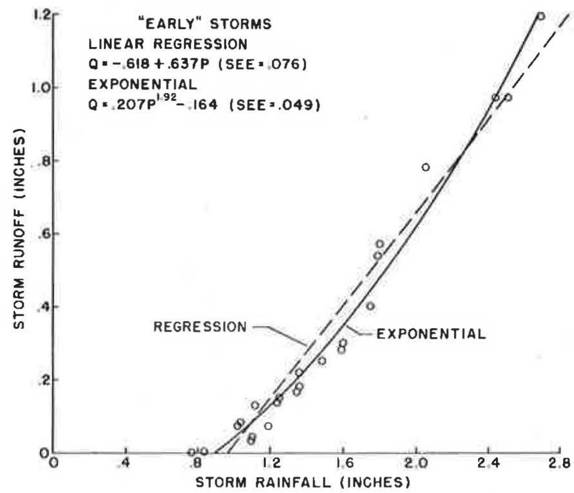


Figure 14. Rainfall versus runoff for simulated late 2-, 5-, 10-, and 100-yr storms.

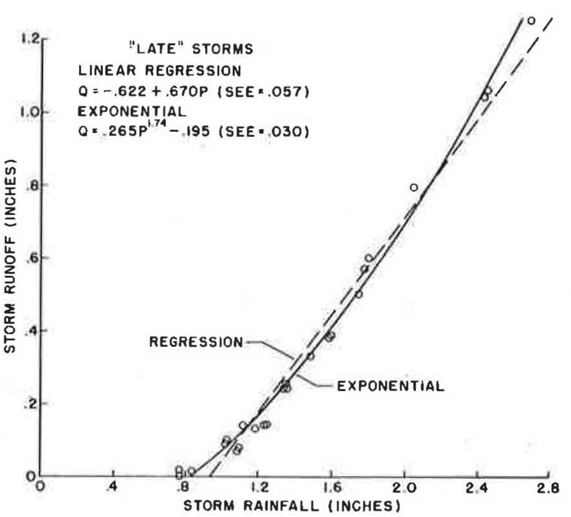


Figure 15. Peak discharge for rainfall frequencies of 2, 5, 10, and 100 yr for selected durations and storm patterns.

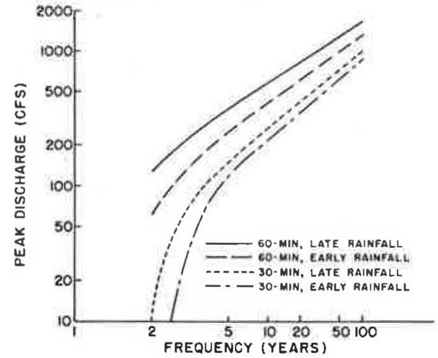
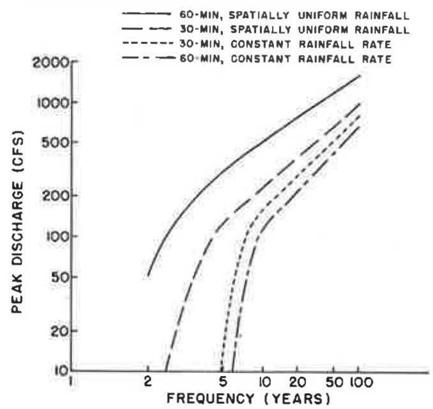


Figure 16. Peak discharge for rainfall frequencies of 2, 5, 10, and 100 yr for selected durations and constraints.



storms. Even for spatially uniform rainfall, the relationships are clearly defined. For more frequent events, however, peak discharges fall off rapidly. For constant rainfall rates, there was no runoff for 5-yr events with 60-min duration and no runoff for 2-yr events with 30-min duration. The curve for peak discharge versus frequency for a 560-acre subwatershed, based on Walnut Gulch data, would plot near the upper curve in Figure 13.

RECOMMENDATIONS

The results of this study indicated that for a small semiarid rangeland watershed (560 acres), the spatial and temporal distributions of thunderstorm rainfall exert an approximately equal influence on peak discharge from the watershed and that the influences tend to be additive. There are, however, two areas where further research is needed.

First, storm-runoff frequencies as opposed to rainfall frequencies need to be established. In this study, the 30- and 60-min, 2-, 5-, 10-, and 100-yr point rainfall amounts were used to generate peak discharge (Figures 13 and 14). However, these expected rainfall amounts were determined independently from the thunderstorm-cell properties, and a wide range of peak discharges was generated from only eight point-rainfall depths. Furthermore, the relationships between peak discharge and spatial and temporal variability may not be linear.

Second, and equally as important, the relative importance of storm-cell properties with increasing watershed size must be established. The runoff-producing areal extent of thunderstorm cells is limited, and runoff-producing rainfall will cover a smaller fraction of the watershed as the size of the watershed increases. Therefore, where the storm is centered should become increasingly important with increasing watershed size.

On the other hand, the influence of varying the occurrence of maximum intensity within the storm duration is more or less a function of watershed size and becomes relatively less important with increasing watershed size.

Quantitative analysis of the relationships between thunderstorm rainfall and runoff illustrated here is extremely difficult for several reasons. One reason is that rainfall is not uniform in time or space, and rainfall input can only be estimated from rainfall measurements within certain limits of accuracy and precision. Also, channel abstractions may account for much, or all, of on-site runoff. For example, annual runoff from the 58-mile^2 Walnut Gulch watershed is only about 5 percent of summer rainfall (2).

The next step, therefore, would be to model a larger watershed (several square miles) by using KINEROS and simulated rainfall input. In a step-by-step process, by increasing watershed size and complexity, it should be possible to define the interrelationships between storm-cell properties and watershed characteristics. The test of these interrelationships, in each case, would be the comparison of simulated peak discharges and runoff volumes.

REFERENCES

1. H.B. Osborn and L.J. Lane. Point-Area-Frequency Conversion for Summer Rainfall in Southeastern Arizona. In Hydrology and Water Resources of Arizona and the Southwest, Volume 11, Univ. of Arizona, Tucson, 1981.
2. H.B. Osborn and E.M. Laursen. Thunderstorm Runoff in Southeastern Arizona. Journal of Hydraulics Division of ASCE, Vol. 99, 1973, pp. 1129-1145.
3. V.T. Chow. Hydrologic Determination of Waterway Areas for Design of Drainage Structures in Small Basins. Univ. of Illinois, Urbana, Engineering Experiment Station Bull. 462, 1962.
4. C.T. Haan and H.P. Johnson. Hydrologic Modeling of Small Watersheds. American Society of Agricultural Engineers, St. Joseph, Mich., ASAE Monograph, 1982.
5. D.F. Kibler and D.A. Woolhiser. The Kinematic Cascade as a Hydrologic Model. Colorado State Univ., Fort Collins, Hydrology Paper 39, 1970.
6. E.W. Rovey, D.A. Woolhiser, and R.E. Smith. A Distributed Kinematic Model of Upland Watersheds. Colorado State Univ., Fort Collins, Hydrology Paper 93, 1977.
7. L.J. Lane and D.A. Woolhiser. Simplifications of Watershed Geometry Affecting Simulation of Surface Runoff. Journal of Hydrology, Vol. 35, 1977, pp. 173-190.
8. R.E. Smith. A Kinematic Model for Surface Mine Sediment Yield. Trans., ASAE, Vol. 24, No. 6, 1981, pp. 1508-1519.
9. B.M. Reich and L.A.V. Hiemstra. Tacitly Maximized Small Watershed Flood Estimates. Journal of Hydraulics Division of ASCE, Vol. 91, 1965, pp. 217-245.
10. H.B. Osborn, L.J. Lane, and V.A. Myers. Two Useful Rainfall/Watershed Relationships for Southwestern Thunderstorms. Trans., ASAE, Vol. 23, No. 1, 1980, pp. 82-87.
11. B.M. Reich, H.B. Osborn, and M.C. Baker. Tests on Arizona's New Flood Estimates. In Hydrology and Water Resources of Arizona and the Southwest, Vol. 9, Univ. of Arizona, Tucson, 1979.

Conceptual and Empirical Comparison of Methods for Predicting Peak-Runoff Rates

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A wide variety of hydrologic methods have been proposed by hydrologic design. Because peak-discharge methods are the most widely used, it is instructive to compare the methods that are used most frequently. The methods compared include the rational formula, the U.S. Geological Survey urban peak-discharge equations, and the Soil Conservation Service peak-discharge methods. In addition to a comparison of the methods by using data from 40 small urban watersheds, the methods are compared on the basis of their input requirements and the means by which channel systems are accounted for. These latter two comparison criteria appear to be more important in selecting a method than accuracy.

The adverse hydrologic effects of land-cover changes and the different design solutions that have been proposed to overcome these effects have led to a diverse array of hydrologic methods. Many state and local policies on floodplain management, erosion control, watershed planning, and storm-water management (SWM) require a specific hydrologic method for design. Such policies usually generate considerable controversy among hydrologists and design engineers because each hydrologic method has one or more disadvantages. More important, the different methods lead to different designs at the same location. The failure to specify a specific design method in the design component of a drainage or SWM policy often leads to significant difficulties in the review and approval process.

A number of studies have been undertaken to identify the best method (1,2). Most of the comparisons were limited in some respect. For example, some publications involved data obtained for a limited region, whereas others were based on a limited sample size. In some cases, the criteria for comparison were limited. In all cases, the comparisons were limited to empirical analyses. McCuen and others (3) concluded that (a) there is a noticeable lack of consistency in the structure and presentation of results of comparisons of hydrologic methods, (b) the literature does not accurately reflect the methods that are most frequently used in hydrologic design, and (c) the literature is often defi-