RAINFALL POINT INTENSITIES IN AN AIR MASS THUNDERSTORM ENVIRONMENT: WALNUT GULCH, ARIZONA

AIDA MENDEZ, DAVID C. GOODRICH, AND HERBERT B. OSBORN

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ABSTRACT: Point rainfall intensities for a given return period are often used to formulate design storms for rainfall/runoff models to simulate design floods. These design floods are in turn used to design bridges, culverts, and a variety of drainage and flood control structures. The projected rapid growth in the southwestern United States will require very substantial monetary investments in drainage infrastructure. Accurate estimates of point rainfall intensities are critical to ensure both safe designs while not wasting dollars in overdesign. Rainfall point intensities (accumulated rainfall depth over a specified duration) for 5-, 15-, 30-, and 60-minute durations for the 2-, 5-, 10-, 25-, 50-, and 100-year return periods were determined for southeast Arizona. Thirty-five years of rainfall record (1961 to 1995) were used in this study. The records came from 20 stations that were grouped into five sets of four independent stations to extend the rainfall records. The stations are in the USDA-ARS Walnut Gulch Experimental Watershed (WGEW), which is representative of large portions of the Southwest whose runoff generation is dominated by air-mass thunderstorms. The 5-, 15-, 30-, and 60-minute maximum intensities per year followed lognormal distributions. The mean point rainfall intensities of the five sets of gages are very close (between 0 and 11 percent) to the NOAA values of the 5-, 15-, 30-, and 60-minute durations for all return periods. Much larger differences between the mean point rainfall intensities for all durations were found when these results were compared to those of a previous study done with a shorter rainfall record (between 14 and 33 percent for the 25-, 50-, and 100-year return-periods). The difference between the largest and the smallest values of point rainfall intensities recorded by each group, for all durations, usually increases as the return period increases.
(KEY TERMS: meteorology/climatology; Walnut Gulch watershed; rainfall; frequency analysis; climate variability.)

INTRODUCTION

In the southwestern United States watershed storm runoff is dominated by intense, short duration convective rains of limited areal extent (Osborn and Laursen, 1973; Osborn et al., 1979; Osborn and Lane, 1981; Renard et al., 1993). The Walnut Gulch Experimental Watershed (WGEW) near Tombstone, Arizona (Figure 1), was selected by the U.S. Department of Agriculture (USDA)-Agricultural Research Service (ARS) for the study of these processes, the hydrology of semiarid watersheds, and the effects of watershed management on runoff response in these environments. The first recording rain gage in the WGEW was established in 1953, and since that time a myriad of research on semiarid watershed processes has been conducted (see USDA-ARS-SWRC, 2003).

In 1988, Osborn and Renard published a paper with rainfall intensity duration frequency values for one hour and less, based on data from the dense network of 80 rain gages in the WGEW completed in 1964. The authors compared their findings with values derived by extrapolation from the maps of 6-hour and 24-hour rainfall amounts having different frequencies published by the National Weather Service of the National Oceanic and Atmospheric Administration (NOAA) Atlas 2 series (Miller et al., 1973). The NOAA rainfall values are often used to design bridge openings, culverts, and other storm drainage and flood control structures. With the rapid growth of the semiarid Southwest and its related infrastructure, there are substantial economic and risk implications if proper sizing of drainage and flood control structures is not achieved.
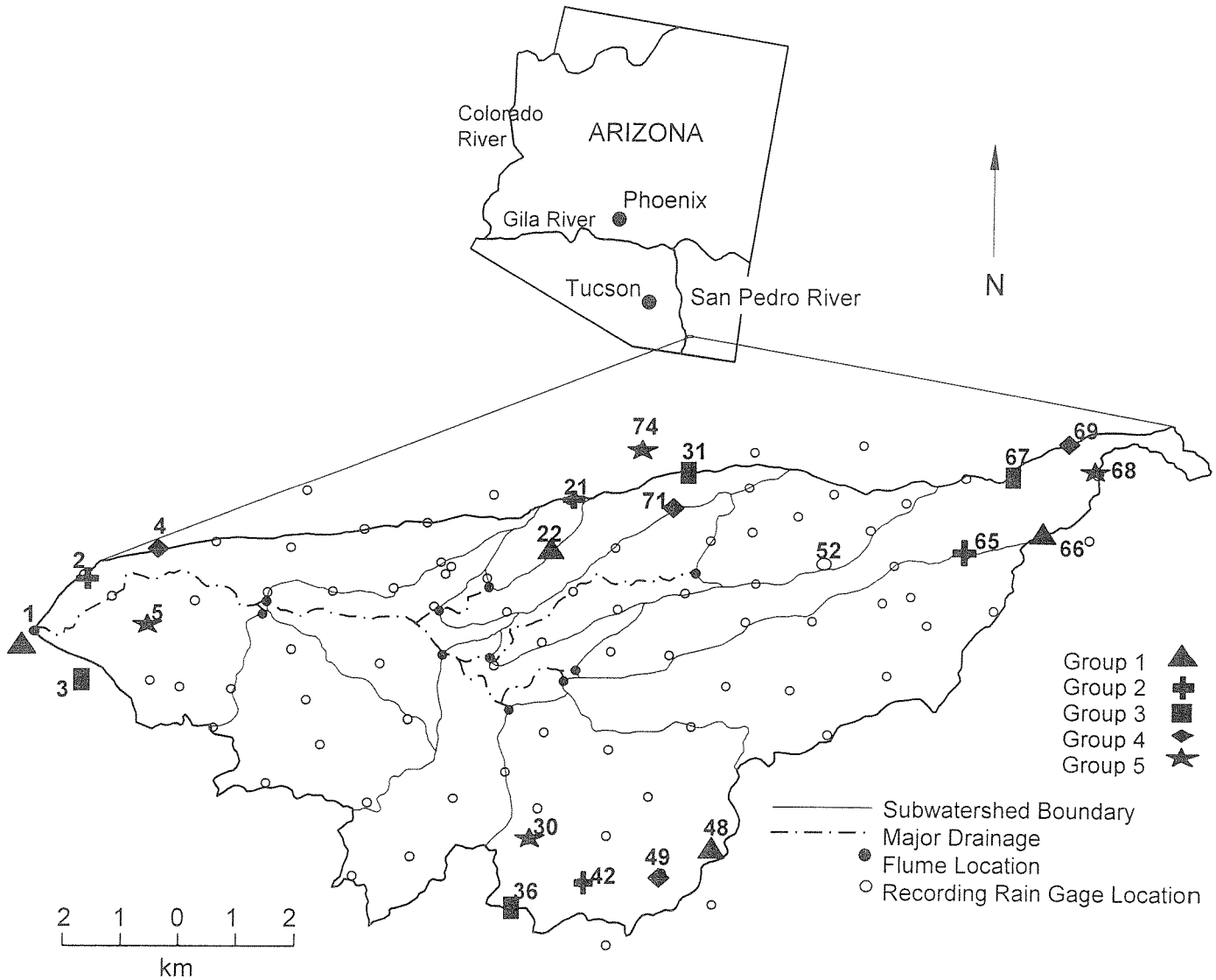
Figure 1. The USDA-ARS Walnut Gulch Experimental Watershed: Location Map, Groups
of Rain Gages Used in This Study, and Primary Runoff Measuring Flumes.

Osborn and Renard (1988) found that the estimates of short duration precipitation intensities, based on NOAA Atlas 2, were substantially lower than estimates based on data from the Walnut Gulch network for less frequent events (50- and 100-year frequencies). Since the publication of Osborn and Renard's 1988 paper, 15 years of additional data have been collected from the rain gage network to augment the original record. The objectives of this work were: (1) to calculate new estimates of 2-, 5-, 10-, 25-, 50-, and 100-year return period rainfall amounts for durations of 5, 15, 30, and 60 minutes using the additional information; (2) to compare the results of the current analysis with those presented by both Osborn and Renard (1988) and in the 1973 NOAA Atlas 2; and (3) to present possible implications of the results.

BACKGROUND

The Walnut Gulch Experimental Watershed covers 148 km² and surrounds the historical town of Tombstone, located in Southeastern Arizona (Figure 1). The watershed is representative of approximately 60 million hectares of brush and grass covered rangeland found throughout the semiarid southwest. Elevation in the watershed ranges from 1,250 m to 1,585 m MSL. Records from 1956 to 1980 indicated that the mean annual precipitation is 305 mm and varies considerably from season to season and from year to year; the annual precipitation varied from 170 mm in 1956 to 378 mm in 1977; summer rainfall varied from

104 mm in 1960 to 290 mm in 1966; and winter precipitation varied from 25 mm in 1966 to 1967 to 233 mm in 1978 to 1979.

Approximately two-thirds of the annual precipitation occurs as high intensity, convective thunderstorms of limited areal extent. The moisture source for these thunderstorms is primarily the Gulf of Mexico, although Pacific Ocean storms from southwest of Arizona also produce moisture surges that result in convective storms. Runoff occurs almost exclusively from these summer convective storms. Winter rains and occasional snow are generally low intensity events associated with slow moving cold fronts and are generally of greater areal extent than summer rains (Renard *et al.*, 1993).

Initially a "more than adequate" network of 30 recording rain gages was planned for the watershed, but due to limited funding, standard (nonrecording) gages were placed at some of the sites. Maximum runoff peaks recorded in 1954 and 1955 at two of the tributary stations pointed to the need for more precipitation gages. It was recognized that a 30-gage network was inadequate in estimating the rainfall producing these peaks. Recording rain gages were added as rapidly as funding permitted, but the largest peak discharge on Walnut Gulch during the period of 1954 to 1998 occurred in 1957, before the full network of over 80 recording rain gages was completed in 1964.

Currently, there are 93 rain gages in place, which constitutes the densest network of rain gages in the semiarid southwestern United States. Because of the long and detailed rainfall record (2-, 5-, 10-, 15-, 30-, and 60-minute rainfall intensities), these watershed data have been used widely in the United States and throughout the world to study hydrologic processes in semiarid lands.

PROCEDURE

An assumption of this study is that gages within the network are recording independent information and therefore it is possible to combine observations from independent sampling points to effectively extend the record. This assumption was tested in two different studies for rainfall amounts of various durations. In Reich and Osborn (1982), correlations in space between 13 gage pairs for maximum within storm five-minute rainfall and total storm rainfall were computed. By using storms totals or maximum amounts for a given duration, it was assumed that time variability was eliminated and the simple correlations between gages provided an indication of spatial rainfall variability. In the case of total storm

rainfall, gage pairs were included in the computation if at least one gage recorded 5 mm or more of rainfall. For maximum five-minute totals, one gage had to record 1 mm or more of rainfall. At least 80 storms per rain gage were used in the analysis.

An approximate test, t* (Storch and Zwiers, 1999), indicates that for $\alpha = 0.01$, a correlation coefficient, r = 0.27, is the value below which correlation is not significant. This value of r corresponds to distances greater than 8 km for storm totals; that is, rain gages separated by approximately 8 km provide independent samples for frequency analysis. The correlations are illustrated in Figure 2. The correlations decrease more rapidly for maximum five-minute depths than storm totals, as might be expected. Reich and Osborn (1982) also confirmed that extreme events occurred randomly over the watershed, noting a lack of correlation with gage elevation. In Nichols *et al.* (1993), spatial correlations were computed for summer daily, winter daily, and annual rainfall totals. For these longer durations, correspondingly longer correlation scales were found with none falling below the 99 percent significance level for distances up to 20 km.
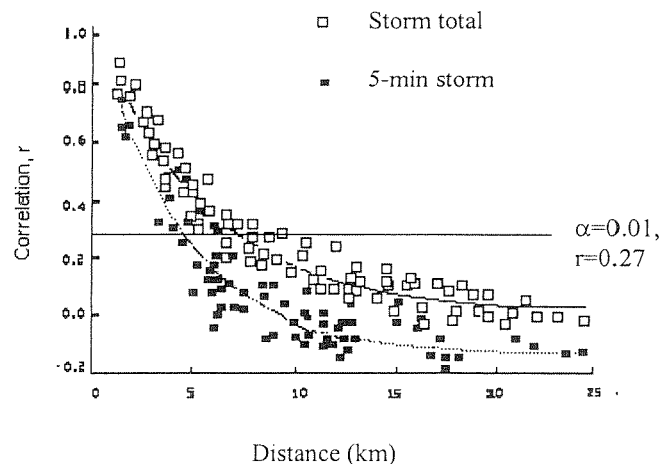
Figure 2. Correlation of Storm Total and Maximum Five-Minute Rainfall With Distance Between Rain Gage Pairs on Walnut Gulch (from Reich and Osborn, 1982).

Based on the assumptions of independent sampling points for storm totals for well separated rain gages noted above, a stationary process, and the validity of the station year method (Hafstad, 1942), Osborn and Renard (1988) created three records of 90, 91, and 92 years in length using three sets of four gages each. The 2-, 5-, 10-, 25-, 50-, and 100-year return period rainfall depths for 5-, 15-, 30-, and 60-minute durations were estimated. In the current work, five data sets (groups) were created using four gages each.

Each of the four gages making up a group was selected so that it would be separated by at least a distance of 8 km from any other rain gage in the group in any direction. The selected gage sets for each group are depicted in Figure 1.

The selection of the gages that were included in a set was based on the criteria of independency of rain gages and distribution of gages over the whole watershed. Each gage has 35 years of record (from 1961 to 1995), compared to fewer than 25 years of record in the original study. Each group of four gages has a total record length of 140 years, as opposed to 90 plus years in the original study. It was expected that adding approximately 50 additional years of record would improve estimates of maximum rainfall intensities.

An additional group (Group 6) was constructed by substituting Gage 52 for Gage 66 in Group 1. This group was included in the study (although it had two fewer years of data than the other groups) because in 1967 Gage 52 recorded the largest 60-minute rainfall depth recorded on Walnut Gulch to date (86.7 mm).

The Walnut Gulch Experimental Watershed database contains the maximum rainfall depth for each duration and rain gage on a per storm basis. The annual maximum depth per duration and rain gage for each summer season was selected from this database (n = 35). The 35 annual maximum values for each of the four independent gages forming a group were joined into a single series of 140 values, which were ranked and used for the frequency analysis. It should be noted that the annual maximum depths per gage for different durations may not come from the same storm.

According to previous studies (Reich and Osborn, 1982; Osborn and Renard, 1988), the data set formed by the combination of maximum annual rainfall intensities per duration from various rain gages follows a lognormal distribution. To be consistent with the previous studies and because of the good fit of the lognormal distribution to the data (R^2 is between 90 to 99 percent for the six groups and maximum rainfall intensities series), the lognormal distribution was utilized for the current analysis. However, in the NOAA Atlas 2 analysis, the maximum annual rainfall intensities per duration were fitted to a Gumbel distribution. In this study, frequency estimates using the Gumbel distribution were also computed for comparisons to NOAA Atlas 2 results.

The rainfall intensities were plotted on a logarithmic scale versus the inverse of the standard normal cumulative distribution function, z_p, of the Weibull plotting position probability, p, assigned to the ranked intensities (Stedinger *et al.*, 1992). The numeric value of p was determined from i (N + 1), where i is the rank of an intensity when the intensities are ordered from the smallest to the largest, and N is the number of intensity values.

The maximum point rainfall intensities for 5-, 15-, 30-, and 60-minute durations for the 2-, 5-, 10-, 25-, 50-, and 100-year return period rainfalls for the six groups of gages were computed using the linear model

$$Ln(\text{intensity}) = \beta_0 + \beta_1 z_p \tag{1}$$

where Ln is the natural logarithm; β_0 is the regression coefficient; β_1 is the regression coefficient; intensity is the rainfall intensity; and z_p is the inverse of the standard normal cumulative distribution function.

Note that the probability of an intensity occurring on a T-year return period is p = 1-(1/T). The numeric value of z_p was computed from (Stedinger *et al.*, 1992):

$$z_p = \frac{p^{0.135} - (1-p)^{0.135}}{0.1975} \tag{2}$$

RESULTS

Figure 3 illustrates the upper tail of the 5- and 30-minute maximum rainfall intensity series for the groups of gages with the highest 100-year event (Groups 2 and 5, respectively) and for the groups of gages with the lowest 100-year event (Group 3 in both cases). Figure 4 plots the upper tail of the 15- and 60-minute maximum rainfall intensity series for the groups of gages with the highest 100-year event (Groups 5 and 1, respectively) and for the groups of gages with the lowest 100-year event (Group 3 in both cases). The NOAA estimates are also depicted in the figures. The straight lines (full and dotted) are lognormal and are plotted as a reference for the readers. These figures indicate the good fit of the data to a lognormal distribution. Figure 3 shows that, for the five-minute duration, the percentage difference between rain gage Groups 2 and 3 is large and varies between 13 and 26 percent for the 25- to 100-year rainfall intensities. This is an indication of the variability of point rainfall within the watershed. For the 30-minute duration, the percentage difference between Groups 3 and 5 varies between 16 and 21 percent for the 25- to 100-year rainfall intensities.

Figure 4 shows the difference between the smallest and largest series of maximum point rainfall intensities for 15-minute durations recorded by the rain gages of Groups 3 and 5. For the 15-minute duration, the percentage difference between Groups 5 and 3 varies between 4 and 20 percent for all return period

Figure 3. Probability Plot, Using a Linear Scale on the x Axis and a Logarithmic Scale on the y Axis, of Intensity
Frequency Relationships for 5- and 30-Minute Durations for the Groups With the Highest
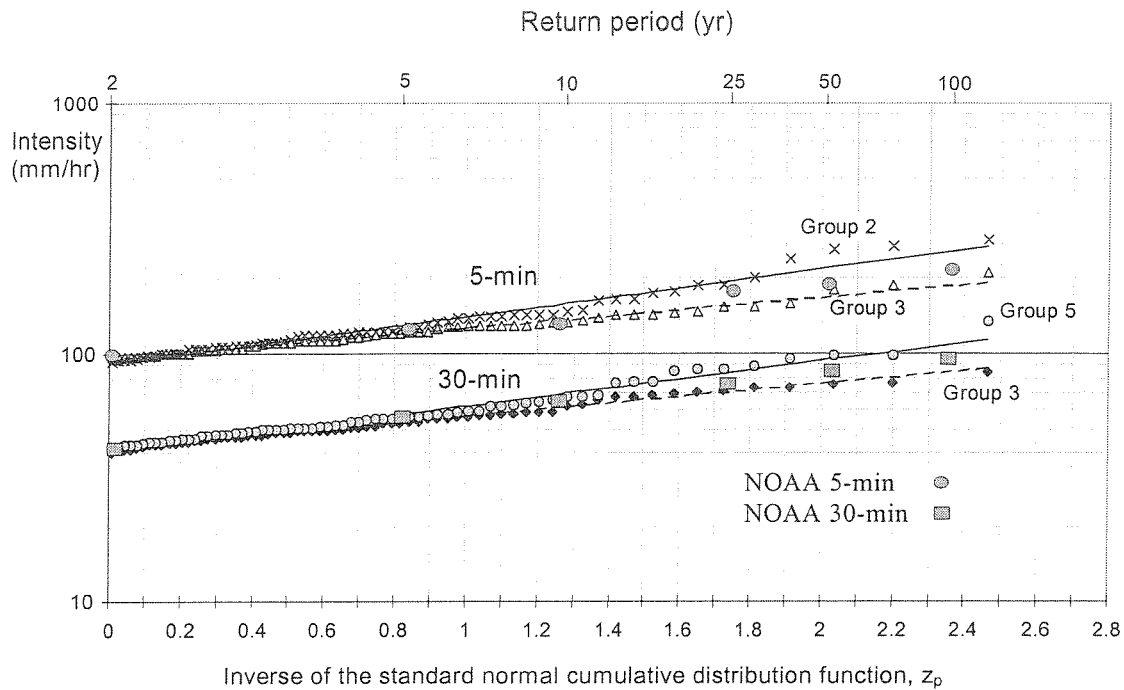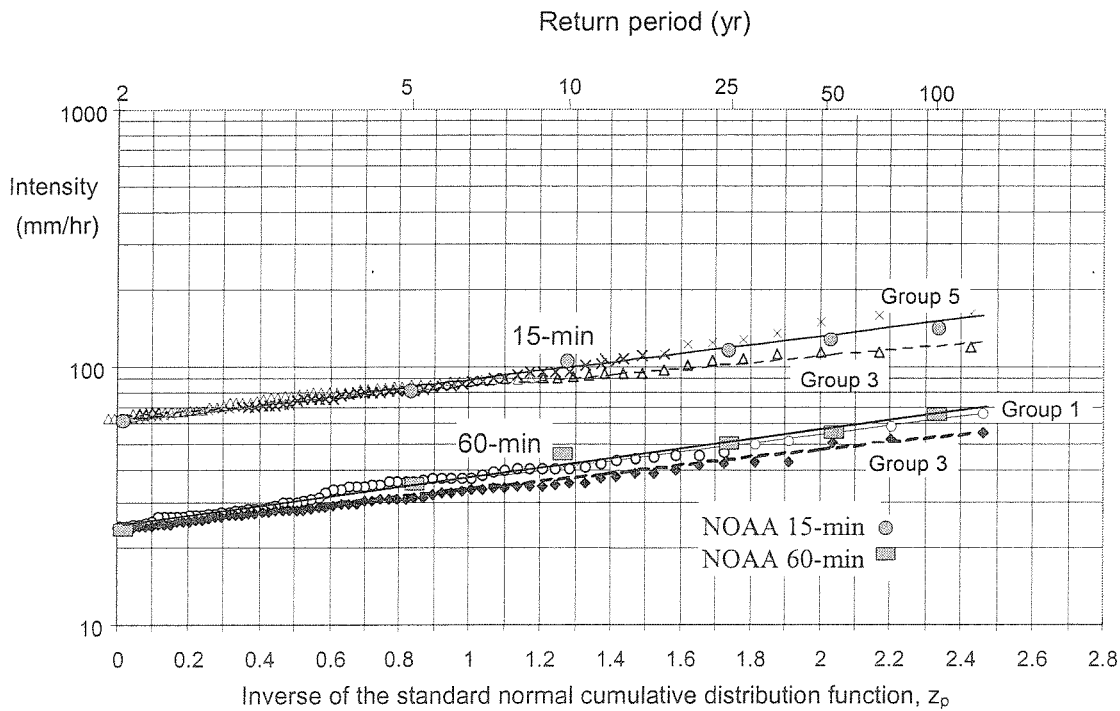and the Lowest Maximum Point Rainfall Frequency for a 100-Year Return Period.

Figure 4. Probability Plot, Using a Linear Scale on the x Axis and a Logarithmic Scale on the y Axis, of
Intensity Frequency Relationships for 15- and 60-Minute Durations for the Groups With the Highest
and the Lowest Maximum Point Rainfall Frequency for a 100-Year Return Period.

rainfall intensities, and increases with greater return-period. For the 60-minute duration, the percentage difference between Groups 1 and 3 varies between 5 and 17 percent for all return period rainfall intensities, and also increases with greater return period.

Tables 1 through 4 include the point rainfall intensities for durations of 5-, 15-, 30-, and 60-minutes, respectively, for the return periods mentioned above for the five groups of gages using the lognormal distribution. Also included are the mean of the five groups (1 to 5) that have the same record length; the mean of these groups (1 to 5) fitted using the Gumbel distribution; the intensities estimated using the lognormal distribution that include the observed maximum rainfall intensity (Group 6); the point rainfall intensities from NOAA and Walnut Gulch, as reported by Osborn and Renard (1988); and the 60-minute duration NOAA point rainfall intensities, as computed by the authors. The 60-minute duration NOAA point rainfall intensities for the return periods mentioned above were obtained using the 6-hour and 24-hour rainfall maps in NOAA Atlas 2, Vol. 8 (Arizona), along with the appropriate equations. The point rainfalls for shorter durations were obtained by applying the appropriate ratio to the 60-minute point rainfall intensities. The values in NOAA Atlas 2 are reported for the partial duration series. These values were transformed, following the indications in the Atlas, to point intensities for the annual duration series.

The mean of the maximum point rainfall intensities per duration and return period for the five groups represented in Tables 1 through 4 computed using the lognormal and the Gumbel distributions are very similar. The maximum difference between these sets of means was 4.29 mm/hr for the 100-year return period, 15-minute duration. However, the differences between the maximum point rainfall intensities (not shown in the table) of each group computed using the Gumbel and the lognormal distributions for the five-minute duration could be large (up to 26.9 mm/hr), especially for the 50-year and the 100-year return periods (not shown in the tables).

For the 5-minute and the 15-minute rainfall intensities and the return periods considered, the difference between the NOAA values and the mean of the five groups of rain gages is between 0 and 7 percent. The percentage difference for both durations between the mean and Group 6, which contains the rain gage with the largest intensity for the 60-minute duration, varies between 1 and 6 percent for all return period rainfall intensities. For both durations, Osborn and Renard (1988) reported higher point values for the 25-, 50-, and 100-year frequency rainfall intensities than for any of the six groups of gages and for the mean of Groups 1 to 5.

Due to the nature of the analog weighing rain gages, with 24-hour paper charts (one rotation of the recording drum per day), as the rainfall duration

TABLE 1. Five-Minute Duration Point Intensities for Various Return Period
Rainfalls in the Walnut Gulch Experimental Watershed, Annual Series.

	Five-Minute Intensity (mm/hr)						
	2 Year	5 Year	10 Year	25 Year	50 Year	100 Year	Maxpoint**
Group 1*	94.6	126.3	147.1	173.2	192.5	211.5	304.8
Group 2	90.9	130.9	158.8	195.2	223.1	251.3	283.5
Group 3	95.6	121.8	137.4	157.1	171.4	185.2	208.8
Group 4	89.1	118.4	137.6	161.7	179.4	196.8	189.0
Group 5	89.1	125.8	150.9	183.5	208.1	232.9	277.4
Mean	91.9	124.5	146.3	174.1	194.9	215.5	252.7
MeanG[1]	93.7	125.8	147.1	174.0	193.9	213.7	252.7
Group 6	96.5	126.2	145.3	169.1	186.5	203.5	304.8
OR88[2]	84.0	122.4	144.0	198.0	228.0	259.2	250[4]
NOAA[3]	91.2	122.4	144.0	182.4	198.0	216.0	-[5]

Notes:
  *Groups 1 to 6 – Values estimated using a lognormal distribution.
  **Observed maximum intensity.
  [1]Mean of five-minute duration intensities of Groups 1 through 5 obtained using Gumbel distribution.
  [2]Data from Table 1 in Osborn and Renard (1988).
  [3]Data from Table 1 in Osborn and Renard (1988).
  [4]Data point from Figure 1 in Osborn and Renard (1988).
  [5]Not available.

TABLE 2. Fifteen-Minute Duration Point Intensities for Various Return Period
Rainfalls in the Walnut Gulch Experimental Watershed, Annual Series.

| | Fifteen-Minute Intensity (mm/hr) | | | | | | |
	2 Year	5 Year	10 Year	25 Year	50 Year	100 Year	Maxpoint**
Group 1*	63.4	83.7	96.8	113.3	125.3	137.2	166.1
Group 2	64.7	85.9	99.7	117.0	129.7	142.3	141.0
Group 3	64.1	80.5	90.8	103.3	112.3	121.0	116.3
Group 4	60.3	78.1	89.4	103.5	113.7	123.7	133.7
Group 5	60.3	83.8	99.6	119.9	135.2	150.5	157.5
Mean	62.6	82.4	95.3	111.4	123.3	134.9	142.9
MeanG[1]	61.3	82.1	95.9	113.4	126.4	139.2	142.9
Group 6	64.7	85.1	98.4	114.9	127.1	140.0	166.1
OR88[2]	58.4	91.2	112.0	137.2	152	177.6	170[4]
NOAA[3]	60.8	86.4	101.6	116.8	127.2	142.4	_[5]

Notes:

    *Groups 1 to 6 – Values estimated using a lognormal distribution.
    **Observed maximum intensity.
    [1]Mean of 15-minute duration intensities of Groups 1 through 5 obtained using Gumbel distribution.
    [2]Data from Table 1 in Osborn and Renard (1988).
    [3]Data from Table 1 in Osborn and Renard (1988).
    [4]Data point from Figure 1 in Osborn and Renard (1988).
    [5]Not available.

TABLE 3. Thirty-Minute Duration Point Intensities for Various Return Period
Rainfalls in the Walnut Gulch Experimental Watershed, Annual Series.

| | Thirty-Minute Intensity (mm/hr) | | | | | | |
	2 Year	5 Year	10 Year	25 Year	50 Year	100 Year	Maxpoint**
Group 1*	42.1	58.0	68.8	82.5	92.8	103.1	103.0
Group 2	43.8	57.6	66.6	77.8	86.0	94.1	97.5
Group 3	41.7	53.7	61.5	71.0	77.9	84.6	84.1
Group 4	40.0	54.3	63.7	75.6	84.5	93.3	98.0
Group 5	40.9	57.9	69.5	84.7	96.2	107.8	135.1
Mean	41.7	56.3	66.0	78.3	87.5	96.6	103.6
MeanG[1]	41.0	55.9	65.7	78.2	87.4	96.5	103.6
Group 6	42.5	59.3	70.6	85.3	96.3	107.3	126.1
OR88[2]	42.0	63.6	76.0	96.4	111.6	127.0	112.5[4]
NOAA[3]	43.2	58.4	68.6	78.8	88.8	96.0	_[5]

Notes:

    *Groups 1 to 6 – Values estimated using a lognormal distribution.
    **Observed maximum intensity.
    [1]Mean of 30-minute duration intensities of Groups 1 through 5 obtained using Gumbel distribution.
    [2]Data from Table 1 in Osborn and Renard (1988).
    [3]Data from Table 1 in Osborn and Renard (1988).
    [4]Data point from Figure 1 in Osborn and Renard (1988).
    [5]Not available.

TABLE 1. Sixty-Minute Duration Point Intensities for Various Return Period
Rainfalls in the Walnut Gulch Experimental Watershed, Annual Series.

| | Sixty-Minute Intensity (mm/hr) | | | | | | |
	2 Year	5 Year	10 Year	25 Year	50 Year	100 Year	Maxpoint**
Group 1*	24.8	34.6	41.3	49.9	56.5	63.0	65.5
Group 2	23.6	33.0	39.5	47.8	54.0	60.3	63.3
Group 3	23.6	31.4	36.5	42.9	47.6	52.3	55.6
Group 4	23.8	32.0	37.4	44.2	49.2	54.2	55.0
Group 5	23.8	33.8	40.6	49.4	56.2	63.0	75.8
Mean	23.9	33.0	39.0	46.9	52.7	58.6	63.0
MeanG[1]	24.1	32.6	38.3	45.4	50.7	56.0	63.0
Group 6	24.3	34.8	42.1	51.7	59.0	66.4	86.7
OR88[2]	25.0	37.5	49.0	60.0	70.0	76.0	75.0[4]
NOAA[3]	26.4	36.5	44.0	50.8	55.9	64.5	_[5]

Notes:
  *Groups 1 to 6 – Values estimated using a lognormal distribution.
  **Observed maximum intensity.
  [1]Mean of 60-minute duration intensities of Groups 1 through 5 obtained using Gumbel distribution.
  [2]Data from Figure 2 in Osborn and Renard (1988).
  [3]Data derived by the current authors.
  [4]Data point from Figure 1 in Osborn and Renard (1988).
  [5]Not available.

decreases, the error in digitizing the pen trace of cumulative rainfall increases. With the assumptions made (independent sampling points for well separated rain gages, a stationary process, and the validity of the station year method), it would be expected that a longer record would provide an improved estimate of the values of point rainfall intensities for greater return periods than would a shorter record. However, to be conservative, when designing runoff control structures, the largest point rainfall value could be used, instead of the mean.

For the 30-minute duration (Table 3), the percentage difference between the mean point frequency for each return period rainfall and the NOAA values is between 1 and 4 percent; whereas the difference between the mean point frequency for each return-period rainfall and those values reported by Osborn and Renard (1988) varies between 1 and 32 percent, and increases to 23 to 32 percent for the 25-, 50-, and 100-year return period rainfalls. For the 60-minute duration (Table 4), the percentage difference between the mean point frequency for each return period rainfall and the NOAA values derived by the current authors (Table 4, footnote 3) is between 6 and 11 percent. The difference between the mean point frequency for each return period rainfall and the values reported by Osborn and Renard (1988) (Table 4, footnote 2) increases to 26 and 33 percent for the 10-, 25-, 50-, and 100-year return period rainfalls. For the 30- and 60-minute durations, the percentage difference

between the groups with the largest and the smallest 100-year point frequency rainfalls, varies between 2 and 21 percent, for all return period rainfalls. For the 30- and 60-minute durations, the percentage difference between the mean and Group 6, which contains the rain gage with the largest intensity for the 60-minute duration, varies between 2 and 13 percent for all return period rainfalls. For both durations, Osborn and Renard (1988) reported higher values for the 25-, 50-, and 100-year frequency rainfall intensities than any of the six groups of gages in the current analysis.

The maximum point rainfall intensities for a 30-minute duration (126.1 mm/hr), and a 60-minute duration (86.7 mm/hr) were recorded on October 9, 1967, at gage 52 (column 7 in Tables 3 and 4, respectively). Based on the fitted line to the upper tail of the lognormal distribution of the sixth group of gages, the return periods for these rainfall intensities are 334 and 500 years, respectively. The difference in the samples of the point rainfall intensities for the 30- and 60-minute durations is what causes the different return periods.

DISCUSSION

An accepted method of analysis that assumes that a longer data set derived from combining data sets from independent recording rain gages provides an

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improved estimate of rainfall intensity occurrence than shorter record from a single gage was applied to the rainfall intensity data (Osborn and Renard, 1988). The Walnut Gulch watershed is subdivided into subwatersheds and runoff at the outlet of the subwatersheds is recorded, as is runoff at the outlet of Walnut Gulch. The runoff records provide additional information regarding rainfall intensity and volume.

In this study, it was found that estimates of rainfall intensities for the less frequent events were lower than those predicted by Osborn and Renard (1988) due to the extended length of record used in this study, which contained a greater proportion of events with lower intensities. When the Osborn and Renard (1988) study was conducted, only about 20 years of record per gage were used and the earlier part of the records (records from the late 1950s to the 1970s) had more weight on the overall data set than it has on this later study. This may be the reason for the discrepancy between the present results and those obtained by Osborn and Renard (1988), since up to the early 1970s, more "extreme" flood peaks were estimated or recorded than in later years: the maximum flood peak at all main channel stations occurred in 1957, which implies that the maximum rainfall also occurred in 1957.

The second largest peak discharge at the main channel stations, and at two of the major tributary stations, occurred in 1964. The maximum one-hour rainfall was recorded in 1967, producing major flood peaks on several of the smaller watersheds and the main channel stations. This suggests a possible bias toward lower intensities in analyses of rainfall weighted toward the latter part of the Walnut Gulch rainfall record. On the other hand, the mean total summer rainfall of four rain gages (1, 22, 48, and 66) distributed throughout the Walnut Gulch watershed, does not show a decreasing trend (Figure 5), which agrees with the results reported for summer rainfalls by Nichols et al. (2002).

It should be noted, though, that the trends of annual or mean rainfall from a set of selected gages typically have little or no relationship to the occurrence of record events on Walnut Gulch. Still a step change in over 40 environmental variables over North America and the Pacific suggests a change in decadal-scale climate variability in or near 1976 (Ebbesmeyer et al., 1991). This change is attributed to a post-1976 period when the Southern Oscillation locked into an El Niño phase (Swetnam and Betancourt, 1998). This change is attributed to a phenomenon with a longer period, deemed the Pacific Decadal Oscillation (PDO) (Bond and Harrison, 2000), which typically runs in cycles of between 20 and 30 years in contrast to a one- to two-year cycle of El Niños.
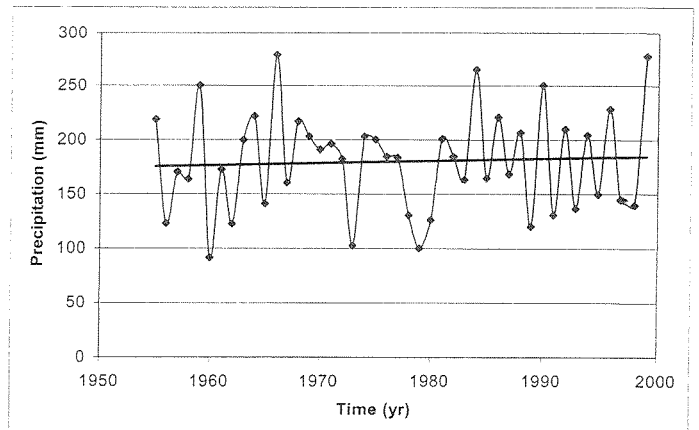

Figure 5. Mean Total Summer Rainfall
Based on Four Rain Gages.

Trenberth and Hoar (1996) noted that the frequent occurrences of El Niño and the extended 1991 to 1995 El Niño should only occur with a return period of 1,000 years. Swetnam and Betancourt (1998) further noted that in the Southwest, this protracted period of post-1976 El Niño events produced a string of wet winters and springs and erratic summer rainfalls. Impacts on summer monsoonal rainfall are less conclusive. Harrington et al. (1992) noted a tendency for July rainfall to be drier in years following an El Niño event. The same study indicated no significant tendencies for August rainfall.

In Tombstone, for the period of 1897 to 1997 the lowest continuous five-year average of monsoonal precipitation (June to October) occurred from 1991 to 1995. The analyses presented in this paper are statistically accurate, but we suggest that any user of these analyses be aware that early Walnut Gulch records suggest greater rainfall intensities. Evidence of large, decadal scale climatic variability potentially affecting the post-1976 record may invalidate the assumption of stationarity and a single sample population, although a longer period of record is needed to tell whether this is a decadal scale variation in climate as suggested by a change in the PDO (Bond and Harrison, 2000) or long term change in the background climate.

Webb and Betancourt (1990) noted that vastly different flood frequency estimates are obtained when events resulting from El Niño years are segregated from non-El Niño years. The true rainfall frequencies may lie between the mean values in this study and the estimates in the earlier paper by Osborn and Renard (1988). There is an indication that in the post-1997 period the PDO is coming out of the El Niño phase and strong monsoon seasons with numerous high intensity rainfall events were observed in 1999

and 2000. However, the number and intensity of rainfall events in the 2001 and 2002 monsoon season were small. A future area of research would be to combine what we know from the early runoff record on Walnut Gulch with the rain gage record to derive a more certain estimate of rainfall frequencies.

There are a number of implications of the current findings for infrastructure development in the Southwest. First might be that the often employed assumption of climatic stationarity should be further called into question given increasing evidence of climatic variation on decadal scales. Record lengths to derive frequency estimates will have to be much longer to adequately capture variability on these time scales. Although paleo records, such as tree rings (Swetnam and Betancourt, 1998), do not have the resolution to discern rainfall intensity patterns at the event scale, they may be employed as proxies to put the period of record used to compute rainfall intensity frequencies in context.

There are important implications for infrastructure development in the rapidly growing Southwest because point rainfall intensities of a given return period frequency are often used as design storm inputs to rainfall/runoff models to compute corresponding design floods. These flood values are in turn used to size bridges, culverts, and a variety of detention and flood control structures. The lower point rainfall intensities found in this study versus the earlier work by Osborn and Renard (1988) could therefore have profound economic implications if adopted for design purposes. However, given the increasing evidence of decadal scale climatic variability, caution should be exercised in adopting lower point intensities that may largely be the result of Walnut Gulch records now including a greater proportion of the El Niño phase (approximately 1976 to 1997) of the Pacific Decadal Oscillation.

SUMMARY

Statistical analyses of comparative records from recording rain gages on the Walnut Gulch watershed are, by necessity, limited to periods with records of identical length. Rainfall frequencies for selected durations and return periods were estimated from Walnut Gulch rainfall records (1961 to 1995), based on assumption of stationarity and the station year method. The mean point rainfall intensities of the five sets of gages are very close (between 0 and 11 percent) to the NOAA values of the 5-, 15-, 30-, and 60-minute durations for all return periods. Much larger differences between the mean point rainfall intensities for all durations and those from Osborn and Renard's

(1988) were found (between 14 and 33 percent for the 25-, 50-, and 100-year return periods). The difference between the largest and the smallest values of point rainfall intensities recorded by each group, for all durations, usually increases as the return period increases. As noted in the discussion section, careful consideration is warranted in selecting these, or other, point rainfall intensities for design storm purposes given the increasing evidence of decadal scale climatic variability and its influence on the period of record over which rainfall intensity frequencies are computed.

APPENDIX: NOTATIONS

The following symbols are used in this paper:

i = rank of an intensity;

N = number of intensity values;

p = Weibull plotting position probability;

r = correlation coefficient;

T = length of a return period;

z_p = inverse of the standard normal cumulative distribution function;

α = 0.01;

β_0 = regression coefficient; and

β_1 = regression coefficient.

Subscripts

p = probability.

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