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MAXIMUM RAINFALL INTENSITIES OF SOUTHWESTERN THUNDERSTORMS

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1. INTRODUCTION

In the Southwestern intermountain and high plains areas, most summer precipitation occurs as short-duration, high-intensity thunderstorms from purely convective buildup or from convective cells developing in conjunction with weak cold fronts (Sellers, 1960). Almost all runoff from small watersheds (200 km^2 and less) results from summer thunderstorm rainfall (Osborn and Hickok, 1968), and these rains are difficult to characterize in hydrologic models used to estimate or predict runoff or erosion from rangeland watersheds. Accurate estimates of the magnitude and frequency of short-duration amounts are needed, for example, to estimate rainfall excess for various infiltration models and to calculate potential splash and sheet erosion. Estimates of rainwater infiltration depend on good estimates of input, and potential onsite erosion is highly dependent upon the most intense portion of the thunderstorm rainfall. Finally, success or failure of many range renovation programs depends on the occurrence, amount, and intensity of thunderstorm rainfall. For example, where grass is being established, rain is needed for plant growth, but very intense rainfall may damage the seedbed and seedlings.

In this paper, the extreme variability of maximum point short-duration rainfall amounts is documented, and the impact on rainfall-runoff relationships is explored. Also, a method for developing synthetic rainfall distributions is tested. Analyses are based on 20-yr records (1956-1975) from two dense USDA raingage networks, Walnut Gulch in southeastern Arizona, and Alamogordo Creek in eastern New Mexico (Fig. 1), and on rainfall and runoff records from a very small subwatershed on Walnut Gulch.

2. RAINGAGE NETWORK

In general, thunderstorms in the Southwest can be divided into two classes, those occurring from purely convective activity (airmass) and those occurring from combined convective and frontal activity (frontal-convective). In southeastern Arizona (Walnut Gulch), runoff-producing thunderstorm rainfall is dominated by airmass events; in eastern New Mexico (Alamogordo Creek), although airmass storms are more common, frontal-convective storms lead to the largest runoff-producing events (Osborn and Laursen, 1973). Data from a network of 95 weighing-type recording raingages on the 150-km^2 Walnut Gulch experimental watershed and a network of 65 weighing-type recording raingages on the 170-km^2 Alamogordo Creek experimental watershed were used to delineate regional differences and similarities in short-duration rainfall amounts in the Southwest. Thirteen widely-scattered raingages with 24-hr charts were selected from each of the watersheds for the analysis (Fig. 1). Data from several weighing-type gages with shorter records (including those with 6-hr per revolution charts) were used in analyzing rainfall-runoff relationships on Walnut Gulch. The shortest duration for

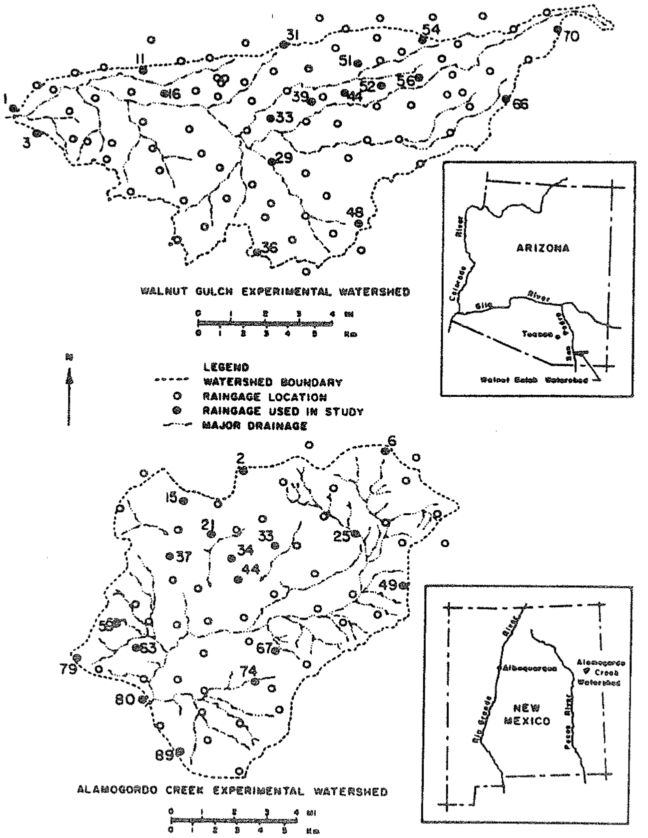

Figure 1. Location and description of Walnut Gulch and Alamogordo Creek raingage networks (numbered gages were used in the study)

which accurate estimates of rainfall intensity can be made are 4 or 5 min for 24-hr charts and 2 min for 6-hr charts (Renard and Osborn, 1966).

3. CORRELATION BETWEEN GAGES

Maximum short-duration rainfall depths at adjacent gages for airmass thunderstorm rains are highly variable. For example, hyetographs of the raingage recording the maximum 30-min rainfall for each of the three largest runoff-producing rains on Walnut Gulch and Alamogordo Creek are shown in Fig. 2. Hyetographs are also shown for the next largest 30-min depth at an adjacent gage (within 2 km distance) except for the storm of 21 August 1966. The pairs of hyetographs vary considerably, both in time and rate.

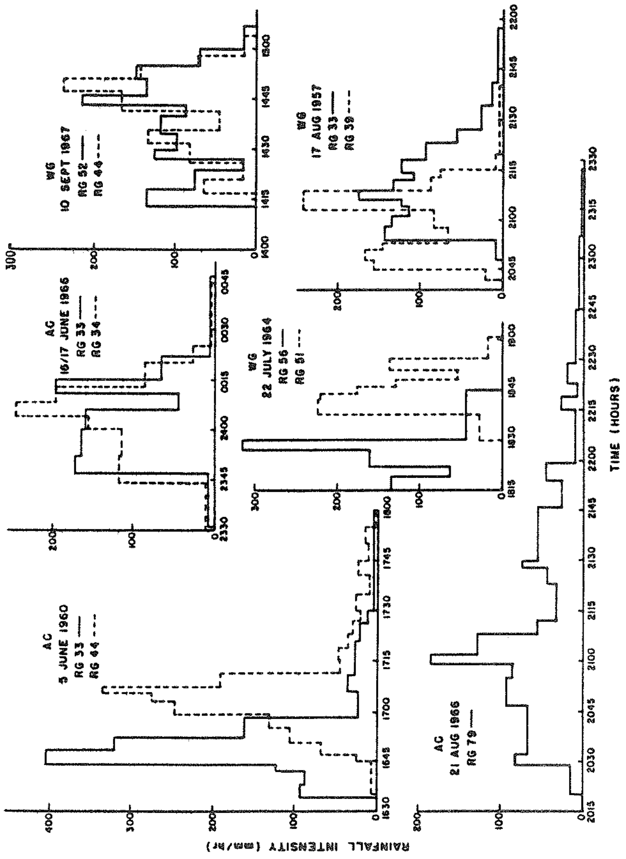

Figure 2. Hyetographs of maximum point rainfall for major runoff-producing storms on Walnut Gulch (WG) and Alamogordo Creek (AC)

Osborn et al. (1979) calculated correlation coefficients between raingage pairs for total thunderstorm rainfall amounts of 5 mm or more on Walnut Gulch and Alamogordo Creek. By using storm totals or maximum amounts for selected durations, they assumed that time had been eliminated as a variable, and that the simple correlation between raingage pairs, on a per storm basis, produced an indication of the spatial variability in thunderstorm rainfall. In our analysis, the same assumptions were used to develop the relationships between correlation coefficient and distance between gages for the two watersheds (Fig. 3). The correlation between gages decreases rapidly with distance on Walnut Gulch where airmass thunderstorms dominate. The poor correlation ($r < 0.4$) between raingages at distances of 5 km and greater suggests that, on a per storm basis, relatively closely-spaced raingages can be considered independent sampling points in regions dominated by airmass thunderstorms. For Alamogordo Creek, there is again considerable time and space variability between gages for many major events (Fig. 4) but much less variability for others. Correlations between raingages with distance do not decrease as rapidly as on Walnut Gulch and, on a per storm basis, raingages must be separated by at least 12 km to be considered independent sampling points ($r < 0.4$). A similar analysis for maximum 5-min storm rainfall amounts showed a greater decrease in correlation with distance between raingages (Fig. 3). From the 13 raingages on Walnut Gulch, three groups of five gages each, in which gages were separated by at least 5 km, were selected assuming that the 20-yr record at each gage could be accumulated to represent three 100-yr records. From the 13 raingages on Alamogordo Creek, three pairs of gages in which each gage was separated by at least 12 km from its paired gage, were selected assuming that the three pairs of gages (20 yr of record each) represented three 40-yr records.

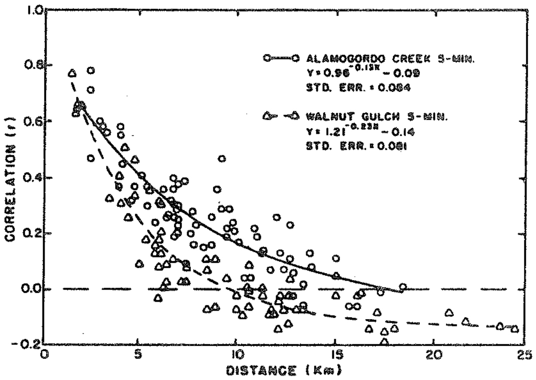

Figure 3. Correlation of storm rainfall depths with distance between pairs of gages on Alamogordo Creek and Walnut Gulch

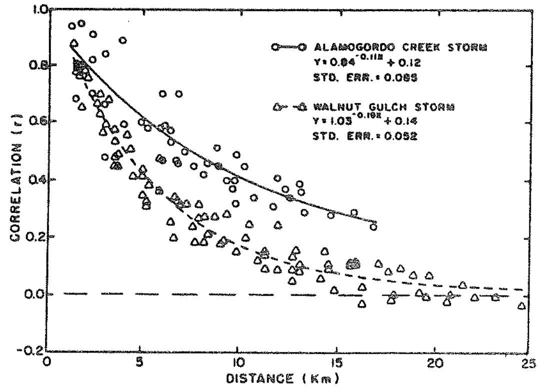

Figure 4. Correlation of maximum 5-min rainfall depths with distance between pairs of gages on Alamogordo Creek and Walnut Gulch

Very little similarity among dates was found when we compared the 10 maximum 5-min depths for 20 years of record for one of the five raingage groupings on Walnut Gulch (raingages 1, 11, 31, 56, and 70) (Table 1). Three events show up at two gages each, but there was no duplication between the two highest ranked events at each raingage. Furthermore, of the maximum point rainfall events (which are also the largest runoff-producing events) on Walnut Gulch (Fig. 2), only the storms of 22 July 1964 and 12 August 1972 appeared in the rankings for two raingages. The storm of September 1967 produced the ninth greatest 5-min rainfall at raingage 56, whereas by chance, the storm of 17 August 1957 did not appear in the 10 largest events on any of the raingages. Comparisons for the other two groups gave similar results. Although not entirely conclusive, the data suggest that, for total storm and maximum 5-min rainfall (Figs. 3 and 4), rain- gages greater than 5 km apart can be assumed independent sampling points if the 20-yr record is a good sample of 100 years of Arizona thunderstorm rainfall, and if the sampling space is relatively homogeneous (no essential variability with elevation or aspect).

A similar comparison for five raingages on Alamogordo Creek showed that, for independent sampling points, raingages must be more widely spaced than on Walnut Gulch. Four major events appear in the top 10 rankings at three or more of the five raingages (Table 2). Even raingages 6 and 67 (11 km apart) had one storm in common. The two largest runoff-producing storms (Renard et al., 1970) showed up high in the rankings for three raingages each (Fig. 2). However, the maximum 10 events at raingages 6 and 80 (16 km apart) were on different dates. Therefore, for maximum 5-min values as well as storm totals, we assumed that raingages spaced at 12 km or more could be independent sampling points.

Finally, correlation coefficients were calculated for maximum 5-min rain depths at paired gages for the dates in Tables 1 and 2. There were no apparent correlations (r ranging from −0.3 to 0.13) between raingages on Walnut Gulch, and only one pair of raingages (15 and 67) on Alamogordo Creek showed any indication of correlation (r = 0.49). However, because of the correlation between pairs of raingages for storm totals, and because of the strong representation of major events between paired raingages on Alamogordo Creek, we felt that this test was not conclusive enough to assume independent sampling points for gages as closely spaced as on Walnut Gulch.

4. MAXIMUM SHORT-DURATION INTENSITIES

Several investigators, including Osborn and Laursen (1973), have found significant differences in maximum point 30-min and longer rainfall depths between southeastern Arizona and eastern New Mexico. The expected maximum point depths for 30-min and longer are greater on Alamogordo Creek than on Walnut Gulch for the same return periods (Osborn et al., 1979). Examination of 24-hr rainfall charts indicated that greater 5-min rainfall depths also had been recorded on Alamogordo Creek than on Walnut Gulch, but the differences appeared less pronounced than for 30-min durations. The Gumbel extreme value distribution (Gumbel, 1958) was used in this analysis primarily because it had been used effectively in similar analyses (Osborn et al., 1979). However, several other distributions, including log normal, would be equally justified and would give similar results.

Table 1
Ranking of 10 annual maximum 5-min depths for selected raingages separated by 5 km or more on Walnut Gulch (1957-1976)

Ranking	Raingage				
	1	11	31	56	70
1	12 Aug 72[1]	22 Aug 61	8 Aug 57	22 Jul 64[2]	5 Jul 59
2	15 Jul 59	2 Aug 57	27 Jul 65	30 Jul 66	2 Aug 64
3	27 Jul 76[3]	12 Aug 72[1]	4 Sep 65[4]	31 Aug 58	12 Jul 64
4	14 Jul 73	27 Jul 73	22 Jul 64[2]	20 Jul 70	1 Sep 72
5	25 Aug 68	18 Jul 61	8 Sep 64	5 Sep 58	31 Aug 57
6	16 Aug 63	19 Jul 57	23 Aug 59	12 Aug 76	29 Jul 61
7	28 Sep 58	18 Aug 71	11 Aug 67	19 Aug 63	10 Sep 61
8	2 Aug 74	31 Aug 68	10 Aug 71	11 Sep 64	3 Aug 66
9	3 Aug 70	14 Aug 66	23 Aug 58	10 Sep 67	5 Jul 67
10	18 Jul 69	6 Aug 69	22 Jul 69	27 Jul 76[3]	4 Sep 65[4]

[1] 14.5 mm and 12.2 mm at gages 1 and 11, respectively.

[2] 21.1 mm and 11.4 mm at gages 56 and 31, respectively.

[3] 12.7 mm and 8.6 mm at gages 1 and 56, respectively.

[4] 11.9 mm and 9.9 mm at gages 31 and 70, respectively.

Table 2
Ranking of 10 annual maximum 5-min depths for selected raingages separated by 5 km or more on Alamogordo Creek (1957-1976).

Ranking	Raingages				
	6	15	49	67	80
1	24 Jun 60[1]	16 Jun 66[2]	5 Jun 60[3]	5 Jun 60[3]	30 Aug 59
2	10 Aug 66	13 Jul 61[4]	24 Jul 62	29 May 69	16 Jun 66[2]
3	24 Jun 62	5 Jun 60[3]	25 Aug 69[5]	16 Jun 66[2]	26 Jun 62
4	25 Aug 69[5]	24 Jun 60[1]	13 Jul 73	17 Jul 69	13 Jul 61[4]
5	5 Jun 60[3]	16 Aug 58	24 Jun 60[1]	13 Jul 61[4]	15 May 59
6	31 May 70	3 Jul 72	20 Aug 62	12 Jun 62	4 Aug 66
7	4 Jun 76	16 Sep 62	23 Jul 62	20 Jul 72	22 Aug 72
8	28 May 67	8 Aug 71	19 Sep 72	20 Aug 70	16 Aug 75
9	10 Sep 69	21 Aug 66	20 Jun 70	3 Jul 76	30 Jul 62
10	18 Jun 63	9 Jul 73	10 Aug 66	24 Jul 68	11 Jul 72

[1] 21.3, 12.4, and 10.7 mm at gages 6, 15, and 49, respectively.

[2] 18.6, 17.3, and 13.0 mm at gages 15, 67, and 80, respectively.

[3] 20.6, 19.3, 12.4, and 9.7 mm at gages 67, 49, 15, and 6, respectively.

[4] 17.3, 13.5, and 11.7 mm at gages 15, 67, and 80, respectively.

[5] 11.9 and 10.2 mm at gages 49 and 6, respectively.

Expected maximum 5-min point rainfall amounts were developed for 2- to 100-yr return periods for thirteen 24-hr raingages on both Walnut Gulch and Alamogordo Creek. Expected amounts for individual raingage records varied between raingages on the two watersheds. For example, the 100-yr maximum 5-min depths range from 16 to 23 mm on Walnut Gulch and from 16 to 28 mm on Alamogordo Creek. However, the 100-yr accumulated records for the three pairs of raingage groups on Walnut Gulch and 40-yr accumulated records for the three pairs of raingage groups on Alamogordo Creek gave similar values for all return periods.

In this analysis, either the assumed record did not improve the average of the 20-yr records or the 20-yr record is a good sample of the 100-yr future. Differences between Walnut Gulch and Alamogordo Creek maximum 5-min rainfall depths are illustrated in Fig. 5.

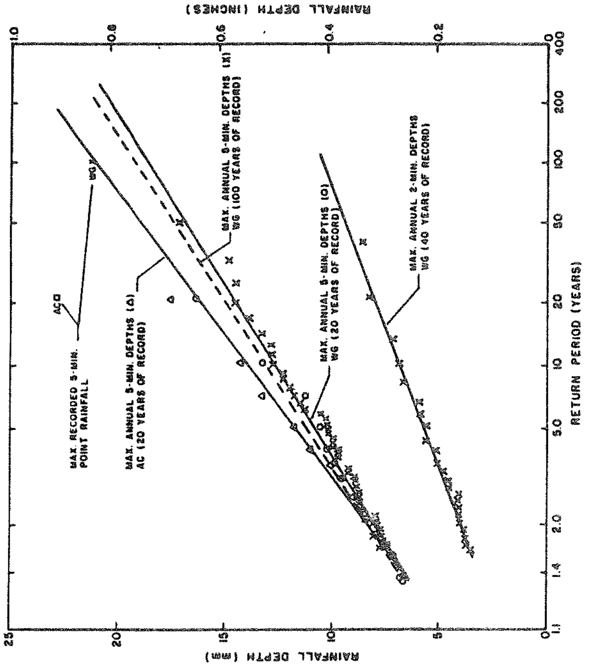

Figure 5. Expected point rainfall depths for return periods of 2 to 100 years for Alamogordo Creek (AC) and Walnut Gulch (WG)

Expected 5-min point rainfall depths are greater on Alamogordo Creek than on Walnut Gulch, but the differences are not as pronounced as for the longer durations (30-min and greater). The maximum 5-min point rainfall depths developed from NOAA Atlas 2 (Miller et al., 1973) indicate somewhat greater values for Alamogordo Creek and lesser values for Walnut Gulch. Unfortunately, the Alamogordo Creek network has been terminated, so it will be impossible, in the future, to compare the data for a longer period of record.

In any event, the differences between expected depths for a given probability between the two locations were more significant for longer durations. Possibly, the greater combined convective and frontal energies in eastern New Mexico go more to extending the duration of intense runoff-producing rainfall than to increasing the short-duration intensities. In other words, the expected maximum 5-min rainfall depths in southeastern Arizona may be almost as great as in eastern New Mexico, but the convective flow energy may not be sufficient to sustain these intensities beyond a very few minutes.

There were no 6-hr raingages on Alamogordo Creek, so 2-min depths were determined only for Walnut Gulch (Fig. 5). The collection of all 6-hr records equalled 40 years. Some of the raingages were quite closely spaced, but none of the records were long enough to analyze separately. Assuming all raingages were independent sampling points, maximum 2-min depths ranged from 4 to 10 mm for 2- to 100-yr return periods.

5. EFFECTS ON RAINFALL-RUNOFF RELATIONSHIPS

5.1 Regression Relationships

Short-duration rainfall intensities can significantly affect watershed runoff rates and volumes. Osborn and Lane (1969) developed linear regression equations to predict runoff volume and peak discharge from a small subwatershed (0.4 ha watershed 63.105) on Walnut Gulch. With additional data, these equations have been modified to the form:

$$Q_{P105} = P_{15} - 17 \qquad (r^2 = 0.80) \qquad (1)$$

$$Q_{105} = 0.7\ P_{TOT} - 6 \ (r^2 = 0.78) \qquad (2)$$

where Q_{P105} = peak discharge from watershed 63.105 (mm/hr),

Q_{105} = total storm runoff from watershed 63.105 (mm),

P_{15} = maximum 15-min rainfall intensity (mm/hr), and

P_{TOT} = total storm rainfall (mm).

For some studies, simple regression equations may be adequate, particularly when the dependent variables, in this case runoff and peak discharge, are strongly correlated to single input variables (total and maximum 15-min rainfall).

However, there are many situations in which simple regression equations may be inadequate and give misleading information. For example, in range renovation programs there is a period of "transition" (associated with major disturbances such as root plowing) between natural (usually brush-covered) watersheds and the hoped-for improved (usually grass-covered) watersheds (Simanton et al., 1978). This period is usually relatively short, compared to the pretreatment period, and individual events during the transition may be extremely important. Data from Walnut Gulch subwatershed 63.105 are used to illustrate the differences in actual and predicted peaks and volumes of runoff using regresson equations.

Maximum 2-min and 15-min rainfall intensities and total storm rainfall for six selected events for 63.105 are listed in Table 3. Peak discharges and runoff volumes were predicted from equations 1 and 2 and compared to actual peaks and volumes (Table 3). In general, peak rates and runoff volumes were underpredicted because of short-duration, high intensity, runoff-producing rainfall within the maximum 15-min rainfall.

Table 3
Rainfall and runoff data for selected events for Walnut Gulch subwatershed 105

Watershed	Date	Max 2-min rain	Max 15-min rain	Total storm rain	Days since previous rain	Pred. peak rate	Actual peak rate	Pred. storm runoff	Actual storm runoff
		(mm/hr)	(mm/hr)	(mm)		(mm/hr)	(mm/hr)	(mm)	(mm)
63.105	24 Sep 67	114	40	10	13	23	36	1.0	3.2
	8 Sep 70	107	78	29	13	61	59	14.3	15.6
	6 Sep 72	99	61	20	8	44	43	8.0	9.3
	19 Jul 74	76	52	24	12	35	31	10.8	7.7
	24 Sep 74	69	47	12	22	30	35	2.4	5.3
	5 Jul 75	130	40	15	30+	23	55	4.5	5.4

The 1975 event produced the highest actual peak discharge, but with regression, was underpredicted by about 50% (Table 3). If the 1975 storm had, for example, occurred during the transition period, the high peak discharge and accompanying erosion might be attributed to the condition of the watershed rather than to rainfall variability, and the success or failure of the project could easily be attributed to the wrong factors. The extreme short duration intensities also affected total storm runoff. In general, runoff was underpredicted for the events with higher short-duration intensities.

The effect of point rainfall variability with time becomes masked with increasing watershed size. Spatial rainfall variability and flow losses in alluvial channels become more important factors in rainfall-runoff relationships as watershed area increases. Hydrographs become "smoothed" and no longer show response to short-duration rainfall variability. For watersheds of about 100 ha and larger, peak discharge is highly correlated to the maximum 30-min rainfall.

5.2 Hydrograph Simulation

The kinematic cascade model, KINGEN (Kibler and Woolhiser, 1970), can be used to simulate runoff from small watersheds. Lane and Woolhiser (1977) described a method for geometric simplification of watersheds into planes and channels which, along with break point rainfall data and estimates of infiltration, allowed simulation of storm hydrographs. This method was applied to subwatershed 63.105, on Walnut Gulch, and illustrated with the six storm events selected for the regression study. Input parameters,representing the widths, lengths, and slopes of the three planes and the length, slope, and shape of the representative channel,were developed from topographic maps and field survey. The six events were simulated assuming both a constant infiltration rate and rainfall excess based on the Philip (1957) equation. The simulated hydrographs, based on break point rainfall and maximum 15-min rainfall (with Philip rainfall excess), are shown in Figs. 6 (the three smaller events) and 7 (the three larger events) along with the actual hyetograph and hydrographs. The runoff peaks and volumes are much better defined using break point rainfall (Figs. 5 and 6), and use of a varying infiltration rate, rather than an average infiltration rate, improves the prediction (Table 4). With regression, there was a wide scatter of predicted versus actual values for both runoff peaks and volumes with a bias torward underprediction (Table 4 and Fig. 8). Simulation with maximum 15-min rainfall led to a strong bias toward underprediction. Simulation with constant infiltration rate reduced the scatter, particularly for volume prediction. Simulation with break point data significantly improved estimates of peak rates and runoff volume and significantly reduced the scatter.

Hershfield and Engman (1978) reported on some characteristics of intense short-duration rainfalls and associated runoff, pointing out that 1-hr rainfall amounts were not adequate to estimate runoff peaks from small watersheds. They extended their work (Engman and Hershfield, 1981) by developing a procedure for making use of readily available 1-hr data in order to synthesize the 5-min rainfall sequence. Engman and Hershfield first extracted the maximum 5-min amount from the 1-hr amount and identified its time of occurrence. Thus, they had two relationships--5-min amounts as a function of the 1-hr amount and when within the hour the 5-min maximum was likely to occur. Using the 1-hr and 5-min rainfall amounts and the timing of the 5-min rainfall, they attempted to represent the entire distribution of 200 selected events. Because of the many shapes and rainfall distributions, they were unable to develop a mathematical relationship that would adequately represent all combinations. However, they did develop a procedure for estimating the 5-min rainfall depths from hourly data as a "tool" to break down hourly depths into a distribution that could be expected on the average. These methods would be valuable for rains lasting about 2 hr and longer.

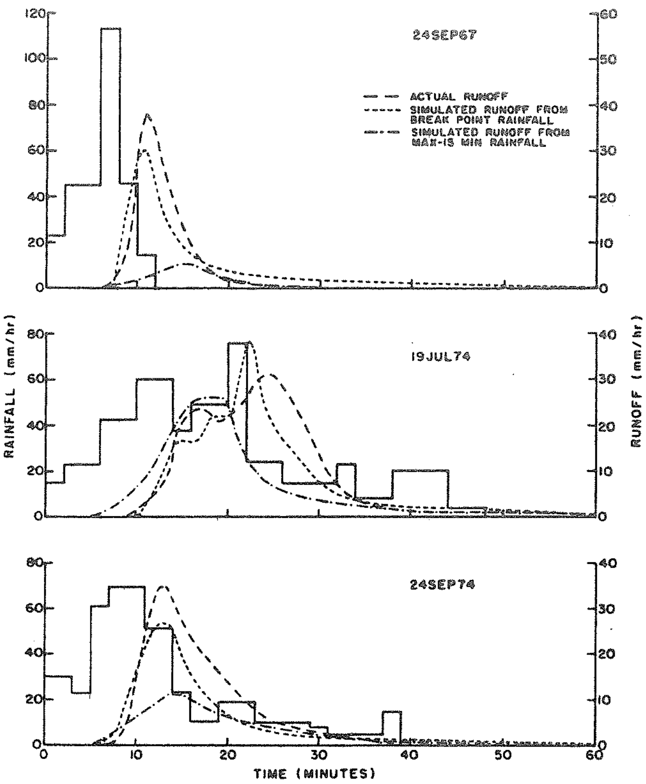

Figure 6. Rainfall hyetoghraphs and actual and simulated runoff hydrographs for three storms on a small Walnut Gulch subwatershed

Unfortunately, the method, in its current form, may be inadequate for the short-duration high intensity rains occurring on small rangeland watersheds in the Southwest. As shown, runoff-producing rainfall only lasted from 8 to 29 min for the six illustrated events on Walnut Gulch subwatershed 63.105, and the triangular distribution with volume reduction suggested by Engman and Hershfield for duration less than 1 hr led to predictions from 15% to over 300% of the actual peaks. Apparently, in areas where very short duration high intensity rainfall normally lasts less than 30 min, either the Engman/Hershfield method must be modified, or another method of synthesizing rainfall developed. We do agree that synthesis of short-duration rainfall is needed in many cases.

6. CONCLUSIONS

1. Correlation between pairs of gages for thunderstorm rainfall for independent events decreases rapidly with distance, suggesting that relatively closely-spaced gages may be assumed independent sampling points.

a. For short-duration airmass thunderstorm rainfall, gages separated by 5 km or more were independent sampling points; for frontal-convective thunderstorm rainfall, gages separated by 12 km or more were independent sampling points.

b. Correlation between pairs of gages decreased more rapidly for 5-min than 60-min rainfall durations.

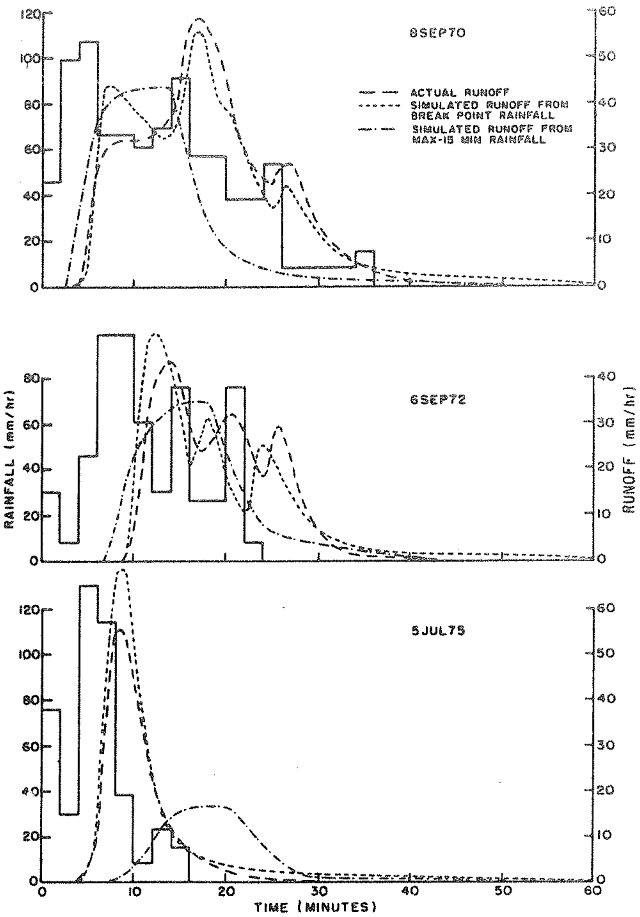

Figure 7. Rainfall hyetographs and actual and simulated runoff hydrographs for three major storms on a small Walnut Gulch subwatershed

2. Simple regression equations can be developed relating point rainfall intensities and volume to runoff peaks and volumes.

a. In general, there is a strong correlation between rainfall and runoff, and such simple equations are useful in many situations.

b. If single-storm prediction of a specific event is needed, regression equations are probably inadequate.

3. Methods have been developed using simplified watershed geometry to more accurately predict individual storm peaks and volumes.

a. If breakpoint rainfall data are available, such methods may be useful in some situations in the Southwest for watersheds up to 100 ha in size.

b. If rainfall data are not available, a method is needed to synthesize short-duration rainfall (at least as short as 5-min intervals). Current methods may not be adequate in regions dominated by short-duration thunderstorm rainfall.

Table 4

Rainfall and runoff data for selected events from subwatershed 63.105 on Walnut Gulch

Date	Rain volume	Duration runoff produced rain	Peak discharge (mm/hr)					Storm runoff (mm)				
			Actual	From regression	KINGEN			Actual	From regression	KINGEN		
					Constant infiltration	Decreasing infiltration				Constant infiltration	Decreasing infiltration	
						Breakpoint rainfall	Max 15-min rainfall				Breakpoint rainfall	Max 15-min rainfall
	(mm)	(min)										
24 Sep 67	10	8	36	23	37	26	5	3.2	1.0	4.3	3.6	1.3
18 Sep 70	29	26	59	61	53	55	43	15.6	14.3	15.0	15.0	10.2
6 Sep 72	20	18	43	44	55	52	33	9.3	8.0	7.9	9.6	7.7
19 Jul 74	24	16	31	35	31	38	25	7.7	10.8	5.8	7.1	5.9
24 Sep 74	12	9	35	30	26	26	11	5.3	2.4	4.3	4.3	2.6
5 Jul 75	15	10	55	23	86	70	16	5.4	4.5	8.6	6.4	0.7

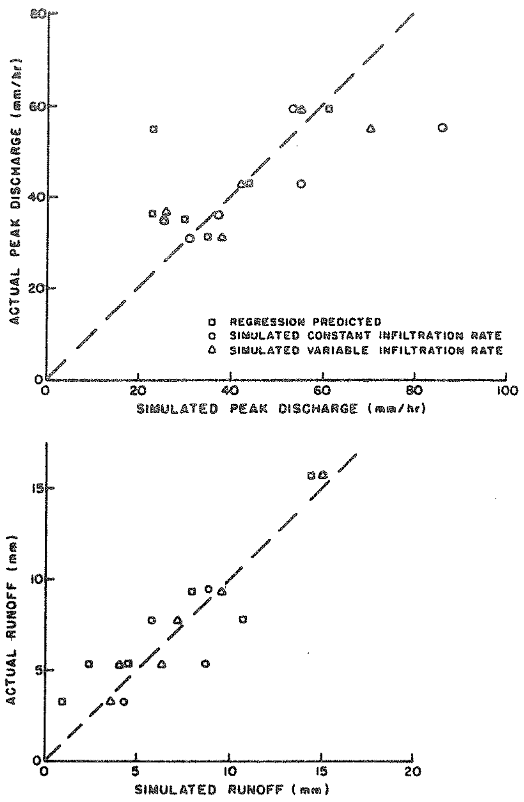

Figure 8. Comparison of actual and simulated peak discharges and runoff volumes for six runoff events on a small Walnut Gulch subwatershed

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