Quantifying Extreme Rainfall Events and Their Hydrologic Response in Southeastern Arizona

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Abstract: Hydrologists are concerned with high-intensity rainfall and peak runoff rates for stormwater infrastructure designs, post-event assessments, and mitigation of environmental impacts. In the southwestern United States the need for accurate information about these rates is increasingly important as population growth and associated development are projected to exceed national averages. Design storm totals for various durations and return period frequencies are routinely derived from the National Oceanic and Atmospheric Administration (NOAA) Atlas 14 and are commonly used as input to hydrologic models to estimate peak runoff rates and runoff volumes. For the southwestern United States during the North American Monsoon, NOAA relies on sparse rain gauge networks to measure rainfall from limited area convective storms primarily at daily time steps and estimates of subdaily event intensities are derived by temporal downscaling from a few point locations. The USDA, Agricultural Research Service, Southwest Watershed Research Center (SWRC) operates the Walnut Gulch Experimental Watershed (WGEW) in the vicinity of Tombstone, Arizona. SWRC maintains a database of 60 years of subdaily, high temporal-precision rainfall intensities and runoff rates for WGEW. Updated, temporally extended, rainfall intensity-duration-frequency relations for WGEW are presented. The current analysis includes intensity-duration-frequency relations for July, August, and September for 53 years, 1961–2013, for durations of 2, 5, 10, 15, 30, and 60 min and return periods of 2, 5, 10, 25, 50, 100, and 1,000 years. The 149 km^2 WGEW is large enough to select groups of four rain gauges whose event totals are independent. This allows combining of the four independent gauges' 53-year time series into a longer time series of 212 years. A comparison of WGEW-generated intensity-duration-frequency curves to those of NOAA Atlas 14 indicated good agreement. However, across the range of durations, many observed events on WGEW from gauges not used in the frequency analysis are much greater than the estimated 100-year event. The dense gauge network appears to capture a substantially greater number of low-frequency, extreme rainfall events not typically observed in sparse networks. To assess the hydrologic consequences of these extreme events they were used as input to a well-tested watershed model for a small gauged watershed that did not experience events of similar magnitude. Simulated runoff volumes and peak discharge rates were up to four times as large as the largest observed runoff event of record. These analyses offer insights into the benefit of long-term watershed research with spatially dense and high temporal resolution observations. **DOI: 10.1061/(ASCE)HE.1943-5584.0001270.** *© 2015 American Society of Civil Engineers.*

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Introduction

Design storms are critical for hydrologic engineering as inputs to watershed models or procedures from local permitting agencies for the design of storm water conveyance, flood control structures, and flood inundation areas (Kimoto et al. 2011; Lee and Ho 2008; Cheng et al. 2001; Chow et al. 1988). Design storms are typically expressed as intensity-duration-frequency (IDF) curves from long records of observed precipitation data under an assumption of stationarity. They are routinely derived from the National Oceanic and Atmospheric Administration (NOAA) Atlas 14 (http://www.nws.noaa.gov/oh/hdsc/currentpf.htm). "The Atlas is intended as the official documentation of precipitation frequency estimates and associated information for the United States." (Bonnin et al. 2011). In the southwestern United States, sparse rain gauge networks measure rainfall primarily at daily time steps and estimates of subdaily and subhourly event intensities are derived by temporal downscaling from a few point locations. To derive subhourly intensities for the NOAA Atlas 14 (hereafter referred to as NOAA14), a few stations with n-minute rainfall resolution are linearly scaled to 60 min observations from colocated stations. N-minute stations measure rainfall at 5-min intervals, which can be summed to durations of 10, 15, 30, and 60 min. The scaling factors are calculated for six regions in the southwestern United States and are averaged over the entire area. Only three such colocated, N-minute stations are in Arizona, and none in Cochise County, which is located in southeastern Arizona.

The USDA Agricultural Research Service (ARS) Southwest Watershed Research Center (SWRC) operates the Walnut Gulch Experimental Watershed (WGEW) encompassing 149 km^2 in Cochise County, Arizona (31°43′ N, 110°41′ W), which surrounds the town of Tombstone, Arizona (Renard et al. 1993;

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Moran et al. 2008). The watershed is contained within the upper San Pedro River Basin, which encompasses 7,600 km^2 in Arizona and Sonora, Mexico. The climate is classified as semiarid, with mean annual temperature at Tombstone of 17.7°C and mean annual precipitation of 318 mm. The precipitation regime is dominated by the North American Monsoon with slightly more than 60% of the annual total coming during July, August, and September. Summer events are localized, short-duration, high-intensity convective thunderstorms and virtually all runoff is generated by these storms as rainfall excess whereby infiltration capacity is exceeded. High-density, rain gauge networks, such as WGEW, recording at subhourly resolution are needed to capture the spatial variability and high intensities of these short-duration events.

From an initial network of 30 recording rain gauges installed in the 1950s, WGEW currently has 88 recording rain gauges (Fig. 1). By 1961, 59 rain gauges had been installed covering the complete watershed. Additional rain gauges were installed after 1961 (Goodrich et al. 2008b). Conversion from mechanical-weighing, analog-recording gauges to electronic-weighing, digital-recording gauges was completed in 1999 (Keefer et al. 2008). Prior to 2000, the temporal resolution of the precipitation data (one revolution of the chart drum in 24 h) from these gauges was limited by the precision of mechanical clocks and the digitizing algorithm to convert from analog pen trace to digital format, generally about 5–10 min, but occasionally 2 min. Since 1999, the digital recording temporal resolution is 1 min. Starting in 2003, the SWRC has expanded the network outside of the WGEW within the upper San Pedro River basin adding another 27 rain gauges.

Much has been documented in the literature about rainfall and runoff processes in monsoon-dominated regions of the

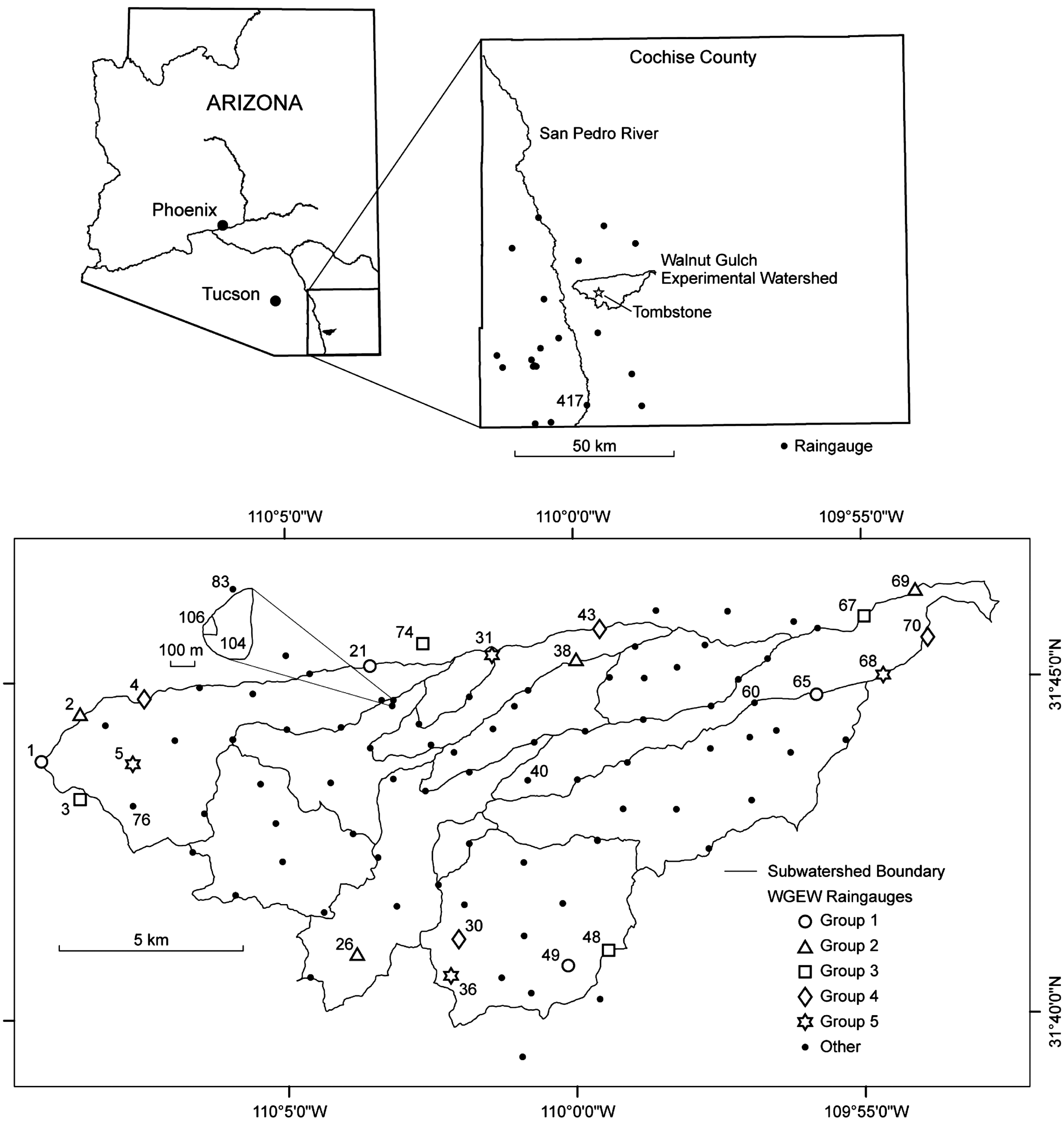

Fig. 1. USDA-ARS Walnut Gulch Experimental Watershed, rain gauge network and groups of gauges used in this study; Rain Gauge 40a is colocated with Rain Gauge 40

southwestern United States based on WGEW data and analysis. Osborn and Lane (1969) reported that for watersheds less than 5 ha, event runoff volume was highly correlated to total rainfall and peak discharge rate was correlated to 15-min rainfall intensity. Osborn and Laursen (1973) investigated runoff producing rainfall events for watersheds less than 250 km^2 and found 30-min rainfall intensity to be highly correlated to runoff at these scales. Osborn et al. (1979) reported that the necessary rain gauge density to capture the spatial variability of runoff producing rainfall events was a 300–800 m grid for watersheds up to 200 km^2. Correlating 15-min rainfall amounts between pairs of gauges, the density of rain gauges on the 150 km^2 watershed needed to be about 1,400 rain gauges and for storm total amounts about 230 rain gauges. This density of rain gauges was never achieved because of limited funding and difficulty of access to all areas of WGEW. Osborn et al. (1980) identified an areal reduction factor that was used to revise those developed by NOAA for the southwestern United States (Zehr and Myers 1984).

Reich and Osborn (1982) made use of the dense rain gauge network to examine the hypothesis of independence of sampling points for extension of data records by the station-year method and determined that the lognormal distribution is superior to other distributions for 5–120-min rainfall. Making use of the station-year method, Osborn and Renard (1988) compared estimates of return period rainfall intensities for various durations to the NOAA Atlas 2 (Miller et al. 1973) estimates and noted that differences could contribute to underestimation of runoff peaks and volumes. Mendez et al. (2003) also made use of the station-year method to produce a 50% longer data set than Osborn and Renard (1988), and found consistent results between WGEW data estimates and NOAA Atlas 2, but cautioned that climate variability and decadal-scale trends can impact the point rainfall used for the estimations of intensities.

A relatively large number of recent extreme rainfall events observed on or near WGEW motivated a review of intensity-duration-frequency (IDF) relations. If low-frequency extreme events are not reflected in NOAA14 IDF relations, storm water infrastructure designed to protect high-value construction may be inadequate. The largest single point rainfall storm total of 109 mm occurred on August 11, 2000, with the highest 60-min intensity, 100 mmh^{-1}, observed on WGEW. This event caused one of the largest recorded flows through the main channel of 155 $m^3 s^{-1}$ and total volume of 615,600 m^3. Less than 30 km from WGEW, on July 9, 2013, an SWRC rain gauge (RG417, indicated in Fig. 1) located along the San Pedro River near Hereford, Arizona, received over 200 mm in less than 3 h. A nearby rain observer reported over 174 mm for the same event (Rainlog.org 2014). This rainfall event caused flooding on the San Pedro River washing out the road surface of the Hereford Bridge downstream from the SWRC rain gauge. During the 60 year record of rainfall measurements on WGEW other extreme rainfall events have been recorded with large amounts recorded in short intervals from 2 to 60 min.

The purpose of this study is to quantify the estimated return periods of observed extreme rainfall events using IDF relations and to estimate the hydrologic response to these events by simulating small watershed runoff with a rainfall-runoff model. In this pursuit, the approach is to (1) recalculate the IDF relations for WGEW with a 53 year dataset and compare them to NOAA14 estimates; (2) compare intensity-durations for several extreme rainfall events measured on or near WGEW to NOAA14 frequency estimates; and (3) use several of the extreme events as input to the well-tested watershed model KINEROS2 (Goodrich et al. 2012; Kennedy et al. 2013) on a small gauged subwatershed of the WGEW, where the extreme rainfall events were not observed, to simulate peak runoff rates and event runoff volumes and compare them to observed runoff at this small watershed. In the next section a description of the preparation of annual maximum intensities and the use of the station-year method to extend the time-series are provided.

Data Preparation

To verify use of the station-year method for effectively lengthening the rainfall observations record for frequency analysis, the methods used in previous studies by Osborn and Renard (1988) and Mendez et al. (2003) were employed. Five groups of four rain gauges were selected based upon an assumption of spatial independence of summer (July, August, and September) thunderstorms. The correlation of event amounts between two rain gauges was calculated for 1,711 rain gauge pairs from the 59 rain gauges operational from 1961 to 2013. A paired event is defined as rain at one or both gauges and at least one gauge must have received at least 5 mm of rainfall. The average number of events per rain gauge was 1,829, ranging from 1,702 to 1,978, and the total of number of paired events was 107,908. Distances between rain gauges ranged from 0.9 to 24.3 km.

To determine the significance of correlation, von Storch and Zwiers [1999, p. 149, Eq. (8.7)] present an approximate test of the null hypothesis, $H_0{:}\rho_{xy} = 0$, given by

$$T = |\hat{\rho}_{xy}|\sqrt{\frac{(n-2)}{(1-\hat{\rho}_{xy}^2)}} \qquad (1)$$

where T is a test statistic to be compared to critical values from the Student's t distribution, and $\hat{\rho}$ is an estimator of the correlation, ρ, between variables x and y. For a significance level of 0.01, and large $N(>30)$, H_0 is rejected for a correlation of 0.27 and greater. From this, rain gauges separated by a distance with correlation less than 0.27 are not significantly correlated and can be considered independent. The distance at which gauges can be considered independent for storm total accumulation is 8.5 km (Fig. 2), slightly longer than the 8 km found by Reich and Osborn (1982) and used by Mendez et al. (2003).

Based on the assumption of independence, a group of four rain gauges, for which each pair of gauges are separated by at least

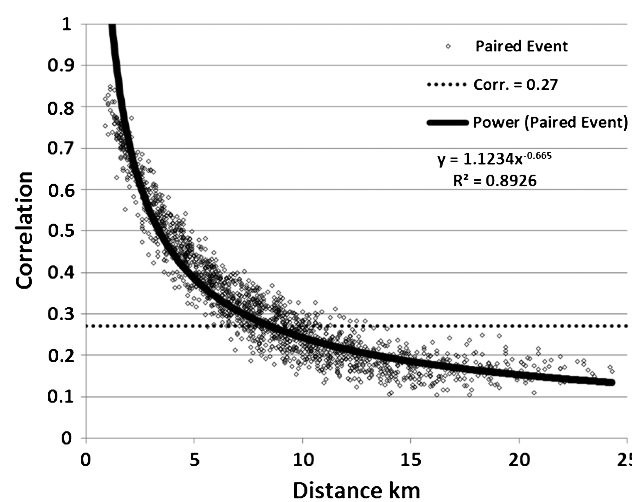

Fig. 2. Spatial correlation of storm total depth for pairs of WGEW rain gauges using 59 rain gauges 1961–2013; pairs of rain gauges are considered independent for storm total depth if spatial correlation is less than 0.27, which occurs at 8.5 km

8.5 km, was selected. A total of five groups were formed (indicated in Fig. 1) and each rain gauge had 53 years of record. Rain gauges within the central area of the WGEW are prevented from being part of the groups because the required minimum distance between all six pairs formed from the four gauges cannot be met, primarily in the north-south direction. Assuming the validity of the station-year method (Hafstad 1942), Osborn and Renard (1988) and Mendez et al. (2003) combined independent rain gauge observations for gauges within groups and created record lengths of about 90 and 140 years, respectively. Using the data available for this study, four 53 year records of the rain gauges within a group are combined into a single record of 212 years. In this way, the record is extended 50% longer than Mendez et al. (2003).

In addition to the assumption of spatial independence, two other assumptions are implied. First it is assumed that there is no elevation trend in rainfall over the 450 m elevation difference between the lowest and highest rain gauges. Goodrich et al. (2008a) found no significant elevation trend in summer rainfall intensity. The second assumption is that rainfall storm intensities are stationary over the period of record. For all groups and all durations no temporal trend was found for the intensities during the full period or 30 year subperiods (Fig. 3).

For each of the operational rain gauges within the five groups (20 gauges) on WGEW during the 53 year period of record, an annual maximum series was created of rainfall depth for each of six durations: 2, 5, 10, 15, 30, and 60 min. The depth-durations are represented herein as intensity (mmh^{-1}). The annual maximum intensity for each duration, for each year, for each rain gauge was selected from the SWRC database (2015). For each of the four rain gauges making up one of the five groups, the 53 annual values were combined with like data from the other three rain gauges within a group, as described previously, into 212 year series.

The following section explains the methods employed to identify the IDF relations and the various IDF comparisons and rainfall-runoff simulations to be presented in the results.

Methods

For each group of four gauges, the 212 year annual maximum series of intensities for each of the six durations are ranked from smallest to largest and each series fit to a lognormal distribution. The lognormal is chosen to be consistent with previous studies of IDF relations at WGEW (Reich and Osborn 1982; Mendez et al. 2003). Each found the lognormal suitable and better than alternatives. Each of the regression equations developed from fitting the data to the lognormal are then used to estimate the 2-, 5-, 10-, 25-, 50-, 100-, and 1,000-year events. These are the events that have an expectation of occurring in a year with probability of 0.50, 0.20, 0.10, 0.04, 0.02, 0.01, and 0.001, respectively.

The updated rainfall IDF curves for durations of 5, 10, 15, 30, and 60 min and return periods of 2, 5, 10, 25, 50, 100, and 1,000 years are then compared to those of the NOAA14. Observed point rainfall maximum intensities from individual rain gauges, which may or may not have been one of the 20 gauges used to develop the WGEW IDF curves, are compared to the IDFs to assess the number of occurrences of extreme events that have been measured by the SWRC rain gauge network. Although NOAA14 does not include IDF curves for 2-min durations, these durations are included because high-intensity rainfall at these durations contributes to runoff generation and erosion on small watersheds (Faures et al. 1995).

Several of these extreme events (1,000-year events) are compared to another large event on WGEW and were used as rainfall input to the KINEROS2 rainfall-runoff simulation model for the LH104 (4.5 ha) gauged subwatershed within the WGEW (see Fig. 1, expanded view in lower figure). KINEROS2 (Smith et al. 1995; Goodrich et al. 2012; Kennedy et al. 2013) is a distributed, physically based, kinematic-wave model of overland flow that has been well tested on LH104 (Goodrich et al. 1993, 1997). The observed extreme rainfall events did not occur at Rain Gauge 83 adjacent to LH104 but at other rain gauges within the WGEW or in the larger San Pedro watershed. For the rain gauges where extreme rainfall events did occur there are no nearby runoff gauging stations. Some runoff stations on WGEW did capture runoff events 2–10 km downstream from the rain gauges recording the several extreme precipitation events, but from contributing areas of 1,700–14,900 ha. A USGS river gauging station is located on the San Pedro River 16 km downstream from the Rain Gauge 417 with contributing watershed area of 215,000 ha. But what is of interest is the hydrologic impact identifiable from the singular extreme rainfall event, not to be distorted by issues of channel transmission losses and spatial rainfall intensity. Thus the authors' choice to model runoff at the small watershed scale. If observed runoff were available at the scale attributable to the intensity measured at a single gauge, the model would not have been necessary to evaluate runoff from an extreme rainfall event.

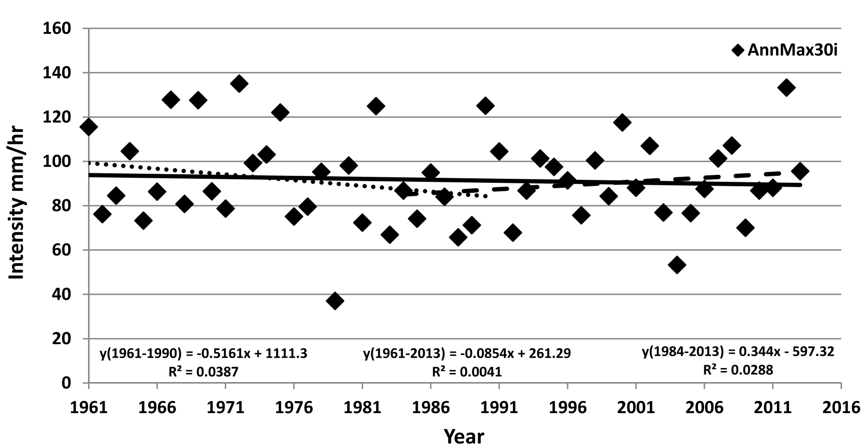

Fig. 3. Annual 30-min maximum intensity, 1961–2013; no trend detected for this or any other intensity duration for full 53 year period or any 30 year periods

Therefore to assess the hydrologic response from observed extreme events on small watersheds the authors followed the method employed by Osborn and Renard (1988) and spatially transposed the observed extreme rainfall to the location of Rain Gauge 83 and used the observed time-intensity pairs from the other gauges as input into the KINEROS2 watershed representation of LH104. KINEROS2 was set up and parameterized for this watershed using high-resolution topography, soils, and cover data. The model has been calibrated using eight events and validated with an independent set of 16 events (Fig. 4). The Nash-Sutcliffe coefficient of efficiency (NSE) for the validation event set was 0.99 for volume and 0.96 for peak rate. These results provide some level of assurance that simulation of runoff volume and peak runoff rate from the LH104 calibrated and validated KINEROS2 model driven by the extreme rainfall observations from other rain gauges will be representative of the actual watershed response if it were subjected to the extreme rainfall event. The simulated runoff volumes and peak discharge rates from the transposed extreme rainfall events will then be compared to the maximum observed discharge from LH104.

Results are presented in the next section showing (1) the recalculated IDFs and comparison of these to NOAA14 IDFs and comparison of intensity-durations for several extreme rainfall events observed on or near WGEW to NOAA14 frequency estimates; and (2) the use of several of the extreme events as input to the KINEROS2 watershed model on a small gauged subwatershed of the WGEW, where the extreme rainfall events were not observed, to simulate peak runoff rates and event runoff volumes and compare them to observed runoff at this small watershed.

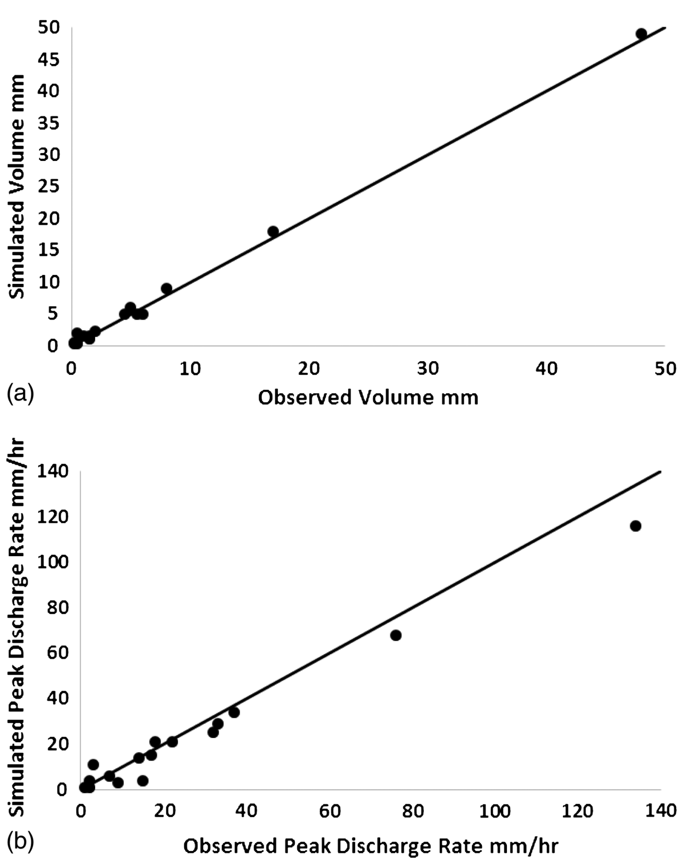

Fig. 4. KINEROS2 model evaluation for 16 validation events from the period 1973–1977 on LH104 for (adapted from Goodrich et al. 1993): (a) event runoff volume; (b) peak runoff rate

Results

IDF Calculations and Comparisons

The intensity data were fit to a lognormal distribution with all coefficients of determination, r^2, greater than 0.95 and all p values much less than 1.0E-100 (Fig. 5) for all groups and all durations. Making use of the regression equation for each duration, the return period intensities of 2, 5, 10, 25, 50, 100, and 1,000 years were calculated. The resultant IDF relations were compared to NOAA14 estimates and to the observed maximums of groups and all WGEW rain gauges.

The differences between the calculated and NOAA14 estimated return period intensities of 2, 5, 10, 25, 50, 100, and 1,000 years for durations of 5, 10, 15, 30, and 60 min are less than 15% (Tables 1–5). At the 5-min duration, the differences range from 0 to 15% and decrease with increasing duration: 2–12%, 0–7%, 2–4%, 0–2%, respectively for durations of 10, 15, 30, and 60 min. Mendez et al. (2003) compared their IDF results to NOAA Atlas 2 (Miller et al. 1973) for the 2–100-year return periods with differences ranging from 1 to 5%, 3 to 6%, 1 to 4%, and 6 to 11% for durations of 5, 15, 30, and 60 min, respectively. Although the differences of the Mendez et al. (2003) results tend to increase as durations increase, the reverse pattern is seen in the current data. The differences between Mendez et al. (2003) and the current means of the five groups' intensities are less than 7% for all durations and return periods 2–100 years, indicating that the additional years of data may not have improved the estimates substantially. However, Mendez et al. (2003) also noted that the maximum differences between the groups with maximum and minimum lognormal estimates of intensities for the durations lasting 5, 15, 30, and 60 min for all return periods were between 17 and 26%, but the maximum differences between the current groups are between 6 and 14%. This may be explained in part because the selected rain gauges within each group are different, between Mendez et al. (2003) and the current study, due to the required increase in separation distance between pairs of rain gauges to ensure spatial independence. Also, the additional years of observed data may have contributed to better fit of data to the lognormal distribution. Mendez et al. (2003) reported r^2 of 0.90–0.99, while the r^2 are greater than 0.95 and most are greater than 0.98 in the current analysis. The mean of the groups' intensities for all durations and all frequencies are within the 90% confidence intervals (CI) of the NOAA14 mean intensity.

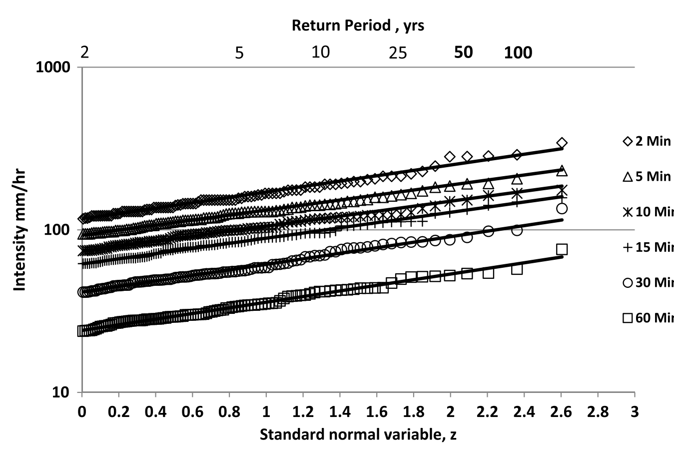

Fig. 5. Upper half of probability plot with lognormal fit for rain gauge Group 5

Table 1. Intensities in mmh^{-1} of 5-min Duration for 2, 5, 10, 25, 50, 100, and 1,000 Year Return Periods

		Return period (years)						
IDF source	Period	2	5	10	25	50	100	1,000
Mean of five groups	1961–2013	94	126	146	172	191	210	270
NOAA14_lower90%CI		82	116	138	165	184	203	258
NOAA14		94	132	157	190	214	239	320
NOAA14_upper90%CI		107	150	179	216	245	274	376

Table 2. Intensities in mmh^{-1} of 10-min Duration for 2, 5, 10, 25, 50, 100, and 1,000 Year Return Periods

		Return period (years)						
IDF source	Period	2	5	10	25	50	100	1,000
Five groups mean	1961–2013	75	100	116	136	152	166	214
NOAA14_lower90%CI		63	88	105	125	140	155	197
NOAA14		71	101	120	144	163	182	243
NOAA14_upper90%CI		81	114	136	164	186	209	286

Table 3. Intensities in mmh^{-1} of 15-min Duration for 2, 5, 10, 25, 50, 100, and 1,000 Year Return Periods

		Return period (years)						
IDF source	Period	2	5	10	25	50	100	1,000
Five groups mean	1961–2013	63	84	99	117	130	143	186
NOAA14_lower90%CI		52	73	87	104	116	128	163
NOAA14		59	83	99	119	135	150	201
NOAA14_upper90%CI		67	95	112	136	154	173	236

Table 4. Intensities in mmh^{-1} of 30-min Duration for 2, 5, 10, 25, 50, 100, and 1,000 Year Return Periods

		Return period (years)						
IDF source	Period	2	5	10	25	50	100	1,000
Five groups mean	1961–2013	42	58	69	83	93	104	138
NOAA14_lower90%CI		35	49	58	70	78	86	109
NOAA14		40	56	67	80	91	101	135
NOAA14_upper90%CI		45	64	76	91	104	116	159

Table 5. Intensities in mmh^{-1} of 60-min Duration for 2, 5, 10, 25, 50, 100, and 1,000 Year Return Periods

		Return period (years)						
IDF source	Period	2	5	10	25	50	100	1,000
Five groups mean	1961–2013	24	34	41	50	56	63	84
NOAA14_lower90%CI		24	31	37	43	48	53	68
NOAA14		25	35	41	50	56	63	84
NOAA14_upper90%CI		28	39	47	57	64	72	99

The rain gauge groups' observed and estimated intensities, for the groups with the maximum (Group 1) and minimum (Group 4) intensities, were compared to the NOAA14 estimates. Also, the maximum observed intensities for all durations of all 59 WGEW rain gauges were compared to NOAA14 estimates. Group 1 and Group 4 model estimated intensities for the 5-year and 100-year return periods fit within the NOAA14 90% CI of the 5-year and 100-year estimates (Fig. 6). The maximum observed intensities of Groups 1 and 4 and all WGEW rain gauges were compared to NOAA14 100-year and 1,000-year return periods (Fig. 7).

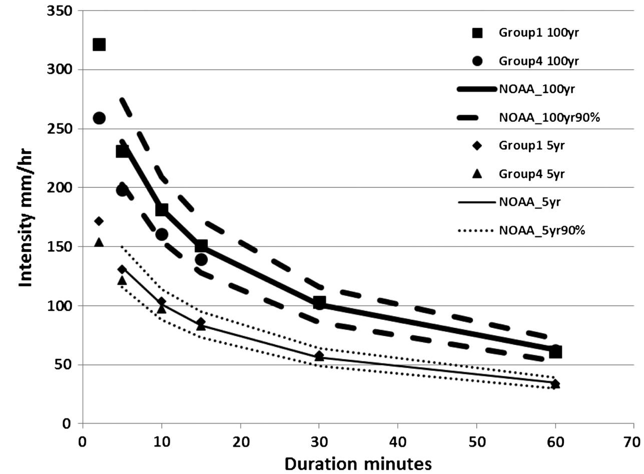

Fig. 6. Five-year and 100-year IDFs for Groups 1 and 4 and NOAA14 five-year and 100-year IDFs with 90% confidence intervals

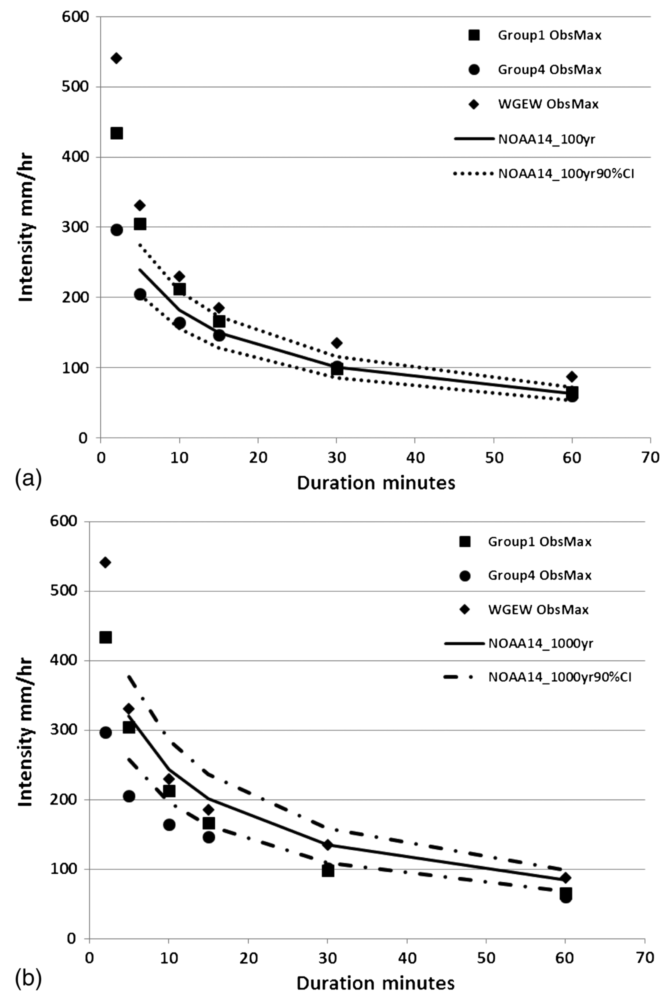

Fig. 7. WGEW rain gauge Groups 1 and 4 and all 59 WGEW gauges 1961–2013 maximum observed intensities and NOAA14 100-year IDF (a) and 1,000-year IDF (b) with 90% confidence intervals

For each duration, the maximum observed intensities of Group 4 are within the NOAA14 90% CI for the 100-year return period. Group 1 maximum observed intensities are within NOAA14 100-year 90% CI for durations of 10–60 min, but for shorter

Table 6. Observed Maximum Intensities and Return Periods Estimated from Group 1 IDF and NOAA14

Duration	Group 1 Maximum intensity (mmh^{-1})	WGEW Maximum intensity (mmh^{-1})	Group 1 IDF equation Group 1 return period (years)	Group 1 IDF equation WGEW return period (years)	NOAA14[a] Group 1 return period (years)	NOAA14[a] WGEW return period (years)
2	434	541	950	9,050	1,000	>1,000
5	305	331	975	2,250	600	1,000
10	212	230	340	680	400	500
15	166	185	200	520	200	500
30	98	135	70	940	100	1,000
60	65	87	170	2,110	100	1,000

[a]Estimated from tables at http://hdsc.nws.noaa.gov/hdsc/pfds.

durations (5, 10, and 15 min) are also within NOAA14 1,000-year 90% CI. WGEW maximum observed for all durations are beyond the NOAA14 100-year upper 90% CI. WGEW maximum observed for all durations are within NOAA14 1,000-year 90% CI. That the Group 1 15-min maximum observed and WGEW 15-min and 30-min maximum observed are 1,000-year events is significant because these intensity durations are highly correlated with runoff at 4 ha and up to 200 km^2 drainage areas (Osborn and Lane 1969; Osborn and Laursen 1973).

Return periods were estimated from the Group 1 regression equation and from NOAA14 for maximum observed intensities for Group 1 and all WGEW rain gauges (Table 6). Estimated return periods from the Group 1 equation, for Group 1 maximum intensities, indicate 1,000-year events have been observed for the 2-min and 5-min durations and greater than 100-year events have been observed for the durations of 10, 15, and 60 min. Applying the Group 1 equation to the maximum observed intensities of the 59 WGEW rain gauges results in return periods over 2,000 years for durations of 2, 5, and 60 min and 500–1,000-year return periods for durations of 10, 15, and 30 min. Estimates of return periods from the NOAA14, by interpolation between return periods and within confidence intervals around mean intensities for return periods, for Group 1 result in 1,000–100-year return periods from 2-min to 60-min durations and for all WGEW gauges result in 500–1,000-year return periods.

The observational network of rain gauges have measured and recorded 1,000-year return period events at least 52 times (Table 7). Some of the WGEW observed events' maximum intensities that fall within NOAA14 1,000-year 90% CI are provided in Table 7. These data are from the annual maximum series and nonmaximum observed intensities of similar magnitudes are not included. Also, the WGEW data do not include events for about 30 rain gauges on WGEW installed after 1961 and the 27 rain gauges located outside the WGEW, such as Rain Gauge 417. Therefore, it can be anticipated that more such extreme events have been observed. The number of extreme events observed in N years fits the binomial distribution, $B(N, p)$, where p is the probability of occurrence in any year. The probability of one occurrence of a 1,000-year event in 53 years is about 0.05. The probability of two occurrences at a rain gauge is 0.001, and this case of two occurrences at a single rain gauge was observed for the durations of 5, 15, and 60 min. If nearby gauges, within a 3 km radius, can be considered as one rain gauge because of high correlation, then three cases (durations of 5, 15, and 30 min) of four occurrences of 1,000-year events have been observed, with probability of 0.0000003. Because of the density of rain gauges, the 53 year record and the high temporal resolution of the recorded data, the WGEW rain gauge network is recording high-intensity, low-frequency events which are unavailable elsewhere in the southwestern United States.

Table 7. WGEW Observed Events' Maximum Intensities in mmh^{-1} That Fall within NOAA14 1,000-Year 90% CI

Duration (min)	NOAA14 Lower 90% CI	NOAA14 Mean	NOAA14 Upper 90% CI	Number of WGEW events	Range of observed intensities[a]
5	258	320	376	10	259–330
10	197	243	286	6	199–230
15	163	201	236	11	164–185
30	109	135	159	14	109–135
60	68	84	99	11	69–87

[a]From annual maximum series.

Six WGEW rain gauges' and RG417 extreme rainfall event statistics are listed in Table 8 and the locations of these rain gauges are provided in Fig. 1. The highest intensity for each duration on WGEW is indicated and similarly for RG417 if greater than WGEW intensity. Several peak 5-min through 60-min intensities are within NOAA14 1,000-year 90% CI. The peak 60 min intensity at RG417 is greater than the NOAA14 1,000-year 90% CI. Also, at a WGEW study area Lucky Hills, for the largest rainfall event at RG83 producing the largest runoff event on Lucky Hills, the 30-min and 60-min peak intensities are within the NOAA14 1,000-year 90% CI. The event of August 11, 2000, on WGEW was recorded by both the analog-recording and digital-recording rain gauges. All but two of the 88 analog and digital rain gauges were located within 2 m of each other during a multiyear comparison period (Keefer et al. 2008). One of the two sets was Rain Gauges 40 and 40a, colocated approximately 30 m apart. Each of these two rain gauges recorded significant rainfall intensities for that date, but the analog Rain Gauge, 40a, recorded more rainfall and greater intensities during the event and thus it is included in the list along with the digital gauge, 40. The event at Rain Gauge 417, not on WGEW, was a particularly extreme event, which equals or exceeds the NOAA14 1,000-year event for durations of 5 min to 7 days (Table 9). The observed events' maximum intensities fall within NOAA14 1,000-year 90% confidence interval (CI) for durations of 5–30 min. Intensities for durations of 60 min to 7 days are greater than the NOAA14 1,000-year event.

Hydrologic Response

The high-intensity, low-frequency events listed in Table 8 were used as input to the KINEROS2 hydrologic rainfall-runoff model to assess the impacts on runoff peaks and volumes. The modeled magnitudes of runoff volumes and discharge rates were compared to the largest observed runoff event at LH104. Observed extreme rainfall events peak 15-min intensities are 120–160% of the Rain Gauge 83 event peak 15-min intensity. As expected, the simulated

Table 8. List of Six WGEW Rain Gauges' and Rain Gauge 417 Extreme Rainfall Event Statistics

Rain gauge	Date	Total depth (mm)	Peak intensity (mmh^{-1})	Peak 5 min (mmh^{-1})	Peak 10 min (mmh^{-1})	Peak 15 min (mmh^{-1})	Peak 30 min (mmh^{-1})	Peak 60 min (mmh^{-1})
76	July 17, 1969	70.9	342.9	294.2[a]	229.6[b,a]	185.4[b,a]	127.6[a]	69.2[a]
5	August 11, 1972	79.5	289.6	182.9	175.3	157.5	135.1[b,a]	75.8[a]
60	August 28, 2008	54.2	746.8[b]	330.7[b,a]	224.8[a]	165.1[a]	107.2	54.2
40	August 11, 2000	91.2	228.6	196.6	165.4	139.2	117.6[a]	87.2[a]
40A	August 11, 2000	108.9[c]	320.0	189.0	155.4	145.3	128.0[a]	100.5[b,a]
417	July 9, 2013	216.9[c]	658.6	302.8[a]	217.3[a]	186.1[b,a]	142.9[b,a]	122.5[b,a,d]
83	July 17, 1975	72.6	190.5	152.4	129.5	116.8	112.8[a]	72.2[a]

[a]Peak 5-min through 60-min intensities that are within NOAA14 1,000-year 90% CI.
[b]The highest intensity for each duration on WGEW indicated and for Rain Gauge 417 if greater than WGEW intensity.
[c]The largest event total depth recorded by SWRC rain gauges on and off WGEW.
[d]The peak 60-min intensity at Rain Gauge 417 is greater than the NOAA14 1,000-year 90% CI.

runoff results for the extreme events are mostly greater than the observed at LH104 (Table 10). At LH104 the simulated runoff volumes are 97–460% of observed and 160–290% of the observed peak rate. Osborn and Renard (1988) did a similar study with 100-year, 1-h rainfall events based on NOAA Atlas 2 and estimates from WGEW observations. Using KINEROS to simulate runoff on two watersheds on WGEW, they showed that the differences in rainfall intensity caused substantial differences in runoff peaks and volumes.

Table 9. RG417 Event of July 9, 2013, Observed Event Intensities in mmh^{-1} and NOAA14 1,000-Year 90% CI

Duration	NOAA14 lower 90% CI	NOAA14 mean	NOAA14 upper 90% CI	RG 417
5 min	258	320	376	302.8
10 min	197	243	286	217.3
15 min	163	201	236	186.1
30 min	109	135	159	142.9
60 min	68	84	99	122.5
2 h	41	50	59	98.6
3 h	28	35	41	72.3
6 h	16	20	24	36.1
12 h	9	11	12	18.1
24 h	5	5	6	9.0
2 day	3	3	3	4.5
3 day	2	2	2	3.0
4 day	2	2	2	2.3
7 day	1	1	1	1.3
10 day	1	1	1	0.9

Return periods were estimated for the six simulated peak discharge rates and the observed July 17, 1975, event at LH104 based on a Log Pearson Type III distribution implemented using the procedures in USGS Bulletin 17B (USGS 1982) through HEC-SSP v 1.1 (http://www.hec.usace.army.mil/software/hec-ssp/). The return period of the peak discharge rate of the July 17, 1975, event at LH104 is 100 years. All of the simulated peak discharge rates are greater than the 500-year return period. All of the six extreme rain fall events that generate the greater than 500-year return period runoff events are 1,000-year rainfall events for one or more of the durations of 15, 30, and 60 min (Table 10).

For watersheds of this size, less than 5 ha, peak runoff rate is highly correlated with maximum 15-min rainfall intensity. The event of July 17, 1975, had maximum 15-min intensity of 117 mmh^{-1} (Table 8) and produced the largest observed runoff volume and peak rate at LH104. This rainfall event is estimated as a 25–50-year event (Table 10) by NOAA14 and the mean of the five groups (Table 3). However, the 30 and 60 min peak intensities for the same event are 1,000-year events. The rainfall event of July 17, 1969, at Rain Gauge 76 on WGEW had the highest 15-min intensity historically on WGEW of 185 mmh^{-1} (Table 8). The event of July 9, 2013, at Rain Gauge 417, not on WGEW, but located near Hereford, Arizona, had peak 15-min intensity of 186 mmh^{-1} (Table 8). Both of these events are considered 1,000-year events (Table 3). The hyetographs of these observed high-intensity rainfall events demonstrate the high intensities at intervals shorter than 15 min, the event peak rates being substantially greater than the 15 min rate [Fig. 8(a)]. The resultant hydrographs for maximum observed and simulated events at LH104 [Fig. 8(b)], show peak runoff rates generated by the 1,000-year events of two to

Table 10. Observed and Simulated Runoff Volumes, Peak Rates, and Return Periods and Associated Rainfall

Observed extreme precipitation event							Runoff			
				Rainfall return period			Observed (O) or simulated (S)			
Gauge	Date	Event depth (mm)	Peak intensity (mmh^{-1})	15-min intensity (year)	30-min intensity (year)	60 min intensity (year)	S/O	Volume (mm)	Peak rate (mmh^{-1})	Return period (year)
83	July 17, 1975	72.6	190.5	25–50	1,000	1,000	O	37.8	101.1	100
76	July 17, 1969	70.9	342.9	1,000	1,000	1,000	S	48.2	240.8	>500
5	August 11, 1972	79.5	289.6	100	1,000	1,000	S	53.2	163.4	>500
60	August 28, 2008	54.2	746.8	1,000	100	25–100	S	36.7	266.5	>500
40	August 11, 2000	91.2	228.6	50–100	1,000	1,000	S	63.6	166.3	>500
40a	August 11, 2000	108.9	320.0	50–100	1,000	1,000	S	78.7	176.4	>500
417	July 9, 2013	216.9	658.6	1,000	1,000	1,000	S	176.0	290.4	>500

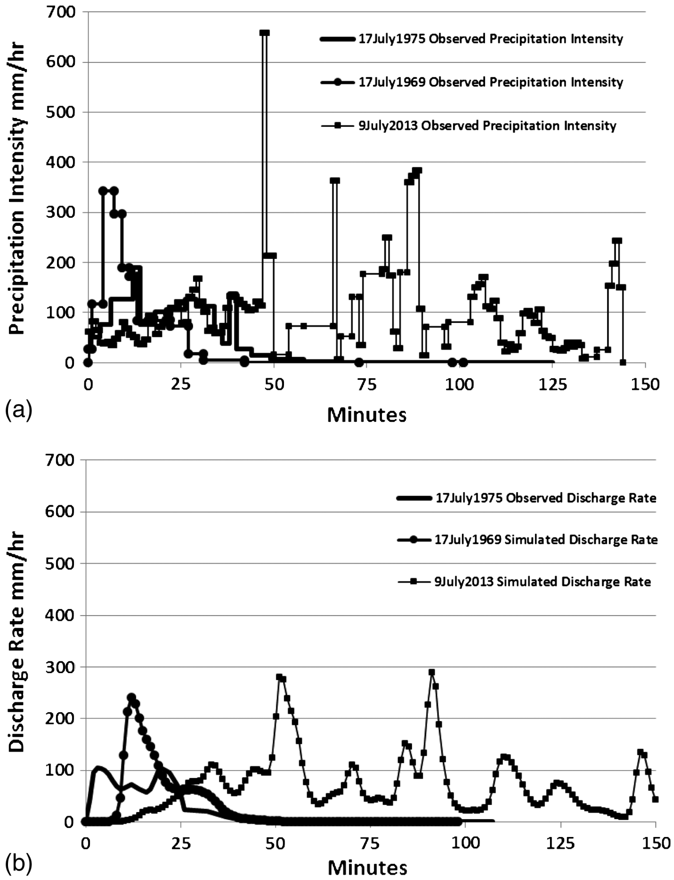

Fig. 8. (a) Observed high-intensity rainfall events' hyetographs; (b) resultant hydrographs for LH104 maximum observed and two simulated events at LH104; simulated runoff volume and peak discharge rates for this small watershed were two to four times larger than the largest recorded event

three times the observed magnitude and volumes up to four times of the observed.

Conclusion

Numerous high-intensity events have occurred recently that have been recorded by the USDA Southwest Watershed Research Center networks of rain gauges. These observations renewed an interest in updating IDF curves for the Walnut Gulch Experimental Watershed near Tombstone, Arizona. The spatial correlation scale to determine spatial independence of gauged storm totals was slightly longer, 8.5 km, than earlier studies had shown. Intensity-duration-frequency relations developed from combining independent observations from four rain gauges in annual maximum series were in relatively good agreement with estimates from NOAA14. Several observed events equal or exceed the 1,000-year event for the various durations. The high-resolution recording of intensities of these extreme events was used as input data for the KINEROS2 rainfall-runoff model for a small (4.5 ha) watershed. Simulated runoff volumes and peak discharge rates for this small watershed were up to four times larger than the largest recorded event.

Although these extreme events are rare, they do occur and the long-term, high-density network of high-resolution rain gauges captures these at subdaily scales, which few other stations in Arizona and the entire southwestern United States are capable of doing. This raises the concern that the sparse gauge networks that are relied upon may not adequately observe the number and magnitude of extreme precipitation events, especially for air-mass thunderstorms of limited spatial extent. The hydrologic effects of these extreme but spatially compact events are attenuated rapidly for watershed areas greater than about 50 ha (Goodrich et al. 1997) but at small watershed scales they can be significant. A higher level of storm water protection infrastructure may thus be warranted for high-value, small footprint developments such as power plants and hospitals.

Dense rain-gauge networks, high temporal-resolution sampling, and long-term data collection are necessary to capture extreme and infrequent events. Analysis of radar-rainfall field may aid in identification of high-intensity events but their length of record is relatively short and there are significant challenges in consistently estimating rainfall intensities from radar (Morin et al. 2003). WGEW and other SWRC rain gauge networks are valuable resources having recorded many of these short-duration, high-intensity events, which sparse rain gauge networks recording at daily time steps inevitably miss.

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