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PROBLEMS OF SIMPLIFICATION IN HYDROLOGIC MODELING

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INTRODUCTION

Thunderstorm rainfall dominates small watershed runoff in the southwestern United States. Thunderstorm rainfall is highly variable, both in time and space, and must be simplified for use in rainfall-runoff models. Often, models are used that are more sophisticated than is justified by the available data. Conclusions, based on sophisticated models with overly simplified watershed characteristics and/or rainfall input, may be incorrect or misleading. There is a tendency to claim better results from more complex models without considering that the quality of the output is dependent upon the quality of the input. Also, significant changes in runoff characteristics may be hidden because of oversimplification in the model. There is a need for hydrologists and others working in water yield and water use investigations to quantify information on the possible errors resulting from simplification in watershed characteristics and rainfall input. In this paper, records from a dense raingage network in southeastern Arizona, along with a kinematic cascade rainfall-runoff model, were used to investigate the problems of spatial representation in hydrologic modeling.

RAINFALL-RUNOFF MODELING

Many different mathematical models have been used to estimate runoff peaks and volumes from small watersheds, but few models are sensitive enough to separate the influences of rainfall variability and watershed characteristics in estimating runoff. In many cases, particularly for very small watersheds (about 100 acres and less), such sensitivity is not needed, and simple models, such as the Rational Formula, may be satisfactory. However, to delineate hydrologic response to changes in rangeland condition when the input is thunderstorm rainfall requires a more complex model. Such a model must represent both thunderstorm rainfall input and watershed characteristics such as infiltration, cover and slope, and channel geometry. For this study, a kinematic cascade model (KINEROS) (Kibler and Woolhiser, 1970; Rovey et al., 1977; Lane and Woolhiser, 1977; Smith, 1981) was chosen as being versatile and sensitive to both rainfall and watershed characteristics (Osborn, 1983).

KINEROS is a well-tested, nonlinear, deterministic, distributed-parameter model (Rovey et al., 1977). Inputs are: (1) the rainfall, (2) the watershed surface geometry, roughnesss, and infiltration characteristics, and (3) the channel network, including slope, cross-sectional area, shape, hydraulic roughness, and abstraction. For a more detailed description of the model, see Smith (1981).

EXPERIMENTAL WATERSHED

Subwatershed 63.011 (2000 acres) is located on the upper end of the Walnut Gulch Experimental Watershed (Fig. 1). It has a combined grass/brush cover, and has been grazed for about 100 years. Subwatershed 63.011 is drained by three principal channels referred to as the north, central, and south branches (Fig. 2, 3). Runoff from the central branch is largely contained by two stock ponds, so the central branch was not included in the mathematical model. The north branch is characterized by an incised sand-bottom channel extending to within 400 yds of the head of the drainage. The south branch is dominated by an incised channel on the lower half of the drainage. An active headcut is moving up the south branch, cutting into a broad swale.

There are 10 weighing-type recording raingages on, or immediately adjacent to, the 2000-acre subwatershed (Fig. 2). Runoff is estimated from water-level recorders located at Walnut Gulch runoff-measuring flume-weirs (Smith et al., 1982).

WATERSHED SIMULATION AND SIMPLIFICATION

In the first part of this study, the sensitivity of KINEROS to the degree of topographic detail was investigated. In the model, topography is a faceted surface of sloping planes and channel segments. Water is routed over planes and through channels using the kinematic approximation to the equations of unsteady, gradually-varied flow. Therefore, the number of elements used to define the watershed surface determines the detail expressed by the input parameters.

For this study, watershed 63.011 was subdivided into planes and channels representing three different levels of detail. The 3 data sets contained large-sized planes (13 planes and 5 channel segments), medium-sized planes (20 planes and 9 channel segments (Fig. 3)), and small-sized planes (40 planes and 18 channel segments). A representative plane for the medium-sized model is shown in Fig. 4. Surface geometries were determined separately for each plane and channel reach. Obviously, there must be considerable simplification for rolling rangeland watersheds such as Walnut Gulch.

Input to the model consisted of measurable quantities and estimated parameters. Areas and lengths were measured directly from maps. Slopes were estimated by inspecting profiles drawn from topographic maps. Roughness and infiltration parameters were treated as lumped parameters

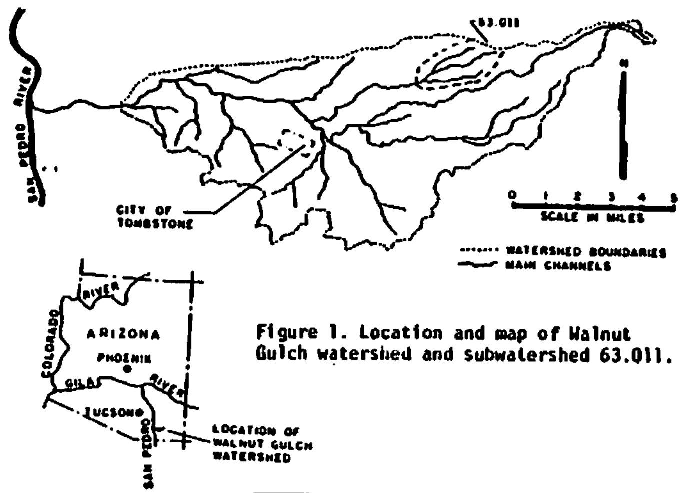


Figure 1. Location and map of Walnut Gulch watershed and subwatershed 63.011.

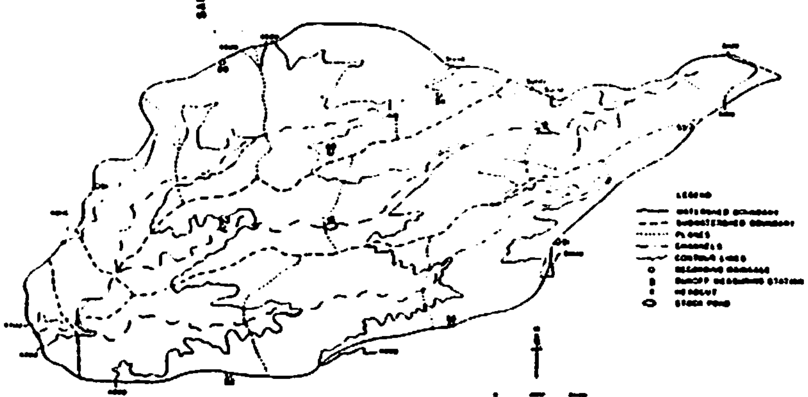


Figure 2. Map of Walnut Gulch 63.011.

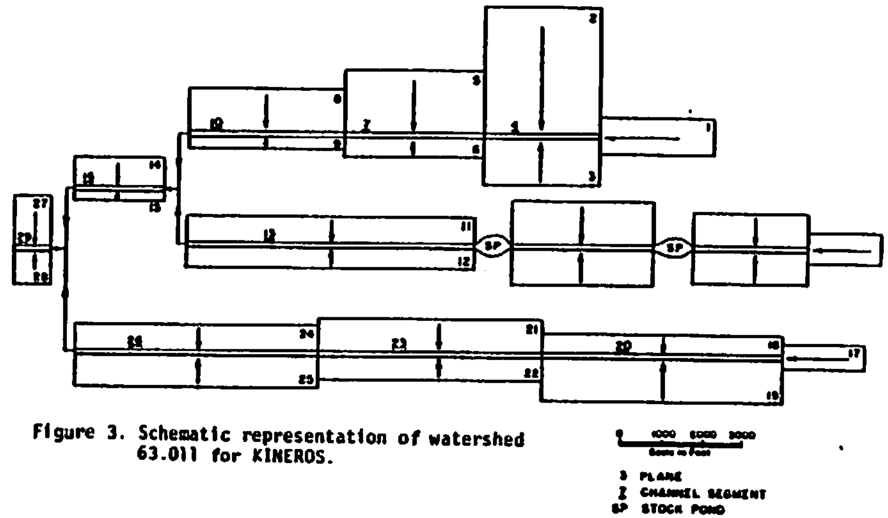


Figure 3. Schematic representation of watershed 63.011 for KINEROS.

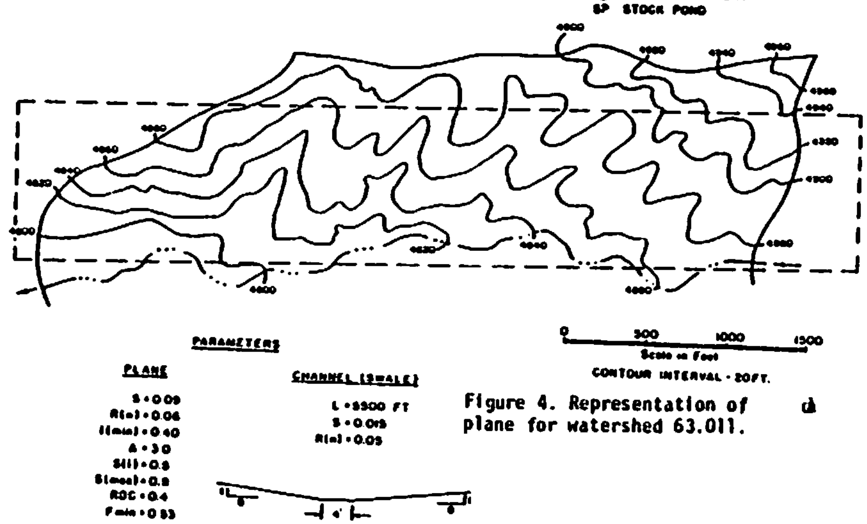


Figure 4. Representation of plane for watershed 63.011.

optimized by trial and error, using actual hydrographs against simulations generated by the medium representation. These 'best fit' estimates were obtained prior to this study, and remained fixed throughout, except for the initial soil moisture, which varied between storms.

Eight actual storm events on 63.011 were selected to compare runoff peaks, volumes, and time to peak for the 3 different spatial representations. These events provided a wide range of rainfall inputs and outfall hydrographs.

RESULTS OF WATERSHED SIMULATION AND SIMPLIFICATION

Since the model parameters were calibrated using the version with medium-sized planes, this version could not be used to make meaningful comparisons. However, the outfall hydrographs of the small- and large-plane models showed consistent differences which could relate differences in total channel length to spatial distribution of the rainfall. Differences in runoff volume and time to peak could be placed in three categories corresponding to three general spatial conditions in the rainfall input: (1) greater volume and shorter peak time for runoff from small planes relative to large which corresponded to a storm center lying on the upper third of the watershed, (2) little difference in runoff with storms centered on the middle third of the watershed, and (3) greater volumes with shorter peak times for large planes, with storms centered on the lower third of the watershed. If the most intense rainfall occurred well into the interior of the watershed, then the efficiency of channelled relative to overland flow becomes dominant, and the more detailed representation yields greater peaks and volumes. If the rainfall is centered near the outlet, then the association of a greater area with high intensities (coarser raingage-plane associations) favors a less detailed version having larger peaks and volumes.

RAINFALL SIMULATION AND SIMPLIFICATION

The emphasis in the second part of the study was to determine the sensitivity of runoff to rainfall simplification via simplification of simulated events for selected durations and recurrence intervals, and temporal simplification of actual storm rainfall. The model for medium-sized planes was used throughout this part of the study. For simplification of simulated events, maximum storm point rainfall was simulated for 30- and 60-min durations for 5-, 10- and 100-yr recurrence intervals (Osborn and Lane, 1981), and the areal distribution and storm shape were based on areal relationships reported by Osborn and Laursen (1973) and Osborn et al. (1980). Model storms were centered on the long axis of the watershed (Fig. 5). Point rainfall amounts were distributed in the same way for each period within the 30- and 60-min durations, respectively (Table 1). Rainfall intensity distributions were determined for all 10 gages for each simulated storm (Table 2). Then simulated storm rainfall for each event was simplified by averaging over the watershed while retaining the distribution of rainfall intensity (Table 3). Finally, the simulated storm events were averaged both in time and space (Table 4).

Table 1.--Distribution of 30-min and 60-min rainfall intensities

	30-min duration (minutes)										
	0	3	6	9	12	15	18	21	24	27	30
Factor*	.13	.17	.17	.13	.13	.11	.08	.04	.03	.01	

*Multiply by 20 P (P is total 30-min storm rainfall) for intensities in in/hr for each 3-min duration.

	60-min duration (minutes)										
	0	6	12	18	24	30	36	42	48	54	60
Factor*	.20	.28	.20	.14	.08	.04	.02	.02	.01	.01	

*Multiply by 10 P (P is total 60-min storm rainfall) for intensities in in/hr for each 6-min duration.

Table 2.--Simulated intensities (in/hr) for 5-yr, 30-min centered storms with simultaneous start times.

Raingage	Time (min) 0	3	6	9	12	15	18	21	24	27	30
44	1.38	1.92	1.92	1.38	1.38	1.19	.92	.46	.28	.41	
51	1.88	2.62	2.62	1.88	1.88	1.62	1.25	.62	.38	.19	
89	1.88	2.62	2.62	1.88	1.88	1.62	1.25	.62	.38	.19	
90	2.88	4.02	4.02	2.88	2.88	2.49	1.92	.96	.58	.29	
52	2.12	2.98	2.98	2.12	2.12	1.84	1.42	.71	.42	.21	
88	2.88	4.02	4.02	2.88	2.88	2.49	1.92	.96	.58	.29	
54	2.38	3.32	3.32	2.38	2.38	2.06	1.58	.79	.48	.24	
56	2.38	3.32	3.32	2.38	2.38	2.06	1.58	.79	.48	.24	
91	1.88	2.62	2.62	1.88	1.88	1.62	1.25	.62	.38	.19	
55	1.50	2.10	2.10	1.50	1.50	1.30	1.00	.50	.30	.15	

Table 3.--Simplified, simulated averaged breakpoint rainfall (inches/hr) for selected storms on Walnut Gulch 63.011

Storm	Rainfall Max.	Rainfall Avg.	Time (min) 0	3	6	9	12	15	18	21	24	27	30
	(in)	(in)											
5-yr, 30-min	1.2	.95	2.38	3.32	3.32	2.38	2.38	2.06	1.58	.79	.48	.24	
10-yr, 30-min	1.5	1.22	3.27	4.25	4.25	3.27	3.27	2.60	2.00	1.00	.65	.33	
100-yr, 30-min	2.3	1.80	4.70	6.26	6.26	4.70	4.70	3.91	3.13	1.57	.94	.47	
			0	6	12	18	24	30	36	42	48	54	60
5-yr, 60-min	1.5	1.2	2.40	3.36	2.40	1.60	.80	.48	.24	.24	.16	.16	
10-yr, 60-min	1.9	1.5	3.16	4.11	3.16	2.05	1.03	.63	.32	.32	.16	.16	
100-yr, 60-min	2.9	2.3	4.76	6.34	4.76	3.17	1.59	.95	.48	.24	.24	.24	

Table 4.--Simplified, simulated rainfall averaged in time and space for selected storms on Walnut Gulch, 63.011

Storm	Rainfall intensity
	(in/hr)
5-yr, 30-min	1.90
10-yr, 30-min	2.44
100-yr, 30-min	3.60
5-yr, 60-min	1.20
10-yr, 60-min	1.50
100-yr, 60-min	2.30

For temporal simplification of storms, 12 actual events were used to investigate the effect of rainfall simplifications based on the temporal pattern of the recording raingage which received the most rainfall. The temporal rainfall pattern of each gage was constructed by multiplying the intensities of the maximum gage by a constant equal to the ratio of their total inputs (Thus, the input to each gage is a scaled-down copy of the intensity pattern at the maximum gage.). Also, as a check of the model sensitivity, more information was added to the input data for three events. The duration, and then the start times, were changed to coincide with the actual data at the other 9 gages. As more information was incorporated into the input for the rainfall-runoff model, the peak and volume estimates were expected to improve.

RESULTS OF SIMPLIFICATION OF SIMULATED EVENTS

In general, simplifying break-point rainfall input by averaging the input over the watershed and retaining the intensity distribution resulted in smaller peak discharges (Table 5, Fig. 6 and 7). However, the differences were small, just 100 cfs (Table 5, Fig. 6 and 7). These differences were insignificant for the larger events, considering the uncertainties in other simulation parameters. One might add about 40 cfs/mi^2 to simplified simulated peaks to make the averages, with and without spatial simplification, come out about the same. There was essentially no difference in runoff volumes between the break-point rainfall simulation and the simulation without spatial variability (Fig. 8 and 9).

Table 5 --Effect of spatial and temporal simplification of simulated rainfall on runoff peaks and volumes, Walnut Gulch, 63.011

	Avg. rain-fall	Varied in time and space				Uniform in space, time varied				Uniform in space and time			
		"wet"		"dry"		"wet"		"dry"		"wet"		"dry"	
		Peak	Vol	Peak	Vol	Peak	Vol	Peak	Vol	Peak	Vol	Peak	Vol
		(cfs)	(in)	(cfs)	(in)	(cfs)	(in)	(cfs)	(in)	(cfs)	(in)	(cfs)	(in)
5-yr, 30-min	.95	1111	.36	135	.04	996	.36	52	.02	878	.32	3	.00
10-yr, 30-min	1.22	1868	.60	749	.21	1751	.63	611	.21	1578	.56	350	.13
100-yr, 30-min	1.83	3773	1.16	2581	.76	3618	1.16	2410	.76	3270	1.10	1898	.60
5-yr, 60-min	1.20	1336	.48	304	.09	1207	.46	172	.07	697	.31	0	0
10-yr, 60-min	1.51	2110	.75	902	.29	1978	.74	792	.29	1248	.58	219	.09
100-yr, 60-min	2.30	4190	1.45	3017	.99	4080	1.46	2895	.99	2728	1.35	1770	.72

There were significant differences in peak discharge between spatially uniform simulations and spatially/temporally uniform simulations (Table 5, Fig. 6 and 7). The differences were particularly apparent with the 60-min storms, since the rainfall intensity is lower over a longer period (Fig. 7). For the 30-min storm, the differences ranged from about 120 cfs for the 5-yr event to about 340 cfs for the 100-yr

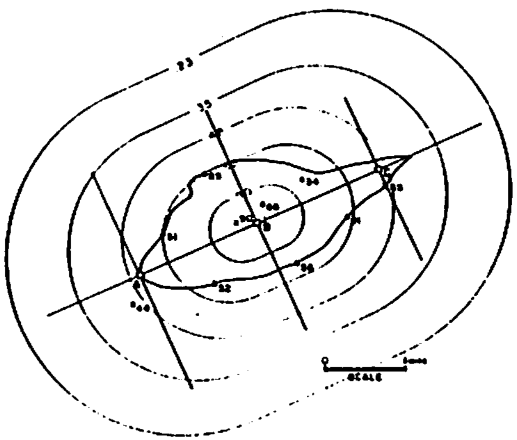


Figure 5. Model of simulated rainfall and orientation on watershed 63.011.

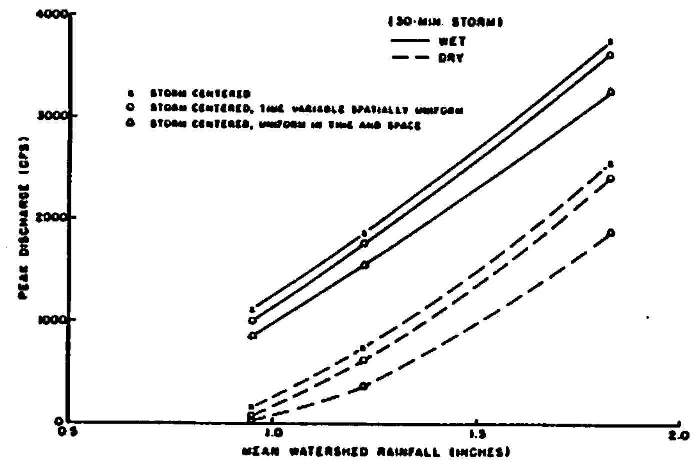


Figure 6. Comparison of peak discharges for 30-min, 5-, 10, and 100-yr simulated storms with differing space and time rainfall simplifications.

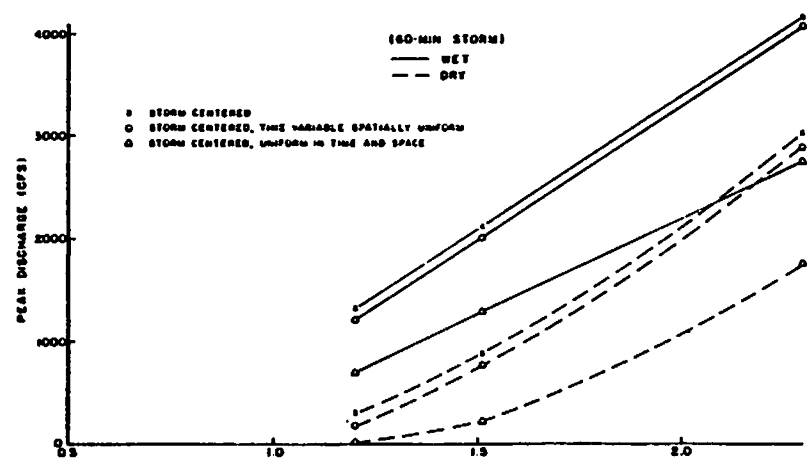


Figure 7. Comparison of peak discharges for 60-min, 5-, 10-, and 100-yr simulated storms with differing space and time rainfall simplifications.

event, or about 12% to 10%. A linear correction of about 10% would probably be safe for the 30-min storms.

Table 6.--Actual and simulated peak discharge for selected events for best fit simulation and simulations based on gage recording maximum storm rainfall, Walnut Gulch 63.011

Date	Actual peak disch	Maximum gage	Best fit	Simulated Peaks (cfs)		
				Maximum gage, varied intensity	Max gage, varied intensity and duration	Max gage, varied intensity, duration, and start times
	(cfs)					
30 Jul 66	956	55	938	668		
5/6 Aug 66	319	91	291	298		
10 Sep 67	1706	52	1711	2006	1842	1653
5 Aug 68	876	90	878	1076		
18 Aug 71	434	91	418	262	458	499
22 Aug 75	780	88	711	957		
22 Jun 77	343	44	319	283		
31 Jul 77	206	54	202	273		
1 Sep 77	988	90	1015	861		
15 Jul 81	340	91	316	417		
27 Aug 82	3400	56	3260	2990		
11 Sep 82	655	56	622	468	577	651
Average	917		890	880		
Standard deviation	886		859	833		
Coeffient of variation	0.97		0.97	0.95		

(Best Fit) $Q_{PA} = 1.03\ Q_{PS} (r^2 = 1.00)$

(Maximum Gage) $Q_{PA} = 8 + 1.03\ Q_{PS} (r^2 = .94)$

The differences for 60-min storms ranged from about 500 cfs (40%) to about 1350 cfs (33%) for the 5-yr and 100-yr events, respectively. A safe correction might be to add about 30%, but the differences are large enough to indicate that drastic simplification of rainfall is probably unacceptable for sophisticated models such as KINEROS, and might lead to serious underprediction of peak discharge with most rainfall-runoff models.

The "wet" and "dry" antecedent conditions for the simulated events were considered near extremes for the Walnut Gulch watershed, so the differences in runoff for the same event were considerable (Table 5, Fig. 6-9). In fact, uncertainty in estimating antecedent watershed condition could mask significant differences caused by simplifications in rainfall input. The differences between wet and dry antecedent conditions for watershed-centered rainfall were about 1200 cfs for peak discharge and 0.4 in. for runoff.

Table 7.--Actual and simulated runoff for selected events based on best peak fit simulation and simulations based on gage recording maximum storm rainfall, Walnut Gulch 63.011

Date	Actual runoff	Maximum gage	Simulated Runoff (inches)			
			From best peak fit	Maximum gage, varied intensity	Max gage, varied intensity and duration	Max gage, varied intensity, duration, and start times
	(in)					
30 Jul 66	.353	55	.301	.230		
5/6 Aug 66	.142	91	.114	.128		
10 Sep 67	.756	52	.651	.746	.698	.708
5 Aug 68	.170	90	.258	.253		
18 Aug 71	.129	91	.151	.077	.130	.134
22 Aug 75	.154	88	.242	.284		
22 Jun 77	.123	44	.098	.080		
31 Jul 77	.046	54	.090	.118		
1 Sep 77	.441	90	.452	.377		
15 Jul 81	.087	91	.125	.152		
27 Aug 82	.970	56	1.024	1.016		
11 Sep 82	.306	56	.302	.214	.289	.295
Average	.306		.317	.306		
Standard deviation	.288		.277	.288		
Coeffient of variation	.941		.874	.941		

(From Best Fit) $Q_A = -.017 + 102\ Q_S (r^2 = .96)$
(Maximum Gage) $Q_A = .012 + 0.96\ Q_S (r^2 = .93)$

RESULTS OF SIMPLIFICATION OF ACTUAL STORM RAINFALL

A general model of thunderstorm rainfall would simulate rainfall intensities in space and time, maintaining the appropriate spatial and temporal correlation structure. Storm movement would be included in the model as well. Such models have been developed for more general,

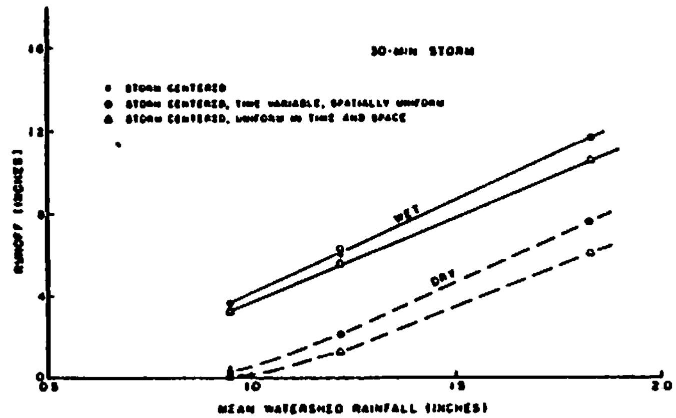


Figure 8. Comparison of runoff volumes for 30-min, 5-, 10-, and 100-yr simulated storms with differing space and time rainfall simplifications.

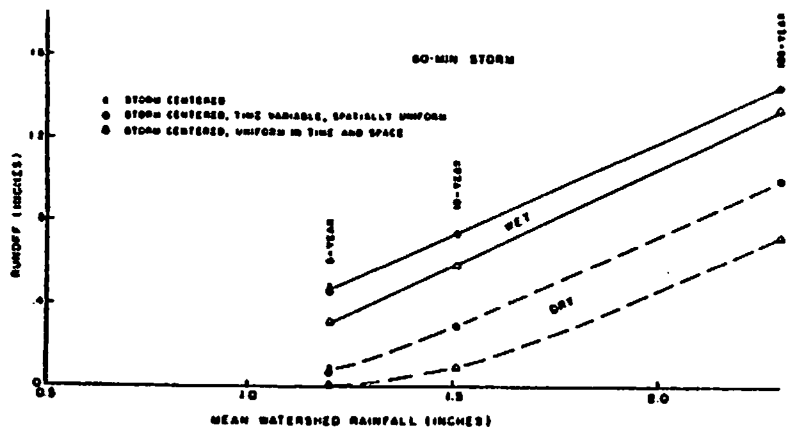


Figure 9. Comparison of runoff volumes for 60-min, 5-, 10-, and 100-yr simulated storms with differing space and time rainfall simplifications.

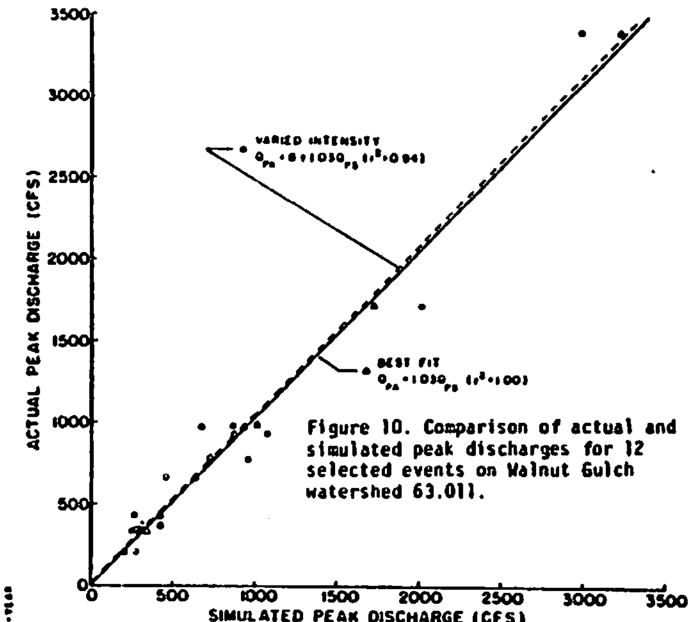


Figure 10. Comparison of actual and simulated peak discharges for 12 selected events on Walnut Gulch watershed 63.011.

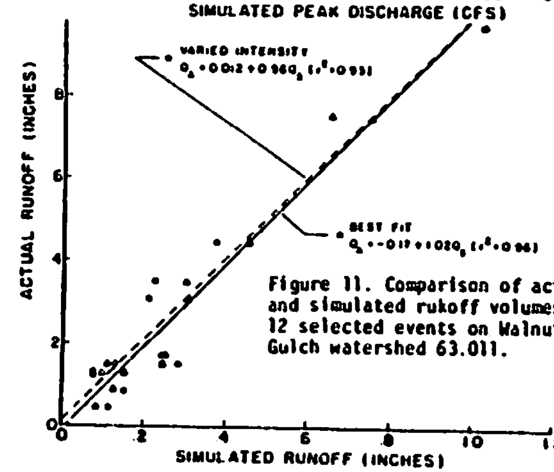


Figure 11. Comparison of actual and simulated rukoff volumes for 12 selected events on Walnut Gulch watershed 63.011.

frontal-type rainfall (Bras and Rodriguez-Iturbe, 1976), but would be exceedingly complex for thunderstorm rainfall. An alternative would be to use a simpler depth-area model of thunderstorm rainfall such as that presented by Osborn et al. (1980), which describes the distribution of total storm depths over the watershed, but does not include spatial and temporal correlation structure or storm movement. The relationship between rainfall amount at the storm center and storm duration could be simulated using the joint distribution of depth and duration presented by Woolhiser et al. (In Press), and the intensity pattern at the center could be simulated using the point disaggregation model of Woolhiser and Osborn (1985). Finally, the intensity patterns at other points could be scaled from that at the center.

Obviously, several simplifications are involved in this approach. The data available from the Walnut Gulch Watershed enables us to examine the relative importance of some of these simplifications. The criteria used to select the 12 events used for this study were: (1) good records must be available from all 10 gages and the runoff-measuring structure, (2) only storms with peaks of 200 cfs or greater were considered (this guaranteed that a significant portion of the watershed received runoff-producing rainfall), and (3) the two largest events during the period of record (1966 - 1982) would be included (10 Sep 1967 and 27 Aug 1982). The other 10 events were chosen randomly from the storm sample.

First, runoff was simulated for all storms using the known intensity-time patterns at each gage. Then, runoff hydrographs were simulated for each storm using the scaled-intensity pattern at the maximum gage and the duration at the maximum gage. Rainfall was assumed to start simultaneously at all gages, so there was no storm movement.

Peaks estimated from the maximum gage were not as well correlated with the actual peaks as were those estimated from the breakpoint data based on all 10 gages (Table 6, Fig. 10). However, there was no indication of a meaningful bias in the estimates, which indicated that maximum point rainfall could be a useful tool for prediction if enough was known about the spatial and temporal distribution of rainfall around the storm center. By chance, the average storm run-off was the same for the actual storms and the storms generated from the maximum gage. However, runoff from the maximum gage simulations were more scattered than those based on best fit (Table 7, Fig. 11)

Three storms with well-fitted actual and simulated hydrographs were chosen to test the model's sensitivity to storm duration and movement (Fig. 12-14). In the successive simulations, more information was used -- first, the storm durations at each gage, and second, the start times for each gage. As was hoped, the improved simulations also improved the accuracy of the peak and volume estimates (Table 6 and 7, Fig. 10-17).

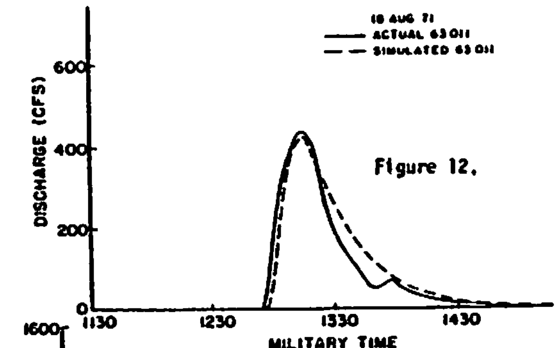
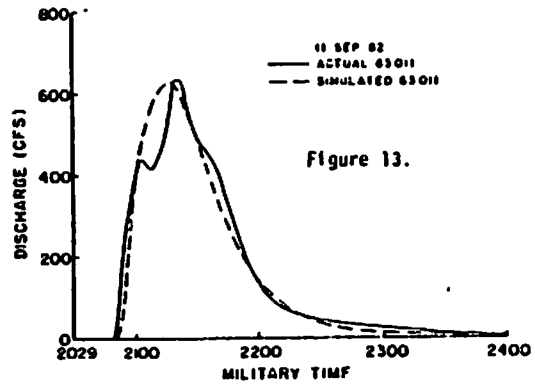


Figure 12.



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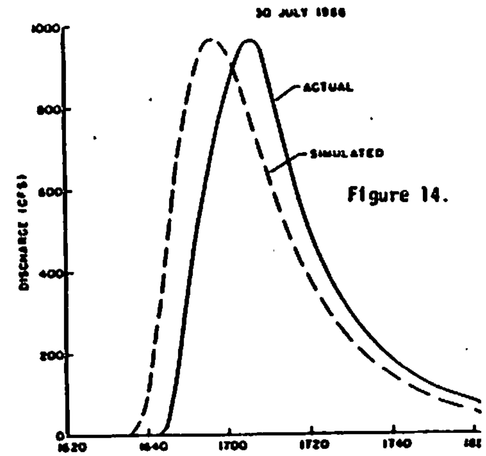

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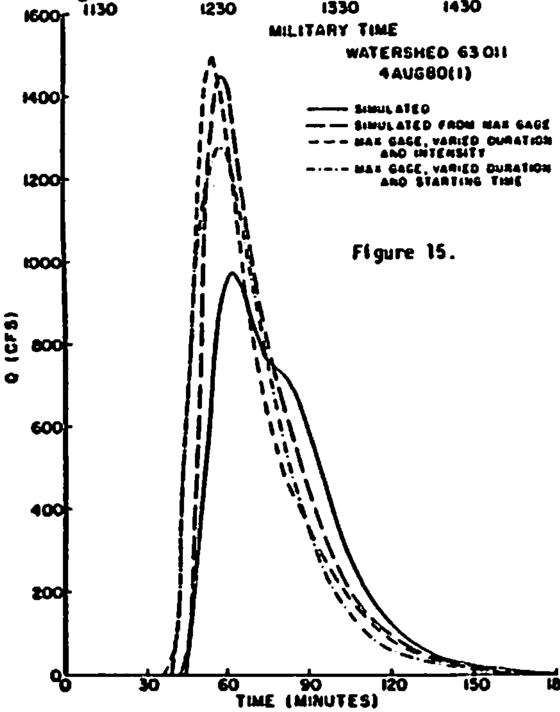

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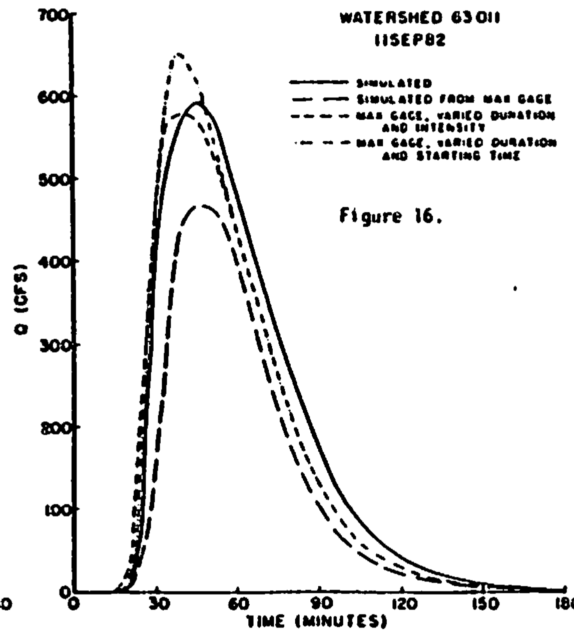

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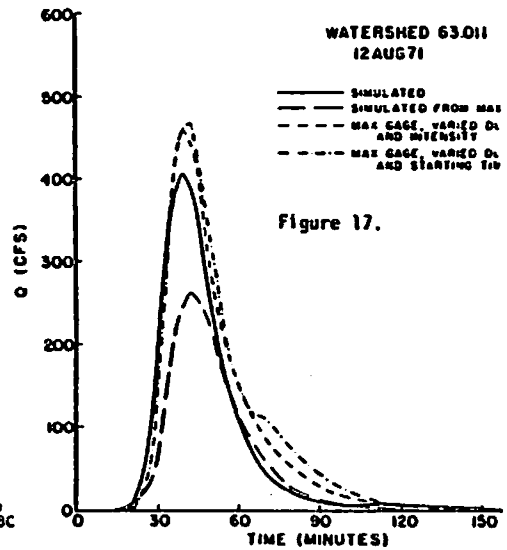

Figure 17.

CONCLUSIONS

This study suggests that for rainfall-runoff models incorporating channel and overland flow elements, the results can be strongly biased simply by how many elements are used in the simplification. Also, representation of the channel network is an important consideration in the model. In this case, a difference in output corresponding to greater model detail was explained solely by the greater extent of channelled versus overland flow.

For spatial representation of rainfall, as long as itensity distribution is incorporated into the rainfall input, several simplifications can be used effectively. Simplifications in actual and simulated rainfall gave the best results when storms were centered on the watershed.

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