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QUANTIFIABLE DIFFERENCES BETWEEN AIRMASS AND FRONTAL-CONVECTIVE THUNDERSTORM RAINFALL IN THE SOUTHWESTERN UNITED STATES

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INTRODUCTION

Regional differences in rainfall amounts and intensities in the Southwestern United States have been noted by several investigators. However, quantifiable descriptions of these differences, usually as depth duration frequencies based on scattered point rainfall records, generally have ignored differences in the storm system that generated the rainfall and have lumped essentially different storm populations together (Leopold 1944, Hershfield 1961, Miller et al. 1973). Sellers (1960) stated that rainfall in Arizona could be subdivided into three categories -- frontal rainfall, air mass thunderstorm rainfall, and frontal convective rainfall. Osborn (1971) and Osborn and Laursen (1973) suggested that these same categories applied to New Mexico and northern Sonora, with frontal-convective events more common in eastern New Mexico and airmass thunderstorms dominating runoff-producing rainfall in southern Arizona and northern Mexico. Until recently, most investigators, including Sellers (1960), Osborn (1971), and Lane and Osborn (1973) assumed that the major moisture source for thunderstorm rainfall in the Southwest was the Gulf of Mexico. However, Hales (1973) hypothesized from satellite photos and surface dew point observations that the principle source of moisture for thunderstorms in southwestern and central Arizona was the Pacific Ocean. Osborn and Davis (1977) developed a rainfall occurrence model assuming the principal moisture sources for eastern New Mexico and southern Arizona were the Gulf of Mexico and the Pacific Ocean, respectively. In this study, data from two USDA raingage networks on experimental watersheds (fig. 1) were used to identify recorded differences in thunderstorm rainfall. Walnut Gulch rainfall is considered representative of southeastern and south central Arizona, southwestern New Mexico, and northern Sonora, Mexico. Alamogordo Creek rainfall is considered representative of much of eastern New Mexico and the high plains of West Texas (Osborn et al. 1979).

RAINFALL VARIABILITY

The extreme spatial variability, limited areal extent, and short-duration intensities of thunderstorms typical of southern Arizona are illustrated with isohyetal rainfall maps and hyetographs of the three major runoff-producing events in 25 years of record on Walnut Gulch (Aug 17, 1957; July 22, 1964; and

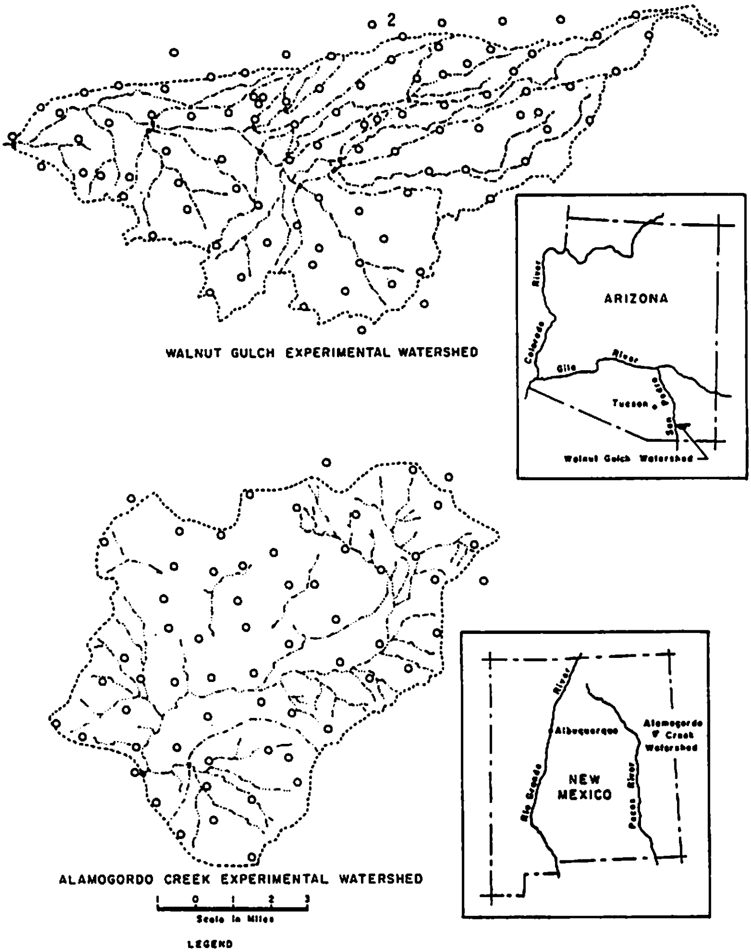

Figure 1. Location and raingage networks for USDA experimental watersheds in Arizona and New Mexico.

Sept 10, 1967) (figs. 2 through 4). Thunderstorms on Alamogordo Creek, in eastern New Mexico, often cover more area, last longer, and produce greater amounts of rainfall than those occurring on Walnut Gulch. The most apparent reason for the larger storms on Alamogordo Creek is the more frequent and stronger frontal activity. The more massive nature and even higher short duration intensities of Alamogordo Creek thunderstorms are illustrated with isohyetal rainfall maps and hyetographs of the two maximum runoff-producing events (June 5, 1960 and June 16, 1966) as well as an unusual long-duration runoff-producing storm (Aug 21, 1966) (figs. 5 through 7). In all three cases, weak cold fronts moving from east to west were associated with the period of rainfall (Keppel 1963; Osborn and Reynolds 1963; and Renard et al. 1970). In many cases, however, frontal activity is not sufficient to identify differences in airmass and frontal-convective rainfall, so this study was concentrated on the relatively few extreme events. Most

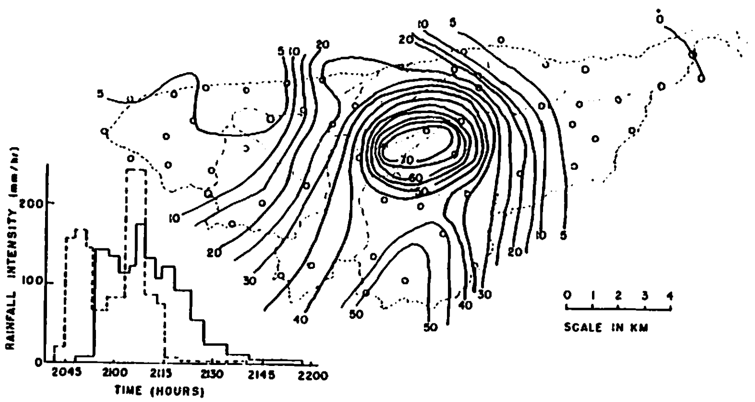

Figure 2. Rainfall isohyetal map and hyetograph of storm on August 17, 1957, at Walnut Gulch.

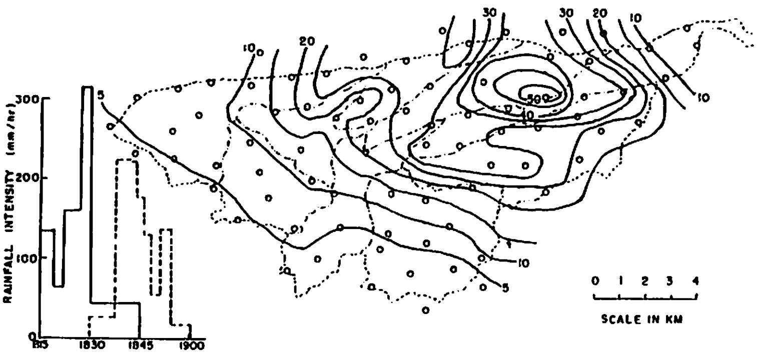

Figure 3. Rainfall isohyetal map and hyetograph of storm on July 22, 1964, at Walnut Gulch.

hydrologic problems are concerned with the rarer events. There are real differences in runoff-producing durations and rainfall amounts for the same durations between the two watersheds, and it is these differences, rather than identifying the storm systems, that are most important to the engineer or hydrologist involved in rainfall-runoff design.

Depth-Duration

The durations of runoff-producing thunderstorm rains are also extremely variable. For example, for the Walnut Gulch storm of September 10, 1967, runoff-producing rainfall lasted up to 70 min at some gages, but only 45 min at the storm center. Intense rainfall (>25 mm/hr) usually lasts for less than 20 min at any one gage; the major events last longer, but do not necessarily have greater short-duration intensities (Osborn et

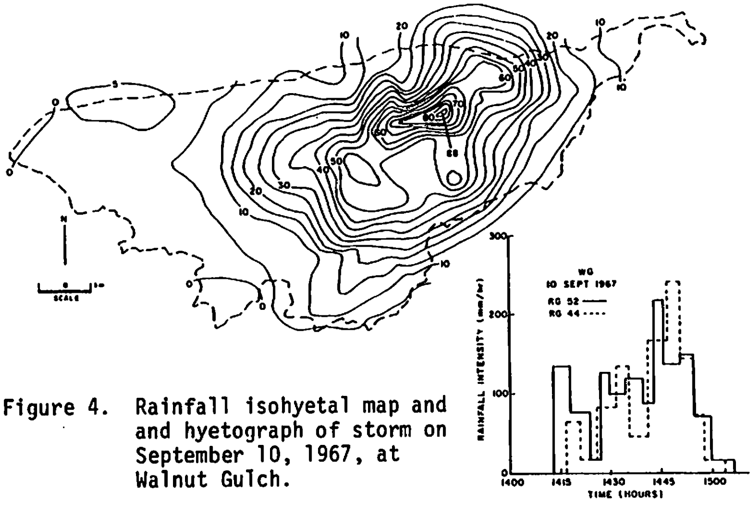

Figure 4. Rainfall isohyetal map and and hyetograph of storm on September 10, 1967, at Walnut Gulch.

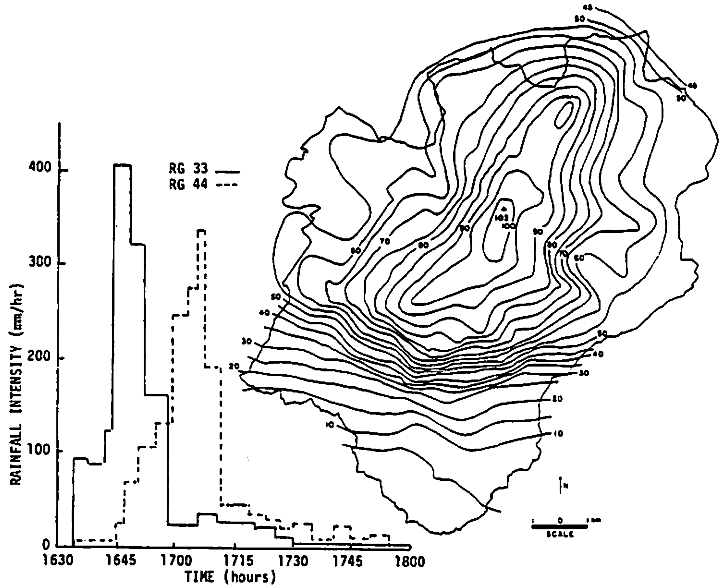

Figure 5. Rainfall isohyetal map and hyetograph of storm on June 5, 1960, at Alamogordo Creek.

al. 1979). However, the combined frontal and convective events on Alamogordo Creek, in eastern New Mexico, have produced both higher intensities for given durations and longer durations of runoffproducing rainfall than on Walnut Gulch, in southeastern Arizona (table 1). Maximum point rainfall depths up to 20-min duration for three events on Alamogordo Creek are about 1 1/2 times anything recorded on Walnut Gulch (A hail storm on Alamogordo Creek on July 13, 1961 was not included in table 1 because of questions concerning the accuracy of short duration amounts, but over 70 mm of precipitation, mostly hail, was recorded in 30 min.). Only on Sept 10, 1967 was an event recorded on Walnut Gulch that approached the 60-min values on

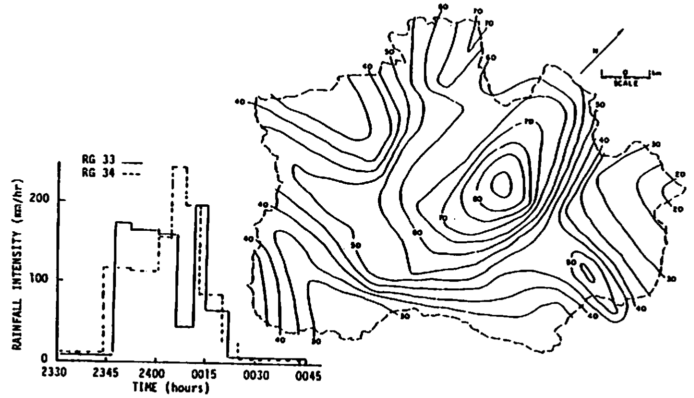

Figure 6. Rainfall isohyetal map and hyetograph of storm on June 16, 1966, at Alamogordo Creek.

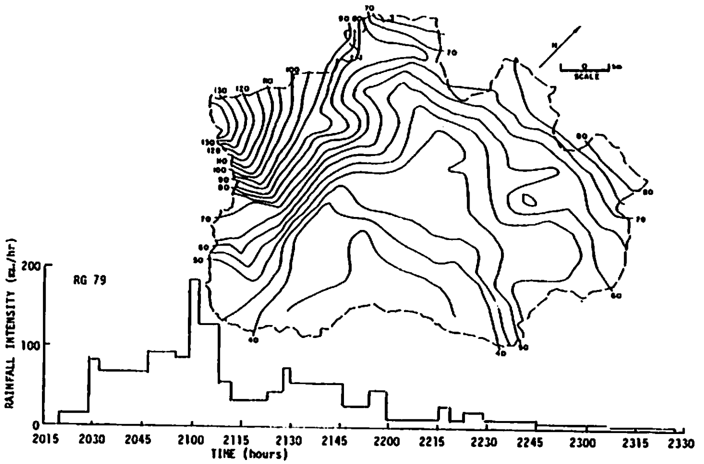

Figure 7. Rainfall isohyetal map and hyetograph of storm on August 21, 1966, at Alamogordo Creek.

Alamogordo Creek, and the rainfall amounts dropped off rapidly from the storm center. Differences in depth with time, along with hyetographs from the two gages recording the greatest depths for the six major runoff-producing events, are illustrated in figures 2 through 7.

The maximum 20-min depths for Walnut Gulch are essentially identical (table 1), while the 60-min values range from 47 to 87 mm. On the other hand, maximum 20-min depths for Alamogordo Creek range from 39 to 74, while the 60-min values show a smaller spread, 76 to 94 mm. This suggests that frontal activity supplies additional energy which can increase the depth and duration of rainfall.

In some methods, estimates of peak discharge from rainfall are influenced by the location of the period of maximum intensity within the storm. Such adjustments may be unnecessary for either airmass or frontal-convective rain in the Southwest.

Table 1.--Maximum point rainfall depths (mm) for selected durations for six major events on Alamogordo Creek and Walnut Gulch

Storm date	Rain gage	Duration (min)						
		5	10	15	20	30	60	120
		Alamogordo Creek						
June 5, 1960	33	31	53	66	74	83	94	103
June 5, 1960	44	25	43	55	66	74	88	92
June 16, 1966	33	14	28	41	53	71	79	85
June 16, 1966	34	20	35	46	56	75	89	96
Aug 21, 1966	61	19	31	42	50	62	91	116
Aug 21, 1966	79	13	24	31	39	51	76	106
		Walnut Gulch						
Aug 17, 1957	33	13	23	35	45	61	69	72
Aug 17, 1957	39	20	30	37	47	66	69	72
July 22, 1964	51	19	33	40	44	47	47	47
July 22, 1964	56	21	31	41	45	52	52	52
Sept 10, 1967	44	19	33	43	48	64	74	74
Sept 10, 1967	52	15	27	36	46	63	87	88

For example, in five of the six cases shown (fig. 8), the runoff-producing rainfall can be clearly separated from the nonrunoffproducing rain at the beginning and end of the storm. This is true in almost all major events--light rain either proceeding or following the intense core of thunderstorm rainfall does not measurably affect the peaks or volumes of discharge. For this reason, at least in Arizona and New Mexico, we may be able to simplify our rainfall-runoff relationships. The exception, of course, is the Alamogordo Creek storm of August 21, 1966 in which rainfall continued at lower runoff-producing rates for over 3 hr. Because the watershed and channels were well saturated early in the event, runoff continued longer than usual. However, the maximum peak discharge occurred from the higher intensity rainfall early in the event.

Finally, estimates of rainfall depths for Walnut Gulch and Alamogordo Creek for return periods up to 100 years are shown in figure 9. The estimated average 100-yr, 60-min point rainfall depths are 85 mm for Alamogordo Creek and 74 mm for Walnut Gulch. All recording gage records were used to identify the annual maximum 60-min rainfall depths occurring somewhere on the watershed rather than at a selected point. The set of annual watershed maxima were used to estimate 100-yr, 60-min depths of 112 mm for Alamogordo Creek (network covers 170 km^2) and 94 mm for Walnut Gulch (network covers 180 km^2). It is uncertain as to whether the greater amounts recorded on Alamogordo Creek are simply much less likely to occur on Walnut Gulch or whether the necessary combination of energy and moisture for such extreme events cannot occur in southeastern Arizona.

Depth-Area

Thunderstorm rainfall varies extremely in space as well as time. Mills and Osborn (1973) found that sequences of annual maximum thunderstorm rainfall in southeastern Arizona could be considered stationary stochastic processes. They also found that rainfall sequences appeared stationary and ergodic for gages located on Walnut Gulch. Osborn et al. (1979) compared total storm rainfall for selected pairs of rain gages on Walnut Gulch and Alamogordo Creek. By using storm totals and assuming

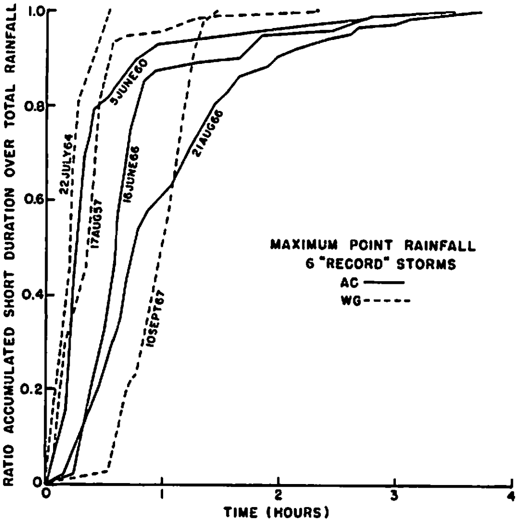

Figure 8. Time distribution of rainfall at storm centers for 6 events on Walnut Gulch and Alamogordo Creek.

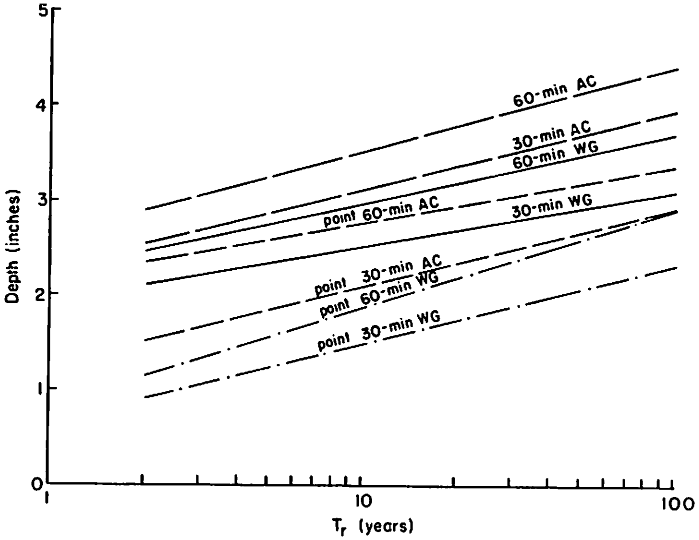

Figure 9. Expected point and watershed 30- and 60-min rainfall depths for Walnut Gulch (WG) and Alamogordo Creek (AC).

stationarity and random occurrence of thunderstorms on the two watersheds, time was eliminated as a variable, and the simple correlations between gages provided a useful indication of spatial variability. Twenty-six gages on Walnut Gulch and 13 gages on Alamogordo Creek with relatively long records were selected to provide as much variability in distances as possible without duplication and without having to compare all possible pairs of gages. Distance between gages ranged from 0.8

to 23 km for Walnut Gulch and 1.3 to 16 km for Alamogordo Creek. The correlation coefficient decreases with distance between gages more rapidly on Walnut Gulch than on Alamogordo Creek (fig. 10). For example, at 5 km, $r \approx 0.65$ on Alamogordo Creek and 0.40 on Walnut Gulch (the value for r^2 of 0.16 for Walnut Gulch compared to 0.42 for Alamogordo Creek might be even more descriptive). On Walnut Gulch, annual maximum point rainfall depths were generally recorded from different events for gages spaced 5 km or more apart. On Alamogordo Creek, annual maximums were often recorded from the same event at gages more widely spaced than on Walnut Gulch.

Because of the poor correlation between gages at relatively short distances on Walnut Gulch, we assumed, for estimating extreme events for airmass thunderstorm rainfall, spatial independence at 5 km ($r^2 = .16$), and that our rainfall records represent a much longer period than 20 yr (also assuming, of course, that the period of record is stochastically representative of a longer period). Because of better correlations between gages on Alamogordo Creek, it is difficult to assume independence except, possibly, for gages on opposite ends of the watershed (for $r \sim 0.35$, the distance between gages is 12 km). In any case, records were assumed equivalent to 100 yr on Walnut Gulch (five gages with 20 yr of record and $r < 0.4$) and 40 yr on Alamogordo Creek (two gages with 20 yr of record and $r < 0.4$) in estimating frequencies for rare events. The premise is that airmass thunderstorms are dominant in southeastern Arizona, and in such regions, gages as close as 5 km can be considered independent records, and that frontal-convective storms are dominant in eastern New Mexico, and in such regions, gages must be at least 12 km apart to be considered independent sampling points.

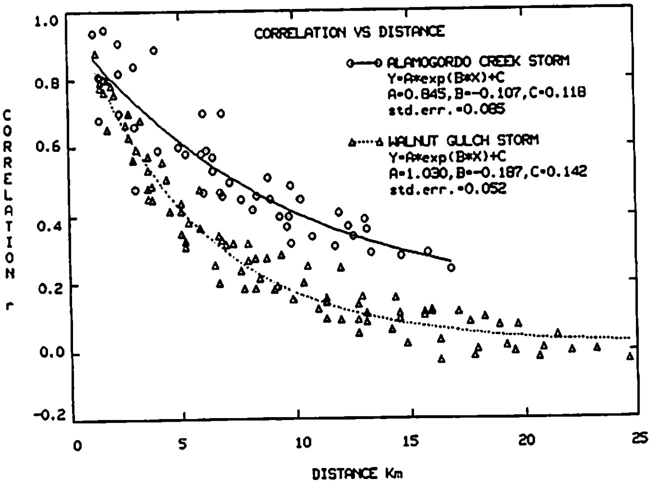

Figure 10. Correlation coefficients for storm rainfall for pre-selected pairs of raingages on Walnut Gulch and Alamogordo Creek.

Depth-area curves for the maximum 1-hr rainfall for the three illustrated storms each on Walnut Gulch and Alamogordo Creek show the large and meaningful differences between air-mass and frontal-convective storms (fig. 11). There is at least three times the volume of rainfall for the "largest" event on Alamogordo Creek than for the "largest" event on Walnut Gulch. The differences in volume at selected isohyets are shown in tables 2 and 3. Differences for the cores of higher intensity runoff-producing rainfall are even more extreme--over 10 times as much area on Alamogordo Creek for volumes within the 50 mm isohyets.

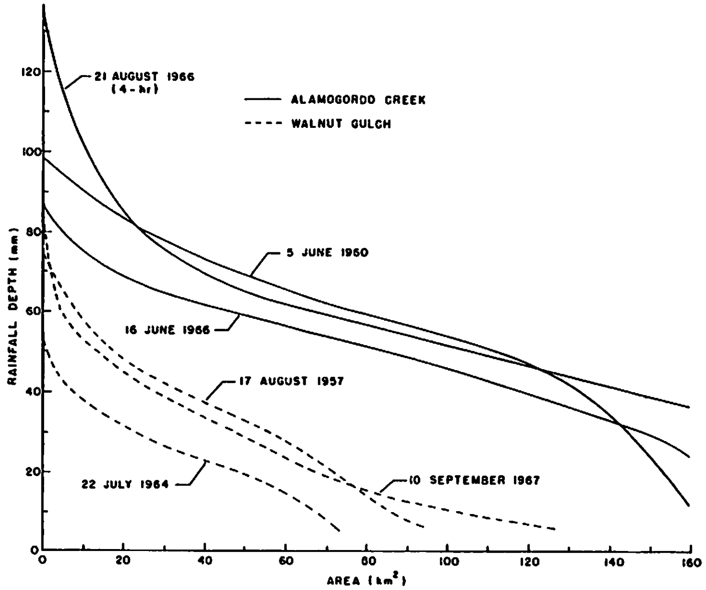

Figure 11. Depth-area rainfall curves for selected events at Walnut Gulch and Alamogordo Creek.

Osborn et al. (1980a) developed depth-area relationships from Walnut Gulch and Alamogordo Creek rainfall records and compared these curves to those published in NOAA Atlas 2 (Miller et al. 1973). Point-to-area ratios for 30-min and 60-min durations are shown in figures 12 and 13. For Walnut Gulch, the new curves plotted well below those in NOAA Atlas 2. For Alamogordo Creek, new curves were much closer to those in NOAA Atlas 2. Differences in rainfall volumes indicated that differences in point-to-area relationships between Walnut Gulch and Alamogordo Creek would be meaningful in most rainfall-runoff models. Also, the 100-yr curve for Walnut Gulch plots below the 2- and 10-yr curves, indicating that the major events are high-intensity, short-duration storms of limited areal extent, whereas the more common events may include lower-intensity rains with greater areal extent. The Alamogordo Creek curves, which are reversed, are identified with the larger storms that are common in eastern New Mexico.

The curves in NOAA Atlas 2 flatten with increasing duration. For the small watershed data used by Osborn et al. (1980b), there was little change in the curves with durations up to 2 hr for either Walnut Gulch or Alamogordo Creek. The NOAA Atlas 2 curves were based on scattered raingage data like those used for large area storms in the eastern United States.

Table 2.--Maximum 1-hr rainfall volumes within selected isohyets for storm of September 10, 1967 on Walnut Gulch (from Osborn et al. 1979)

Isohyet	Area	Volume	Isohyet	Area	Volume
(mm)	(km^2)	(10^5 m^3)	(mm)	(km^2)	(10^5 m^3)
80	0.2	0.2	35	38.5	18.8
75	.6	.5	30	47.7	21.6
70	1.4	1.1	25	57.0[1]	24.1[1]
65	2.6	1.9	20	66.8[1]	26.3[1]
60	4.1	2.8	15	79.3[1]	28.5[1]
55	6.7	4.3	10	104.0[1]	31.6[1]
50	12.4	7.3	5	124.0[1]	33.1[1]
45	22.8	12.2	0	155.0[1]	33.9
40	31.1	15.8			

[1] Partial storm areas and volumes recorded only within the rain gage network.

Table 3.--Maximum 1-hr rainfall volumes within selected isohyets for storm of June 5, 1960 on Alamogordo Creek (from Osborn et al. 1979)

Isohyet	Area	Volume	Isohyet	Area	Volume
(mm)	(km^2)	(10^5 m^3)	(mm)	(km^2)	(10^5 m^3)
95	2.3	2.2	45	153[1]	101[1]
90	8.0	7.1	40	154[1]	102[1]
85	16.3	14.8	35	155[1]	102[1]
80	25.4	22.2	30	156[1]	102[1]
75	34.2	29.1	25	157[1]	103[1]
70	43.8	36.1	20	159[1]	103[1]
65	66.8	51.8	15	161[1]	103[1]
60	97.6	71.0	10	162[1]	103[1]
55	124	86.0	5	164[1]	104[1]
50	148	98.5	0	174[1]	104[1]

[1] Partial storm areas and volumes recorded only within the rain gage network.

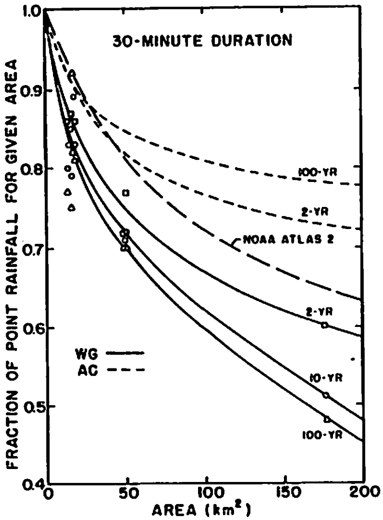

Figure 12. Point-to-area conversion ratios for 30-min duration rainfall for selected frequencies on Walnut Gulch and Alamogordo Creek.

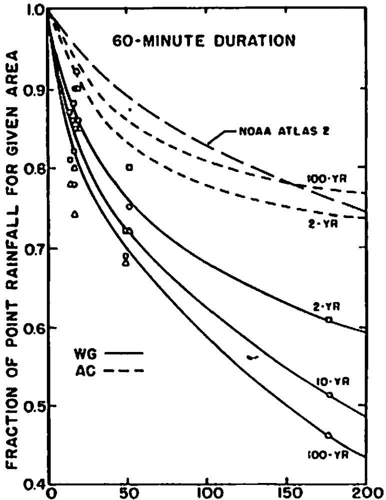

Figure 13. Point-to-area conversion ratios for 60-min duration rainfall for selected frequencies on Walnut Gulch and Alamogordo Creek.

CONCLUSIONS

There are significant differences in the depths, durations, and areal extent of thunderstorm rains occurring in eastern New Mexico and southeastern Arizona. Differences, as measured with recording raingage networks on the Alamogordo Creek (New Mexico) and Walnut Gulch (Arizona) experimental watersheds, may be attributed, primarily, to greater frontal activity in eastern New Mexico. Several investigators have referred to the two types of storms as airmass and frontal-convective, with airmass storms dominating rainfall-runoff relationships in southern Arizona, southwestern New Mexico, and northern Sonora, Mexico, and frontal-convective storms dominating rainfall-runoff relationships in eastern New Mexico and western Texas. More important than definition of storm type, however, is that the precipitation differences are large enough to lead to real differences in estimates of, for example, peak discharge, storm runoff, erosion, and sediment yield.

Quantifiable differences include:

(1) On Walnut Gulch, relatively closely-spaced gages (5 km) can be assumed independent sampling points for estimates of amounts and occurrence of extreme events.

(2) On Alamogordo Creek, gages must be spaced at least 12 km apart to assume independent sampling points for estimates of extreme events.

(3) Point-to-area reduction of factors for estimating rainfall volume on a watershed decrease much more rapidly with distance from storm center on Walnut Gulch than on Alamogordo Creek.

(4) Much greater volumes of runoff-producing rainfall have been measured on Alamogordo Creek--the maximum recorded volume is, roughly, 3 times the maximum recorded runoff-producing rainfall volume on Walnut Gulch.

(5) Estimated point rainfall depths for rare events are greater on Alamogordo Creek than on Walnut Gulch (the 100-yr, 60-min rainfall depth for Alamogordo Creek is 15% larger than for Walnut Gulch).

(6) The chance of extreme rainfall depth occurring someplace on the watershed is greater on Alamogordo Creek than on Walnut Gulch (for the 100-yr, 60-min depth, the estimate is 20% larger for Alamogordo Creek than for Walnut Gulch).

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