Rainfall/Watershed Relationships for Southwestern Thunderstorms

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ABSTRACT

DEPTH-AREA relationships for thunderstorm rainfall were developed from 20 years of record from dense raingage networks in Arizona and New Mexico, using the National Weather Service method described in NOAA Atlas 2. The relationships are compared with similar previously published ones. Relationships also were developed to indicate the distribution of storm rainfall over a watershed. This information could be valuable to agencies, groups, and individuals involved in water resources design and evaluation for climatologically similar areas.

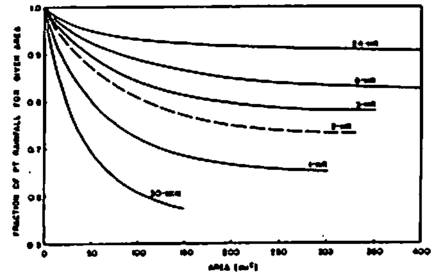

FIG. 1 Point-to-area conversion ratios for selected durations (Fig. 14, NOAA Atlas 2), 2-h interpolated.

INTRODUCTION

The National Weather Service (NWS), National Oceanic and Atmospheric Administration (NOAA), published a precipitation frequency atlas, NOAA Atlas 2 (Miller et al., 1973) for the Western United States, which consisted of a series of volumes, one for each Western state. Volumes 4 (New Mexico) and 8 (Arizona) are of particular interest in this study. A value read from the isopluvial maps in each of these volumes "is the value for that point and the amount for that particular duration which will be equalled or exceeded, on the average, once during the period of time indicated on the individual map." Also, there is a depth-area monogram in each volume to be used to estimate average rainfall over watersheds of up to 1000 km², given the average point value over the basin.

The depth-area curves in NOAA Atlas 2 were developed, by necessity, from groupings of closely spaced recording raingages available in the published data of the regular cooperative network of the NWS. No groupings sufficiently closely spaced for this purpose were available in the Southwest. Significant regional and frequency variations were not detected in the available data from the remainder of the United States. Fig. 1 shows the curve published for Arizona and New Mexico, but derived from regions outside the Southwest. These are based on 2-yr data, but are meant to be applied to all return periods up to 100 years (Miller et al., 1973).

In this paper we use records from dense recording raingage networks, operated by the USDA, Southwest Rangeland Watershed Research Center at the Walnut Gulch Experimantal Watershed near Tombstone, AZ, and the Alamogordo Creek Experimental Watershed near Santa Rosa, New Mexico (Fig. 2), to develop new depth-area curves. We believe the new curves are applicable to southwestern watersheds of similar climates for rainfall durations from 30 min to 6 h over areas up to 200 km². We compared these new curves with the NOAA Atlas 2 curves. Complete descriptions of the experimental watersheds and their instrumentation have been given by Renard (1970) and the Agricultural Research Service (1971). Gage density in each basin is about 1 per 3 km².

For many design problems on Southwestern watersheds, information is needed to supplement the type of information provided in NOAA Atlas 2. Most rain-produced runoff from small Southwest rangeland watersheds results from intense, short-lived thunderstorms of limited areal extent (Osborn and Laursen, 1973). Also, in many cases, an estimate of the distribution of the storm rainfall over the area is important in estimating the runoff from the storm. In a final section of this paper, distribution curves are developed from selected Walnut Gulch and Alamogordo Creek data.

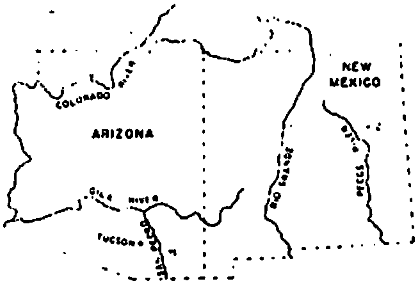

FIG. 2 Location of USDA-SEA-AR experimental watersheds.

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TABLE 1. MAXIMUM ANNUAL RAINFALL FREQUENCIES (mm) ESTIMATED BY FITTING SEVERAL FREQUENCY DISTRIBUTIONS TO 20 YEARS (1957-76) OF DATA FOR WALNUT GULCH

	Log normal			Pearson Type III			Log-Pearson Type III			Gumbel		
	30-min	1-h	2-h	30-min	1-h	2-h	30-min	1-h	2-h	30-min	1-h	2-h
2-yr												
Basin average	14.0	17.0	18.4	15.0	17.9	19.2	14.8	18.0	19.3	14.1	16.9	18.3
RG #3	21.1	25.0	27.2	22.0	24.7	27.1	21.6	24.8	27.3	21.2	25.2	27.3
RG #33	25.8	29.9	31.2	25.0	29.2	30.6	24.6	28.3	29.8	26.2	30.2	31.5
RG #66	22.7	26.1	28.6	24.0	27.6	29.5	22.8	26.4	28.4	23.1	26.4	28.9
10-yr												
Basin average	20.9	24.7	25.8	19.5	23.1	24.5	19.9	23.3	24.5	21.1	24.9	26.2
RG #3	32.9	40.0	43.2	31.8	40.3	43.2	32.3	40.2	43.1	34.1	43.4	46.3
RG #33	43.1	49.2	50.8	45.0	51.4	52.7	44.0	50.2	51.8	49.0	55.7	56.9
RG #66	38.4	43.0	47.0	37.3	41.5	46.6	38.2	42.7	47.2	40.3	44.8	50.1
100-yr												
Basin average	28.9	33.5	34.1	22.4	26.8	28.2	23.0	26.1	27.2	29.8	34.8	36.0
RG #3	47.4	58.6	63.1	40.4	59.2	61.9	42.3	60.9	62.1	50.2	66.0	70.0
RG #33	65.5	50.8	75.5	71.3	79.5	80.1	81.5	93.4	92.8	77.5	87.5	88.7
RG #66	58.9	64.7	70.5	49.5	53.7	63.8	57.1	61.7	72.1	61.7	67.8	76.5

POINT-TO-AREA CURVES

Basic Method

The method used by NWS for developing the point-to-area curves, shown in Fig. 1, was described in detail in U.S. Weather Bureau Technical Paper No. 29 (1958). Briefly, the technique for developing point-to-area curves for a particular duration consisted of the following steps.

1 Annual maximum rainfall amounts were listed by duration for each station in the groups of closely spaced, recording raingages.

2 Similarly, annual maximum rainfall amounts for various durations over areas of several sizes were determined. Areal depths are the average of the gages within the area. These annual maximum areal values did not necessarily occur on the same day as the maximums at individual stations.

3 The same type of frequency distribution was fitted to the annual maximums at each gage and for each area.

4 For a given frequency, the point values within each area were averaged (assuming negligible climatological gradients within the network).

5 The ratios of areal to averaged point values at equal frequencies or return periods defined the point-to-area curve.

Frequency Distribution

The NWS uses the Gunbel extreme value procedure (Gumbel, 1958) for fitting of the Fisher-Tippett Type I distribution for developing rainfall frequency maps and depth-area curves. The choice of this frequency distribution is partly based on work that showed that for the continental United States, this distribution fitted maximum annual point rainfalls fairly well (Hershfield and Kohler, 1960) and was slightly better than some other standard methods used in predicting frequencies for independent samples not used in deriving the curves (Hershfield, 1962). For a limited check on frequency distributions applicable to the data of this study, we fitted Walnut Gulch and Alamogordo Creek basin average and selected station maximum annual storm rainfall with log normal, Pearson Type-III, log Pearson Type-III, and the Gumbel fitting of the Fisher-Tippett Type I frequency distributions, by the method of moments. An illustrative portion of these values for Walnut Gulch are listed in Table 1.

By visually comparing plotted points with computed curves for the several distributions, we concluded that for the data as a whole, the Gumbel distribution seemed to fit best. For this reason and for continuity with previous NWS work, it was selected for this study.

The Gumbel fitting is based on the concept that a series of values, all of which are maximums from independent samples of equal and sufficient size, drawn from the same population (e.g., annual maximum rainfalls), conforms to the probabillity distribution of a dimensionless "reduced variate", y, if suitably scaled. The term y is defined by its probability distribution as:

$$y_{Pr} = -\ln(-\ln Pr) \qquad [1]$$

where Pr is the probability that a reduced variate, y, chosen at random, will be less than or equal to the particular value, y_{Pr}. Following an example given by the National Bureau of Standards (1953), this distribution is fitted to a sample of size N of a real variable, X, by assuming the common plotting position formula

$$Pr = \frac{m}{N+1} \qquad [2]$$

applies to both y and X, where m is rank from lowest to highest. In principle, a linear regression fit is made to the N pairs, X_m, y_m, where X_m's are from the sample and the y_m's are found by substituting equation [2] into equation [1]. This may be simplified by using precomputed tables, which require only the mean and standard deviation of the X's and the sample size N as input. The steps and tables for the simplified procedure are listed by the World Meteorological Orgainzation (1974).

The relatively small values of some of the annual maximums lead to one additional empirical test. At the same stations in Table 1, we applied the Gumbel fitting of the extreme value distribution to the 20 highest rains, regardless of year of occurence (partical duration series), with the thought in mind that "partial duration" storms in an arid climate might be regarded as extremes for this distribution. However, by visual inspection, use of the partial duration series did not improve the fit compared

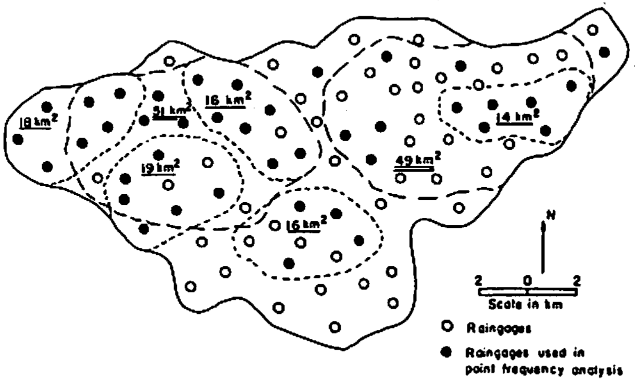

FIG. 3 Recording raingage network and subwatersheds used in determining frequency distributions for Walnut Gulch.

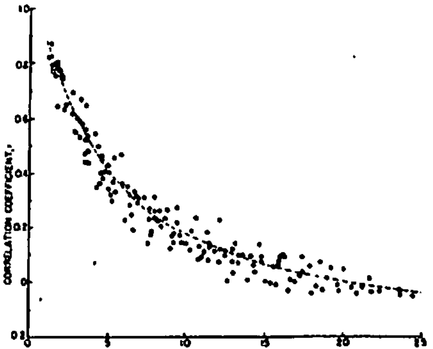

FIG. 4 Correlation coefficients for rainfall amounts for selected pairs of gages on Walnut Gulch.

to the annual series, at least in this case. For this reason, and because the original work was based on annual series, the partial duration series was not used.

Walnut Gulch Curves

Recording raingage records for the period 1957-1976 on and immediately adjacent to the Walnut Gulch Experimental Watershed were used in this study. Gages were added as funds became available through 1965, when the network of 80 gages was completed, as shown in Fig. 3. The 26 gages with a full period of record, are more concentrated on the lower (western) end of the watershed. Therefore, subareas for analysis were chosen mostly on the lower half of the watershed where the records are longest and the gages closest together.

In constructing representative areas (second step of "basic method"), raingages were assumed to represent rainfall within an 0.8 km (one-half-mile) radius. Area outlines were drawn by connecting the imaginary circular areas around each station, tangentially. Areal average rainfalls were obtained by averaging amounts from all existing gages within each area. As gages were added to each area, they were included in the areal average. The raingages were fairly well spaced in most years, so all were given equal weight in averaging areal rainfall. Obviously, the averages are more uncertain in the early years of fewer gages, particularly before 1960. Annual maximum rains were determined for each of 20 years (1957-1976), and the frequency distribution fitted separately for areas of 176, 51, 49, 18, 19, 16, 15, 14 and zero (point) km² (fig. 3), for durations of 30, 60, 120 and 360 min.

Gages used for point frequency comparison to areal values are indicated in Fig. 3. Only gages with no more than 2 yr of missing record were used for this. The few missing years (at 14 of the 40 gages) were filled in by interpolation of annual maximums from adjacent stations. As it turned out, using 20 gages with complete records gives almost the same result as using 40 gages with some estimated record. As stated, there was an uneven distribution of raingages on Walnut Gulch during the early years of record. For better distribution, six of the gages on the lower end of the watershed were omitted in the point analysis comparison with 176 km² area.

The variability of estimating based on point records is illustrated in Table 2. Estimated rainfall amounts for annual series for varying durations and frequencies based on records from 6 raingages were compared. For example, the 100-yr, 1-h rainfall estimate at raingage 33 is about double that of raingage 31. The two gages are only 2 miles apart, and both records are excellent.

As an indicator of the scale of the phenomenon being investigated, correlation coefficients were compared at Walnut Gulch between rains at selected pairs of gages with varying distance between them (Fig. 4). The correlation is for storm depths during 1961-72, when at least one of the two storm gage totals equalled or exceeded 5 mm. No storm had a duration longer tha 2 h. The curve is fitted by eye.

As a check on possible non-random distribution of rainfall on Walnut Gulch, estimated 100-yr, 1-h rainfall amounts were plotted against gage elevation (Fig. 5). The range of values is greater on the lower end of the watershed where there were more gages, but there is certainly no clear evidence of higher or lower average values within the 450 m elevation range on the watershed.

Depth-area curves were constructed through the plotted points (1.0 for zero) for 2-, 10- and 100-yr return periods for durations of 30, 60, 120 and 360 min (Figs. 6-9) by using a method suggested by one of the authors (Myers) for a least squares fit to:

$$r = 1 - M \exp\left[-a\left(\frac{A}{A_o}\right)^{b-1}\right] \qquad [3]$$

TABLE 2. COMPARISON BETWEEN PREDICTED RAINFALL AMOUNTS (mm) FOR ANNUAL SERIES FOR VARYING DURATIONS AND FREQUENCIES USING SIX DIFFERENT STATION RECORDS ON WALNUT GULCH

	2-yr			10-yr			100-yr		
	30-min	1-h	2-h	30-min	1-h	2-h	30-min	1-h	2-h
RG #1	21.8	25.4	26.8	37.3	50.1	55.0	56.5	80.9	90.2
RG #33	26.2	30.2	31.5	49.0	55.7	56.9	77.5	87.5	88.7
RG #66	23.1	26.4	28.9	40.3	44.8	50.1	61.7	67.8	76.5
RG #3	21.2	25.2	27.3	34.1	43.4	46.3	50.2	66.0	70.0
RG #31	19.9	22.1	23.2	30.5	33.5	34.8	43.8	47.6	48.7
RG #70	23.2	28.6	32.3	39.6	49.2	57.6	59.8	74.9	89.4

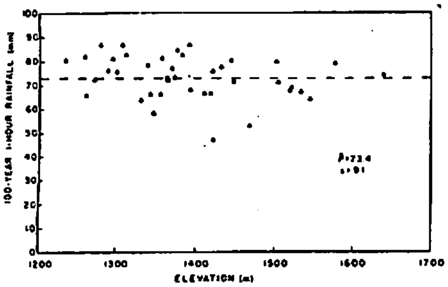

FIG. 5 Comparison of estimates of 100-yr, 1-h rainfall amounts with elevation for selected raingages on Walnut Gulch.

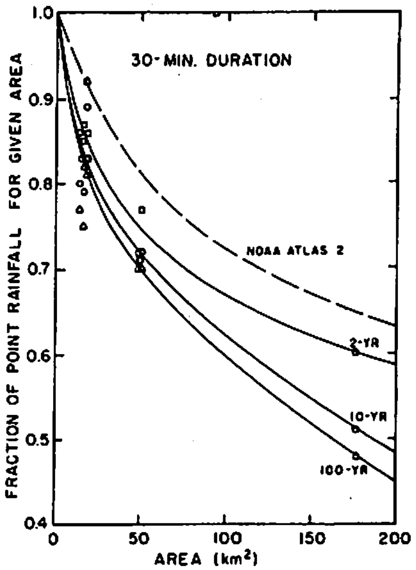

FIG. 6 Point-to-area conversion ratios for 30-min duration rainfalls for selected frequencies on Walnut Gulch.

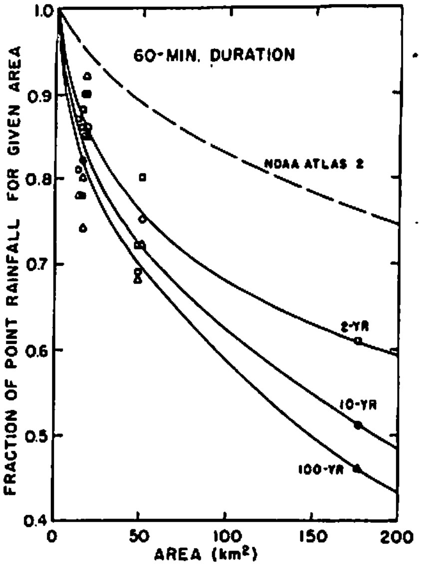

FIG. 7 Point-to-area conversion ratios for 60-min duration rainfalls for selected frequencies on Walnut Gulch.

where r is depth-area ratio for area A in km², A_o is a unit area of 1 km², and M, a, and b are fitting constants. The curves were extrapolated to 200 km², reasonable limit based on available data. The curves lie well below the NOAA Atlas 2 curves, show more change with frequency, and show less change with duration.

To highlight the change with the duration, the 2- and 100-yr event curves from Figs. 6-9 are replotted together on Fig. 10. The difference between the 30-, 60- and 120-min curves for a given frequency are small, and could be due to sampling variation. However, there are real differences between the families of curves of the 2-yr and 100-yr events. Clearly, the curves are consistent with features of summer thunderstorm rain in southwestern Arizona with the following characteristics: (a) the airmass thunderstorms are of short duration and limited areal extent, and (b) the extreme events tend to be confined to about the same areal extent as lesser events. Thus, up to about 2 h, depth-area ratios do not increase with duration. When storms move and deposit their heaviest precipitation some distance apart in succeeding h, area-point differences necessarily are reduced with increasing duration. The NOAA Atlas 2 depth-area curves reflect this characteristic. Many storms move fairly rapidly across the Walnut Gulch watershed, but these fast-moving events do not produce the maximum annual events. In the case of Walnut Gulch, the curves for respectively longer return periods plot below shorter return periods, because the standard deviation, which is most influential on the longer return periods in the Gumbel method, is less for the watershed averages than for point values.

Based on topography, the similarity of point rainfall frequencies, subjective experiences in observing thunderstorms, and qualitative confirmation from a few small watershed networks (with less record than Walnut

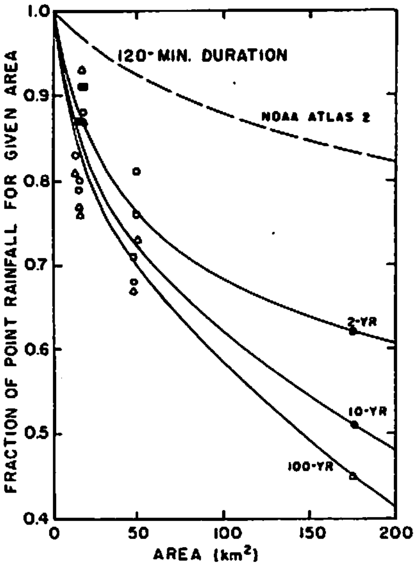

FIG. 8 Point-to-area conversion ratios for 2-h duration rainfalls for selected frequencies on Walnut Gulch.

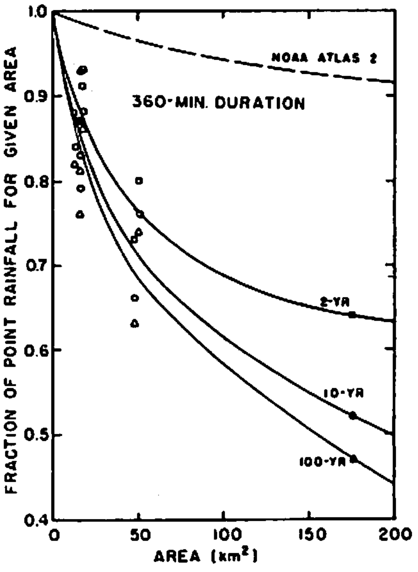

FIG. 9 Point-to-area conversion ratios for 6-h duration rainfalls for selected frequencies on Walnut Gulch.

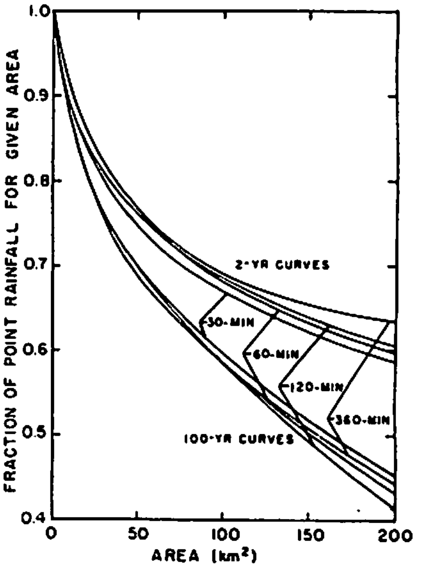

FIG. 10 Comparison of point-to-area rainfall ratios for 2-yr and 100-yr events for Walnut Gulch.

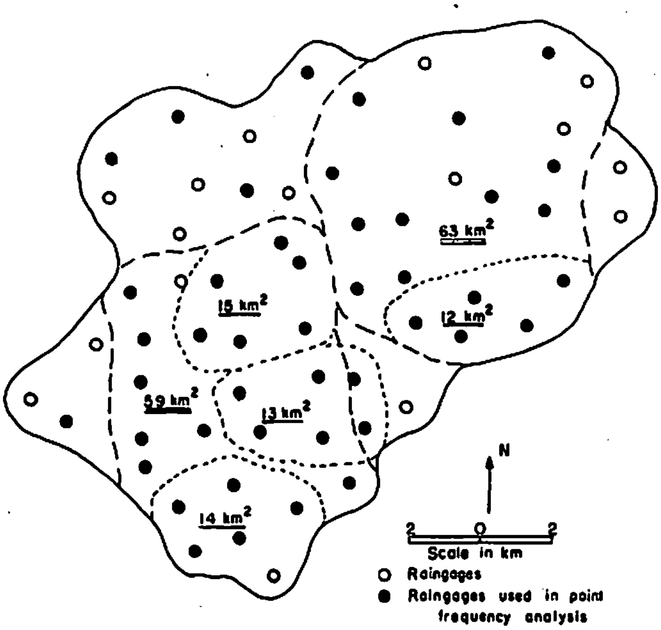

FIG. 11 Recording raingage network and subwatersheds used in determining frequency distributions for Alamogordo Creek.

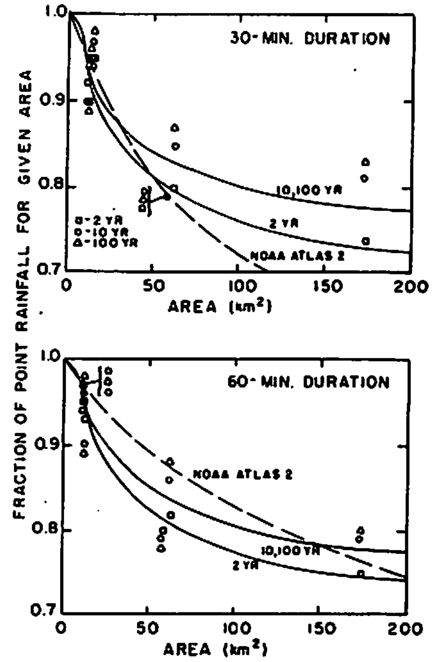

FIG. 12 (top) Point-to-area conversion ratios for 30-min duration rainfalls for selected frequencies on Alamogordo Creek.

FIG. 13 (bottom) Point-to-area conversion ratios for 60-min duration rainfalls for selected frequencies on Alamogordo Creek.

Gulch), the depth-area curves for Walnut Gulch are believed to be characteristic of much of southwestern Arizona, southwestern New Mexico, and north central Mexico.

Alamogordo Creek

The Alamogordo Creek Watershed data were analized identically to that for Walnut Gulch for 174, 59, 63, 15, 12, 13, 14 and 0 km^2 areas. The network is depicted in Fig. 11 along with the sub-areas. The average values were derived from all gages within the respective boundaries. Twenty-one well spaced gages with complete 20-yr records (1957-1976) were used to develop point frequencies for comparison to the 174 km^2 area, and all the indicated gages for the sub-area comparisons. For the latter, the same rules and procedures were used as for Walnut Gulch. In this case, the computed 100-yr depth-area curve lay above the 10-yr curve, but the difference was so slight that its reality is uncertain, and the 10-yr and 100-yr curves have been combined. The resulting depth-area curves are in Figs. 12-15.

The amounts and distributions of thunderstorm rainfall on the Alamogordo Creek Watershed are typical of the high plains in eastern New Mexico and western Texas. The extreme events can occur from either pure air-mass thunderstorms (as on Walnut Gulch) or a combination of frontal activity and convective heating (which is unusual on Walnut Gulch). The rainfalls that are largest both in area covered and depth result from the latter situation. Because of this, for similar durations and frequencies, maximum rainfall on Alamordo Creek is about 10 to 15 mm greater than that on Walnut Gulch.

The major events on Alamogordo Creek also cover larger areas than those on Walnut Gulch, and depth-area ratios were considerably higher than those on Walnut Gulch. Infact, for a 30-min duration the depth-area curve from NOAA Atlas 2 lies generally below the Alamogordo Creek curves (Fig. 12). For longer durations, Alamordo Creek curves decreased more rapidly than the NOAA Atlas 2 curves to a maximum difference at about 80 km^2, and then they approach the NOAA Atlas 2 curves. The range of annual average maximum watershed rainfall amounts varies much more on Alamogordo Creek than on Walnut Gulch because of the occasional massive frontal convective event. Average watershed rainfall was more variable than average point rainfall or area-to-point depth-area ratios for longer

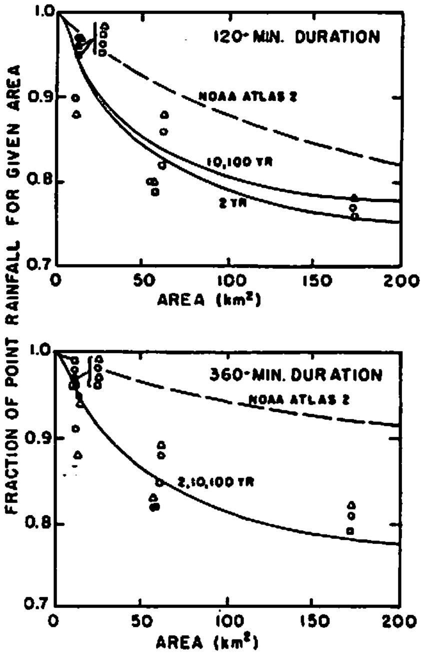

FIG. 14 (top) Point-to-area conversion ratios for 2-h duration rainfalls for selected frequencies on Alamogordo Creek.

FIG. 15 (bottom) Point-to-area conversion ratios for 6-h duration rainfalls for selected frequencies on Alamogordo Creek.

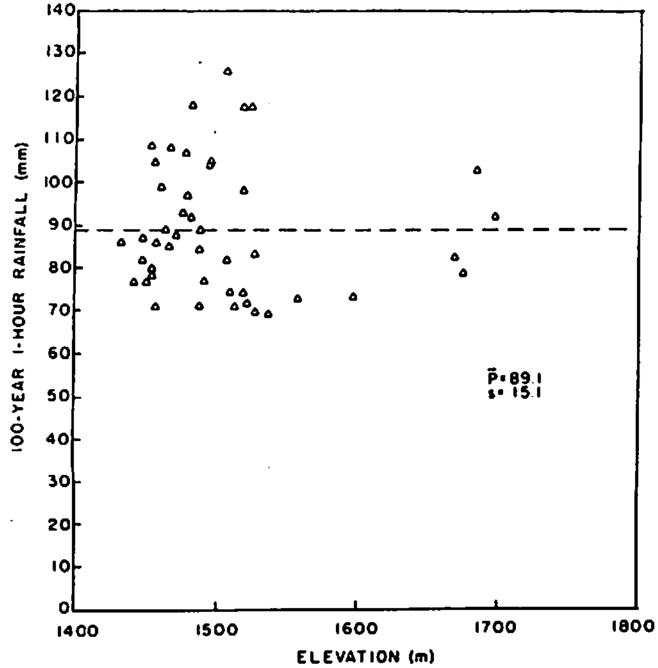

FIG. 16 Comparison of estimates of 100-yr, 1-h rainfall amounts with elevation for selected raingages on Alamogordo Creek.

return periods were greater than for shorter return periods.

Estimated 100-yr, 1-h rainfall amounts were plotted against gage elevation as a check on the assumption of random rainfall distribution on Alamogordo Creek (Fig. 16). Again, the range of values is greater at the lower elevations where there were more gages, but there is certainly no clear evidence of higher or lower values within the 300 m elevation range on the watershed.

DISTRIBUTION OF STORM RAINFALL

Once the engineer or hydrologist has determined the average watershed rainfall from the point frequency value and depth-area curve, there is still the question of the distribution of rainfall within the watershed during the storm. This is needed for runoff prediction based on the precipitation. For example, the 100-yr, 1-h rainfall at a fixed point within a watershed is significantly less than the largest 1-h rainfall expected once in 100 years somewhere within that watershed. Curves were developed from the Walnut Gulch and Alamogordo Creek raingage records for 50- and 150-km² watersheds to indicate this maximum as well as the watershed rainfall distribution in terms of the fraction of the watershed covered by percentages of the basic average (Figs. 17 and 18). The curves are averaged from the five storms on each basin with the largest total storm average basin rainfall in 20 yr. The curves do not necessarily apply to lesser storms expected on the average more often than once in about 5 yr.

As examples of the application of the curves for Walnut Gulch, the 100-yr, 1-h point rainfall averaged over the 40 stations in Fig. 3 is 75 mm (from tabulation not shown). From Fig. 7, the corresponding depth-area ratio for 150 km² is 0.50—average watershed rainfall would be about 38 mm. From Fig. 17, the maximum rainfall at some point within the watershed would be about 110 mm, and only 40 percent of the watershed would be covered by 38 mm or more of rainfall. Similarly, the 100-yr, 1-h point rainfall for Alamogordo Creek is about 90 mm. From Fig. 13, the depth-area ratio is 0.78—the average watershed rainfall is 70 mm. From Fig. 18, the maximum point rainfall at some point within the watershed would be about 140 mm, and about 40 percent of the watershed would be covered by 70 mm of rainfall or more. Similar curves were developed for rainfall distributions with 50 km² basins and are shown on Figs. 17 and 18.

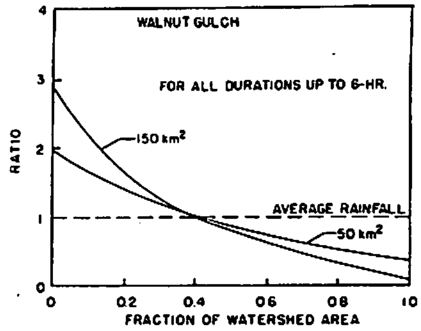

FIG. 17 Fraction of watershed equal to or exceeding average storm rainfall for Walnut Gulch.

The storms, from which Figs. 17 and 18 are derived, are in the 5- to 25-yr return period range. Based on 20 yr of record, it appears the curves would not be greatly different for 100-yr basin averages for Alamogordo Creek; whereas, Fig. 10 implies that the curves would be slightly steeper for the 100-yr return period at Walnut Gulch.

SUMMARY

New depth-area conversion curves for adjusting point rainfall amounts for given frequencies values to areal averages were developed from 20 years' data from densely spaced recording raingages on experimental watersheds of the USDA Southwest Rangeland Watershed Research Center in two climatic zones in the semi-arid Southwest. In southeast Arizona, at Walnut Gulch, the reductions from point-to-area were significantly greater than previously published curves, based on nationwide averages. These results offer opportunities for economy in design without relaxing frequency standards in climatologically similar areas. This is consistent with known limited area characteristics of the air-mass thunderstorms that produce most of the runoff.

New curves at Alamogordo Creek in northeastern New Mexico departed less from previous curves, but still indicate significant differences. The maximum departure of the new curves from the previous curves occurred at an area of approximately 100 km². The significant differences between Alamogordo Creek and Walnut Gulch

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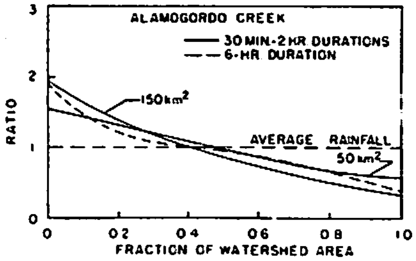

FIG. 18 Fraction of watershed equal to or exceeding average storm rainfall for Alamogordo Creek.

Rainfall/Watershed Relationships

(Continued from page 87)

illustrate the influence of frontal storms with strong convective activity associated with cold air-mass invasions from the north and east into eastern New Mexico.

Curves were also developed indicating maximum expected rainfall and typical areal distributions of rainfall depths during major precipitation events for 50- and 150-km² watersheds. This is neccessary information, along with the revised point-to-area curves, to realistically predict small watershed runoff from precipitation.

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