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Event to multidecadal persistence in rainfall and runoff in southeast Arizona

D. C. Goodrich,[1] C. L. Unkrich,[1] T. O. Keefer,[1] M. H. Nichols,[1] J. J. Stone,[1] L. R. Levick,[1] and R. L. Scott[1]

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[1] Spatial and temporal rainfall variability over watersheds directly impacts the hydrologic response over virtually all watershed scales. Changes in the precipitation regime over decades due to some combination of inherent local variability and climate change may contribute to changes in vegetation, water supply, and, over longer timescales, landscape evolution. Daily, seasonal, and annual precipitation volumes and intensities from the dense network of rain gauges on the Agricultural Research Service, U. S. Department of Agriculture Walnut Gulch Experimental Watershed (WGEW) in southeast Arizona are evaluated for multidecadal trends in amount and intensity over a range of watershed scales (1.5 ha to 149 km^2) using observations from 1956 to 2006. Rainfall and runoff volume and rate variability are compared over the same spatial scales over a 40 year period (1966–2006). The major findings of this study are that spatial variability of cumulative precipitation decreases exponentially with time, and, on average, became spatially uniform after 20 years of precipitation accumulation. The spatial variability of high-intensity, runoff-producing precipitation also decreased exponentially, but the variability was still well above the measurement error after 51 years. There were no significant temporal trends in basin scale precipitation. A long-term decrease in runoff from 1966 to 1998 from ephemeral tributaries like the WGEW may be a critical factor in decreasing summer flows in the larger San Pedro due to changes in higher-intensity, runoff-producing rainfall.

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1. Introduction

[2] Current research of observed precipitation variability over long time periods has primarily focused on linkages to teleconnections [*Ropelewski and Halpert*, 1986; *Mantua et al.*, 1997] and longer-term trends [*Karl and Knight*, 1998]. These studies have considered all areas of the United States at continental [*Karl and Knight*, 1998, *Groisman et al.*, 2001], regional [*Garbrecht et al.*, 2004; *Hamlet et al.*, 2005; *Knowles et al.*, 2006; *Small et al.*, 2006; *Thomas and Pool*, 2006], basin [*Thomas and Pool*, 2006; *Beebee and Manga*, 2004; *Hall et al.*, 2006; *Zume and Tarhule*, 2006], and, less frequently, watershed [*Nichols et al.*, 2002; *Molnár and Ramírez*, 2001] scales.

[3] Many of these studies consider the impacts of observed precipitation variability on agriculture [*Feng and Hu*, 2004; *Garbrecht et al.*, 2004], evapotranspiration [*Reynolds et al.*, 2000], erosion [*Angel et al.*, 2005], ecosystems [*Loik et al.*, 2004], as well as other aspects of the hydrologic cycle including groundwater [*Pool*, 2005] and streamflow [*Redmond and Koch*, 1991; *Beebee and Manga*, 2004]. The western United States has been evaluated in many of these studies because of its reliance on winter snowpack for water supply [*Beebee and Manga*, 2004; *Hamlet et al.*, 2005; *Knowles et al.*, 2006] and the limited water supplies in semiarid regions [*Thomas and Pool*, 2006].

[4] The density of rain gauges used in these and other studies varies considerably (see Table 1). Larger-scale studies may use hundreds or thousands of monitored sites over large areas, but at local watershed scales the number of gauges is usually very limited. Regional trends may miss the fine details of precipitation variability at the watershed scale and make it more difficult to relate runoff to rainfall. This is especially true in semiarid areas with localized events like the Walnut Gulch Experimental Watershed (WGEW) located in southeast Arizona. When the WGEW was originally being constructed, 20 rain gauges were installed. At the time this was considered a very high density of gauges, but subsequent runoff events were observed with no corresponding rainfall (K. G. Renard, personal communication, 2001). Therefore, roughly 65 additional rain gauges were added to the network to capture runoff-producing rainfall with adequate spatial resolution.

[5] This study considers the spatial and temporal variability of precipitation over 50 years using the high-density (~0.570 gauges km^{-2}) Agricultural Research Service, U. S. Department of Agriculture (USDA-ARS) WGEW rain gauge network (see Figure 1 and *Goodrich et al.* [2008])

[1]Southwest Watershed Research Center, Agricultural Research Service, U.S. Department of Agriculture, Tucson, Arizona, USA.

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Table 1. Example Area-Average Gauge Network Densities

Region	Density	Source(s)
USDA-ARS WGEW	0.570 km^{-2}	current work
Western/central Europe	0.002 km^{-2}	*Rodell et al.* [2004], GPCC[a]
Southwestern United States	0.0025 km^{-2}	*Briggs and Cogley* [1996]
Western United States	0.0045 km^{-2}	*Briggs and Cogley* [1996]
Conterminous United States	0.00055 km^{-2}	*Cosgrove et al.* [2003], *Gottschalck et al.* [2005]
Global	0.000045 km^{-2}	*Rodell et al.* [2004], GPCC[a]

[a]GPCC data is available at http://www.dwd.de/en/FundE/Klima/KLIS/int/GPCC/GPCC.htm.

over a range of watershed scales from 1.5 ha to 149 km^2. The precipitation depth and intensity are evaluated for trends and impacts on observed runoff as well as their interaction with land cover.

[6] Previous studies on the WGEW have looked at small-scale variability over shorter periods (hours, days, weeks, seasons) [*Reich and Osborn*, 1982; *Nichols et al.*, 1993; *Renard et al.*, 2008, Figure 3] and return frequencies of various event sizes [*Osborn and Renard*, 1988; *Mendez et al.*, 2003]. *Nichols et al.* [2002] found a long-term (1956–1996) increase in winter precipitation using a subset of six rain gauges on the watershed. This finding fits with the patterns of larger-scale studies of western U.S. precipitation whereby nonsummer precipitation has increased during the same period, associated with the El Nino-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) [*Trenberth and Hoar*, 1996; *Molnár and Ramírez*, 2001].

[7] However, at the river basin scale (e.g., the Rio Grande and Pecos River basins) *Hall et al.* [2006] found climatic variations in the region were not consistent in time or space, with some areas showing increases in temperature or precipitation while others exhibited decreases in the same. *Thomas and Pool* [2006] conducted a regional study of 21 USGS-gauged watersheds and 35 National Weather service precipitation stations in southeast Arizona and southwest New Mexico including the gauges within the San Pedro Basin (the WGEW is a subwatershed of the San Pedro Basin). Except for the San Pedro and several nearby basins, they found few significant trends in precipitation or streamflow for much of the 20th century. "For the trends in precipitation that were significant, 90

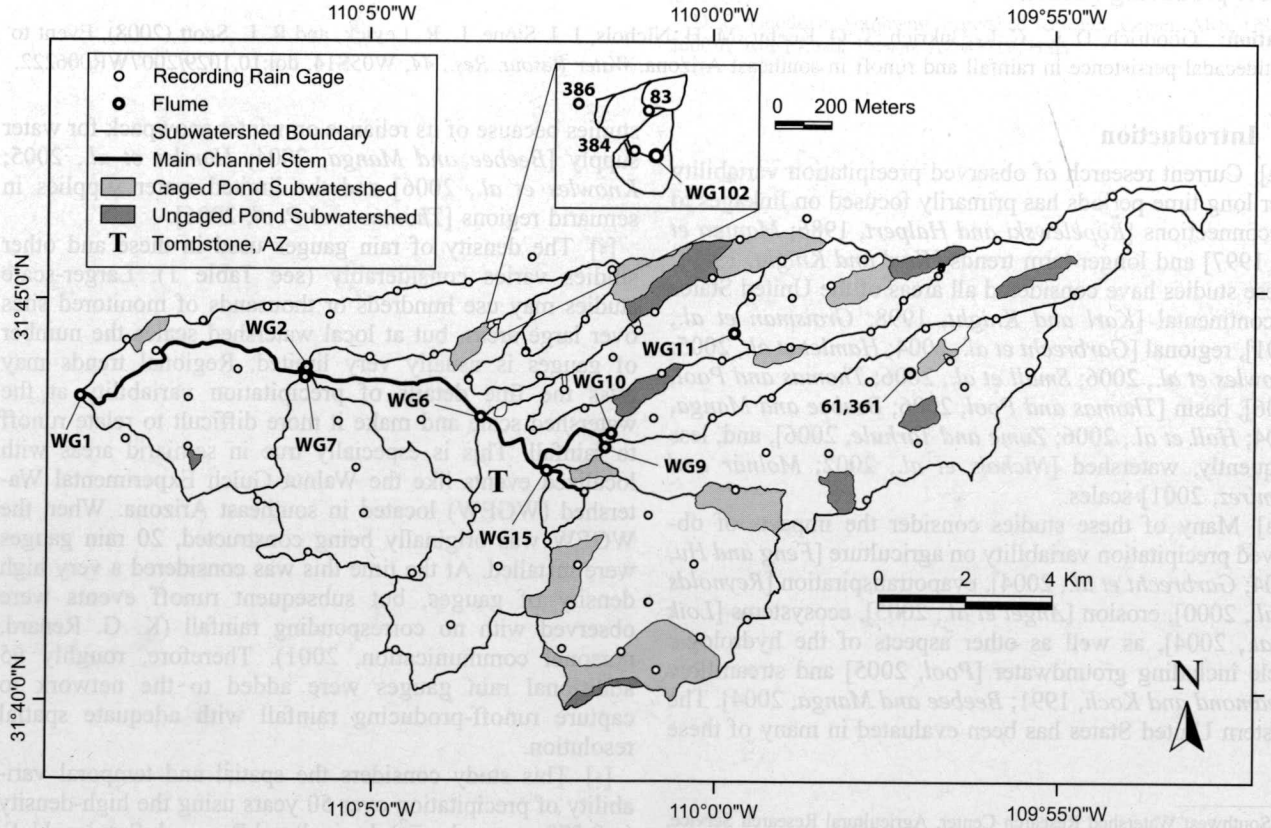

Figure 1. Walnut Gulch Experimental Watershed (WGEW) rain gauge and gauged watershed locations and numerical designation. The WGEW is located approximately 150 km southeast of Tucson, Arizona. See color version of this figure in the HTML.

Table 2. Primary Walnut Gulch Experimental Watersheds Analyzed

Watershed	Area (ha)	Area Above Stock Ponds[a] (%)	Primary Cover Type
WG1	14933	10	Mixed shrub/grass/built-up
WG2	11372	14	Mixed shrub/grass/built-up
WG6	9510	12	Mixed shrub/grass/built-up
WG7	1352	0	Mixed shrub
WG9	2359	5	Mixed shrub/grass
WG10	1663	10	Mixed shrub/grass
WG11	824	18	Mixed shrub/grass
WG15	2393	29	Mixed shrub/grass
WG102	1.46	-	Desert shrub

[a]Area above stock ponds equals the percent of total subwatershed area upstream from stock ponds.

percent were positive and most of those positive trends were in records of winter, spring, or annual precipitation that started during the mid-century drought in 1945–60" [*Thomas and Pool*, 2006, p. 1]. For all but the San Pedro and two streams adjacent to the San Pedro, they found either a significant increasing trend in streamflow or no trend. Within the San Pedro Basin they found a substantial decrease in both annual and summer streamflow during this century. The only significant trends in precipitation (decreasing) for the San Pedro were for the month of July and the summer season.

[8] In their study, *Thomas and Pool* [2006] related monthly and daily precipitation data from the Tombstone, Arizona National Weather Service Cooperative Observer gauge (located within the WGEW but established in 1890) to monthly total streamflow, low flows, and maximum daily stormflows at the Charleston USGS gauging station. Over the period from 1913 to 2002 they found the following percentage changes in precipitation; a 13% decrease in annual, a 6% increase in winter, and a 26% decrease in summer precipitation. Over the same period they found a 66% decrease in total annual streamflow (13% decrease in winter flows and an 85% decrease in summer flows with an acceleration of the decline beginning in the early to mid-1960s). The variation in streamflow caused by variation in precipitation was then statistically removed and they concluded that the decrease in flow was not fully explained by corresponding decreases in precipitation. Other factors were examined to explain the decrease in streamflow including: (1) changes in air temperature; (2) changes in watershed characteristics (riparian and upland vegetation, channel morphology); (3) human activity (e.g., groundwater pumping, urbanization, detention pond construction, and grazing); and (4) changes in seasonal distribution of flow between the San Pedro River and storage in channel banks and the alluvial aquifer. They concluded that vegetation change and near-stream seasonal pumping were likely major factors in the decreasing streamflow trends while the other factors could have had a minor effect. However, they note that quantitatively attributing the effects of these factors to the observed decrease in streamflow is difficult due to the limitations of the data employed and the large number of interacting factors in the transformation of precipitation to streamflow at the basin scale.

[9] The density of historical observations of the WGEW enables a more detailed analysis of the spatial and temporal variability of precipitation and runoff over a range of watershed scales. The objectives of this analysis are to: (1) assess the spatial uniformity of precipitation and its intensity over the WGEW; (2) assess the temporal and spatial trends of precipitation and its intensity over the WGEW versus analysis at one or more rain gauges; and (3) relate watershed-wide precipitation variation to runoff across time and a range of watershed scales.

[10] Objective 1 is motivated by the fact that precipitation amounts are a key factor in vegetation growth, and over the longer term, erosion and landscape evolution, in this water-limited environment [*King et al.*, 2008; *Renard et al.*, 2008, Figure 3] illustrates the persistent degree of spatial variability of precipitation over the WGEW from monthly to seasonal to annual timescales. With over 50 years of high-resolution precipitation observations in the WGEW it may be possible to evaluate whether the watershed will eventually receive a relatively uniform amount of precipitation and intensity (used as a surrogate for erosive energy), and if so, at what timescale.

[11] In the second objective, the analysis of temporal trends presented by *Nichols et al.* [2002] will be extended from six points (individual rain gauges) to the entire rain gauge network and extended in time by adding an additional 10 years of observations which include a major period of drought and several seasons of high runoff volumes.

[12] For objective 3, high-resolution rainfall and runoff observations from the WGEW will enable a more detailed examination of the conclusions of *Thomas and Pool* [2006] in regards to upland tributary flow into the San Pedro. The WGEW is a rangeland tributary to the main stem of the San Pedro River but is isolated from groundwater interactions and significant riparian transpiration from groundwater sources [*Goodrich et al.*, 2004]. The WGEW drains west from the Dragoon Mountains into the San Pedro at a point approximately 10.5 km downstream

Table 3. Summary of Data Used to Estimate Intergauge Variability Due to Measurement and Data Processing Errors

Gauge Pair Numbers	Separation Distance (m)	Length of Common Record (years)	Precipitation Depth Bias (%)	I30 $\geq$ 25 mm h^{-1} Bias (%)
61, 361	<1	10	3.8	1.9
83, 384	144	23	4.8	1.4
83, 386	154	20	5.5	0.7
384, 386	161	20	1.8	3.2

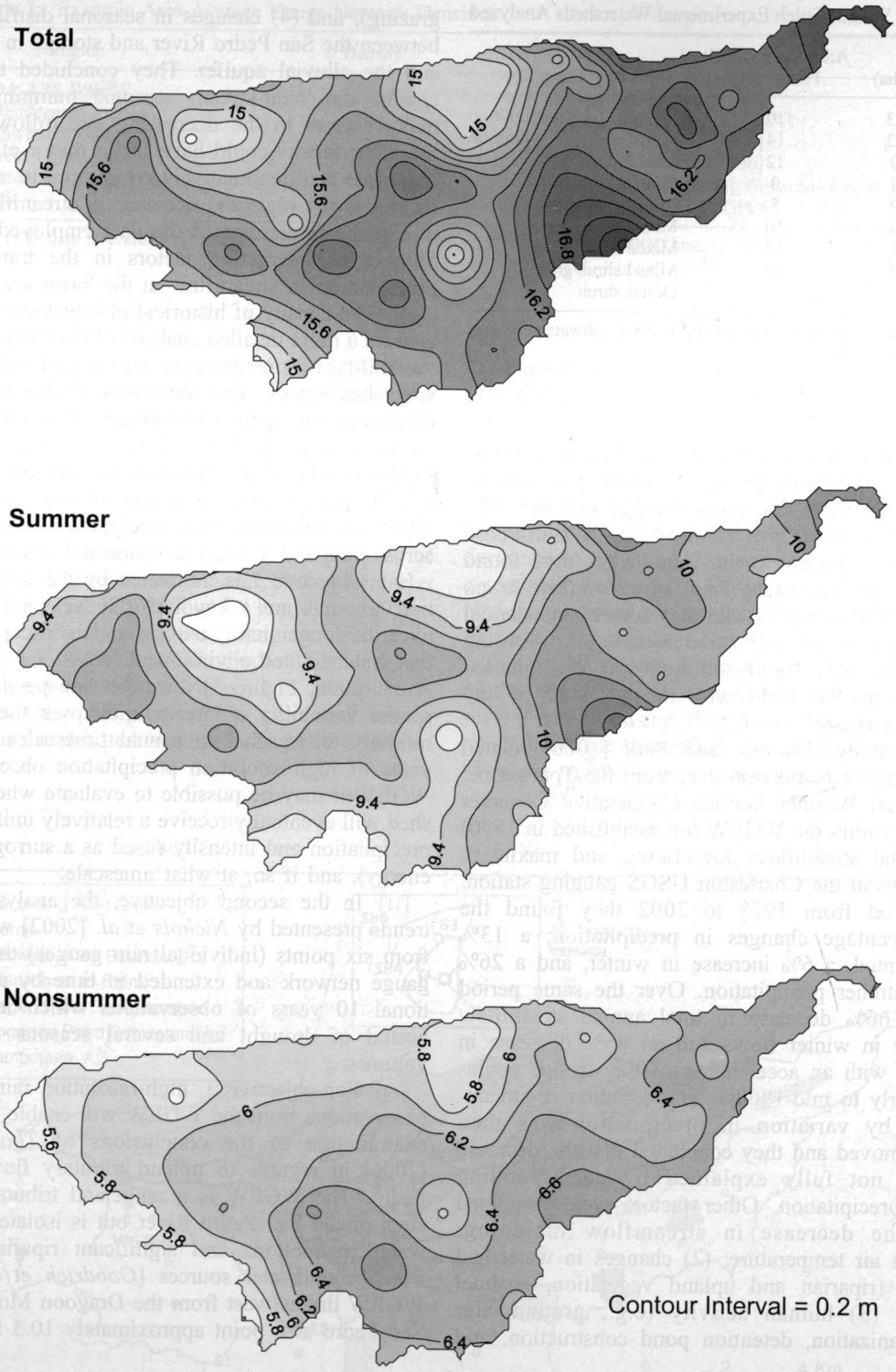

Figure 2. Total precipitation accumulations in meters interpolated over the WGEW from 1956 to 2006 (annual refers to all months; summer refers to July, August, and September; and nonsummer refers to all other nonsummer months).

of the USGS Charleston runoff gauging station used by *Thomas and Pool* [2006]. Virtually all runoff from the WGEW is a product of intense summer thunderstorms associated with the North American Monsoon, occurring in July–September [*Goodrich et al.*, 1997]. Runoff response typically occurs within hours of storm events [*Renard et al.*, 2008, Figure 4]. Runoff is rare during winter months, even under the El Nino conditions conducive

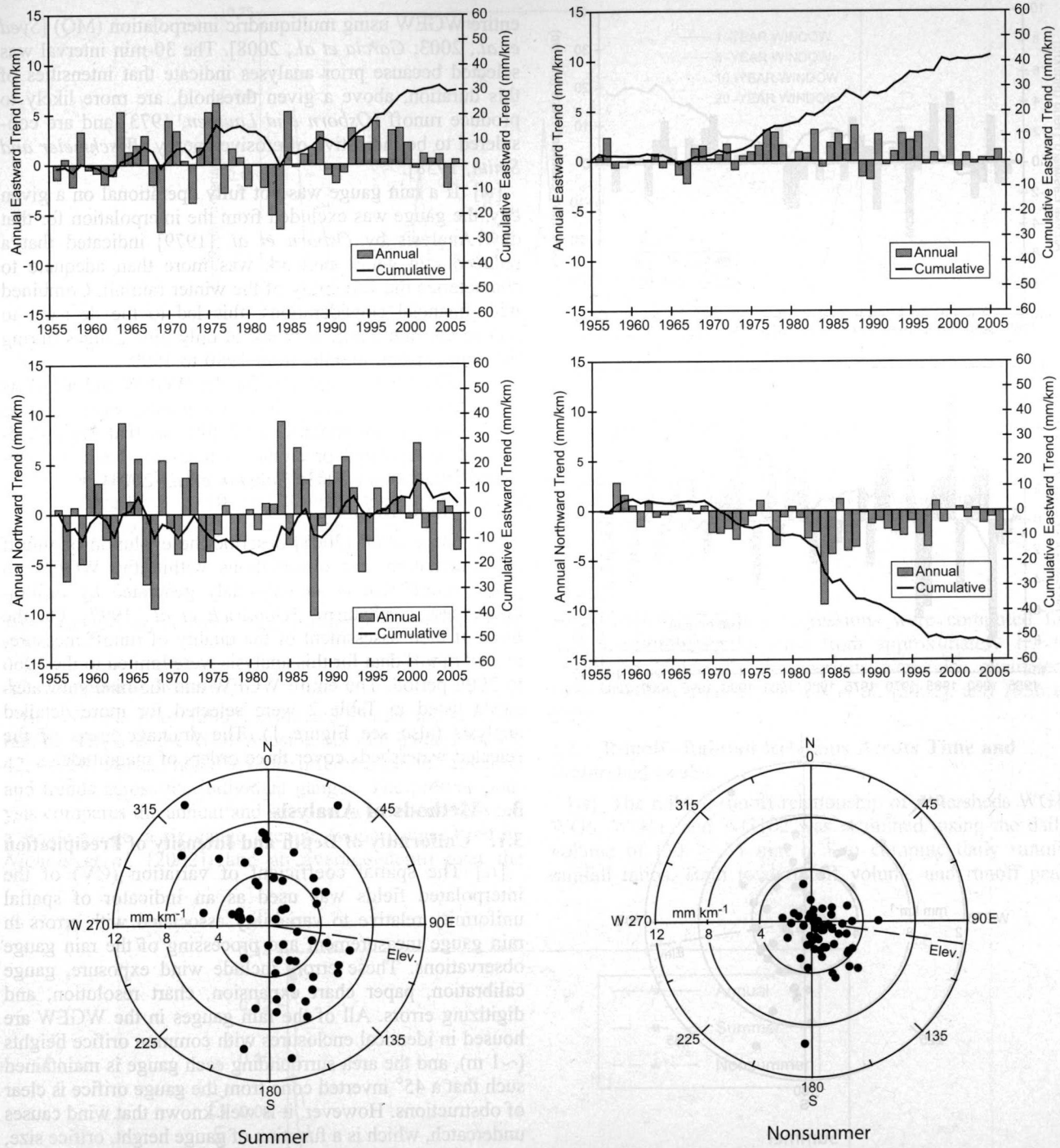

Figure 3. (top) Annual and cumulative general spatial trend components of rainfall depth in the easterly and northerly directions for the summer and nonsummer seasons. (bottom) Magnitude and direction of annual spatial trends of rainfall depth, with direction of elevation trend indicated.

to increased precipitation, because winter precipitation generally falls as low-intensity rain and occasionally snow. In addition, there has been little evidence of significant vegetation changes since observations were initiated within the WGEW [*King et al.*, 2008]. Therefore many of the confounding factors of large lag times, vegetation change, and groundwater storage and pumping effects noted by *Thomas and Pool* [2006] are not present in the WGEW.

2. Data

2.1. Precipitation Data

[13] Rainfall records from 1956 through 2006 for all rain gauges that were operational during at least part of that

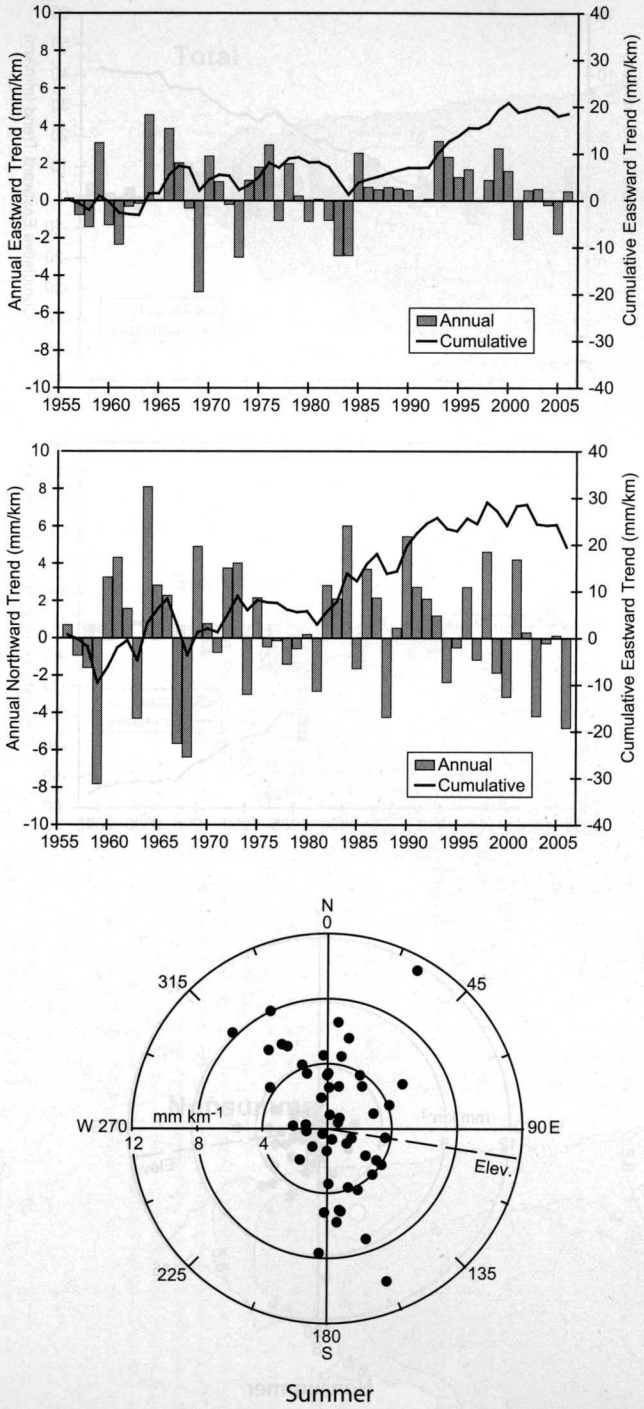

Figure 4. (top) Annual and cumulative general spatial trend components of I30 $\geq$ 25 mm h^{-1} volume in the easterly and northerly directions for the summer season. (bottom) Magnitude and direction of annual spatial trends of I30 $\geq$ 25 mm h^{-1} volume, with direction of elevation trend indicated.

period were utilized (Figure 1). When rainfall was detected at one or more gauges on a given day, the precipitation depth and maximum 30-min intensity (I30) for the day were spatially interpolated on a 100 m $\times$ 100 m grid over the entire WGEW using multiquadric interpolation (MQ) [*Syed et al.*, 2003; *Garcia et al.*, 2008]. The 30-min interval was selected because prior analyses indicate that intensities of this duration, above a given threshold, are more likely to produce runoff [*Osborn and Laursen*, 1973] and are considered to be indicative of erosive energy [*Wischmeier and Smith*, 1958].

[14] If a rain gauge was not fully operational on a given day, the gauge was excluded from the interpolation for that day. Analysis by *Osborn et al.* [1979] indicated that a reduced rain gauge network was more than adequate to characterize the variability of the winter rainfall. Combined with financial considerations, this led to the decision to reduce the rain gauge network to only nine gauges during the nonmonsoon months from 1980 to 1999.

[15] Watershed boundaries for the WGEW and all of its subwatersheds, including detention ponds, were used as masks for the interpolated grid files so that watershed-specific interpolated precipitation measures could be estimated [*Syed et al.*, 2003; *Heilman et al.*, 2008].

2.2. Runoff Data

[16] *Stone et al.* [2008] describe the evolution of runoff instrumentation and observations within the WGEW to gauge runoff that is almost solely generated by infiltration-excess mechanisms [*Goodrich et al.*, 1997]. On the basis of their assessment of the quality of runoff measurements, runoff data for this analysis were limited to the 1966 to 2006 period. The entire WGEW and the nine subwatersheds listed in Table 2 were selected for more detailed analysis (also see Figure 1). The drainage areas of the selected watersheds cover three orders of magnitude.

3. Methods of Analysis

3.1. Uniformity of Depth and Intensity of Precipitation

[17] The spatial coefficient of variation (CV) of the interpolated fields was used as an indicator of spatial uniformity relative to variability associated with errors in rain gauge measurement and processing of the rain gauge observations. These errors include wind exposure, gauge calibration, paper chart expansion, chart resolution, and digitizing errors. All of the rain gauges in the WGEW are housed in identical enclosures with common orifice heights ($\sim$1 m), and the area surrounding each gauge is maintained such that a 45° inverted cone from the gauge orifice is clear of obstructions. However, it is well known that wind causes undercatch, which is a function of gauge height, orifice size, wind speed and direction, and drop size [*Sevruk*, 1989; *Larson and Peck*, 1974; *Goodrich et al.*, 1995]. The issue of intergauge variability due to the above factors was investigated by regressing data from four pairs of gauges located in close proximity to each other (Table 3 and Figure 1). A parallel analysis was done for the maximum intensity greater than or equal to 25 mm h^{-1} occurring over any 30-min interval at a given rain gauge during a given day (I30 $\geq$ 25 mm h^{-1}). An intensity threshold of 25 mm h^{-1} was selected as it is likely to produce runoff within the WGEW [*Simanton and Osborn*, 1983]. For each subwatershed, those grid cells with I30 $\geq$ 25 mm h^{-1} were integrated into a daily volume and areal extent. Annual

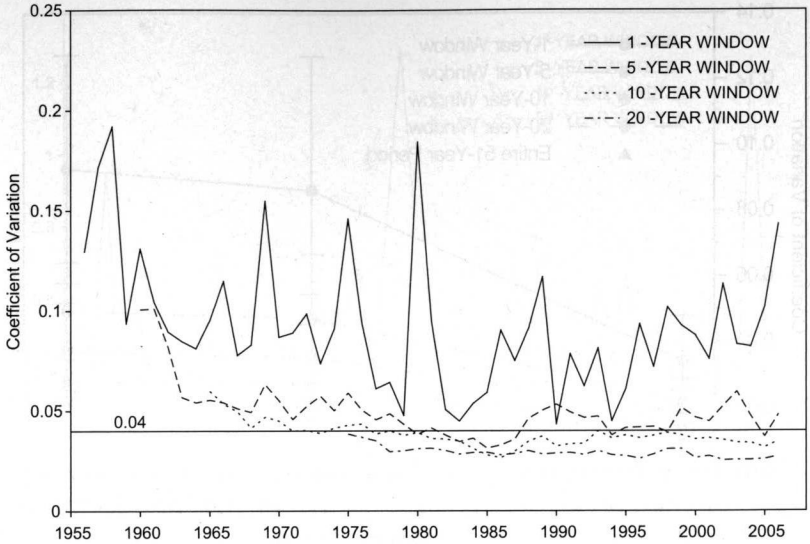

Figure 5. Spatial coefficient of variation (CV) of total annual rainfall over the WGEW as a function of time for 1, 5, 10, and 20 year moving windows. Horizontal line indicates estimated level of variability due to intergauge measurement bias.

volumes and areas were then computed from the daily values.

3.2. Temporal Trends

[18] *Nichols et al.* [2002] evaluated annual and seasonal rainfall trends in the WGEW using six rain gauges (4, 13, 42, 44, 60, 68) and noted several differences in the direction and trends across the individual gauges. The present analysis compares the annual and seasonal regressions between a single gauge, a six-gauge average (same gauges used by *Nichols et al.* [2002]) and an average depth over the interpolated grid. These regressions were computed for watersheds ranging in scale from approximately 1.5 to 15,000 ha (Table 2). Two periods were also examined; 1956–1996 as used by *Nichols et al.* [2002], and 1956 to 2006.

3.3. Runoff–Rainfall Relations Across Time and Watershed Scales

[19] The rainfall-runoff relationship of watersheds WG1, WG6, WG11, and WG102 was examined, using the daily volume of I30 $\geq$ 25 mm h^{-1} to compute daily runoff/rainfall ratios. Both total runoff volume and runoff peak

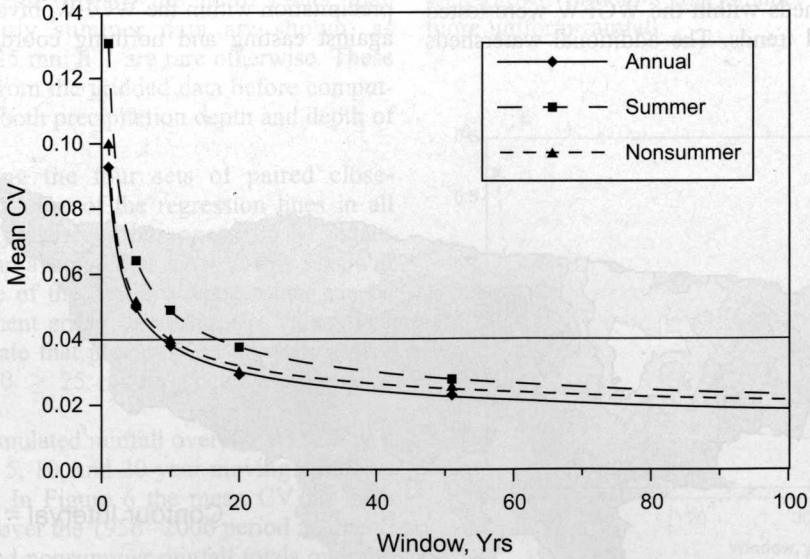

Figure 6. Mean spatial coefficients of variation (CV) and fitted power law relationships between the annual, summer, and nonsummer rainfall totals for the entire WGEW as a function of moving window size for 1956–2006. Horizontal line indicates estimated level of variability due to intergauge measurement bias.

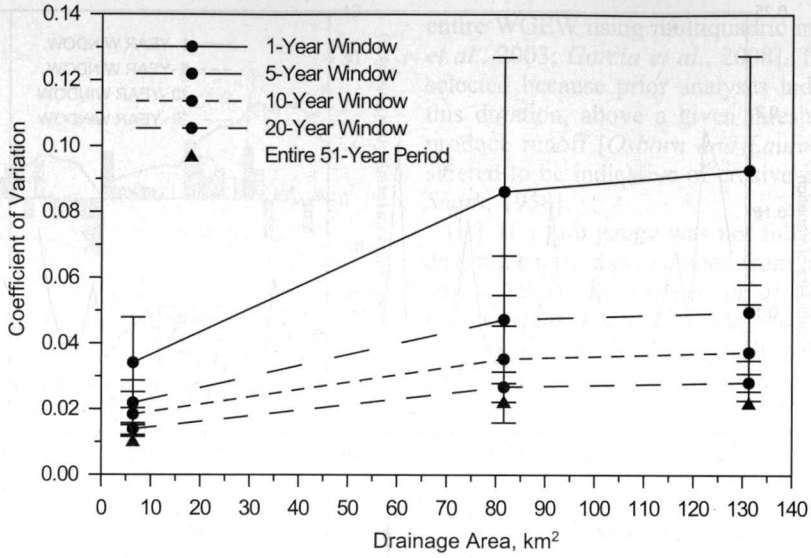

Figure 7. Mean spatial CV of accumulated rainfall for each window size as a function of drainage area. Vertical bars indicate one standard deviation.

rate from WG1 were tested for significant trends over the 1966 to 2006 period. Annual runoff from WG1 was regressed against annual I30 $\geq$ 25 mm h^{-1} volume to assess how much of the temporal variability of annual runoff could be explained by variations in the annual volume of higher rainfall intensities. The residuals of the regression were then tested for a significant trend that might indicate the presence of other important factors. Two factors considered were changes in vegetation and changes in channel morphology that could affect channel transmission losses. Regional and local data describing spatial and temporal changes in land cover were used to estimate the potential impacts of vegetation change on runoff generation in the WGEW. Finally, annual runoff data from other watersheds within the WGEW were tested for significant temporal trends. The additional watersheds considered were WG2, WG7, WG9, WG10, and WG15 (Figure 1).

4. Results and Discussion

4.1. Uniformity of Depth and Intensity of Precipitation

[20] In Figure 2 the total accumulated precipitation over the WGEW for the 51-year period from 1956 to 2006 is plotted, as well as the precipitation totals for the summer months (July, August, and September) and all other months over the same time span. A small increasing west to east gradient is apparent in each of the plots, with a larger contribution to the gradient from the nonsummer months.

[21] To further explore the overall spatial trends in precipitation within the WGEW, bivariate linear regressions against easting and northing coordinates were computed

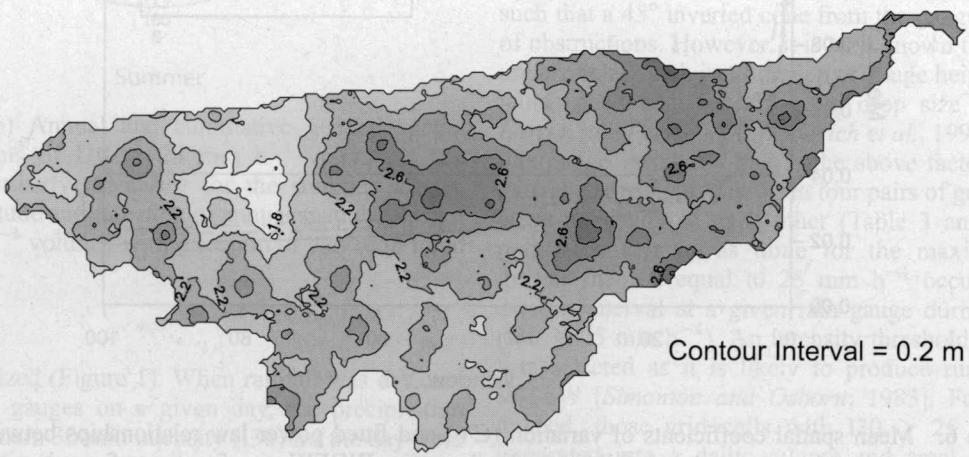

Figure 8. Total accumulated volume of I30 $\geq$ 25 mm h^{-1} in meters interpolated over the WGEW from 1956 to 2006.

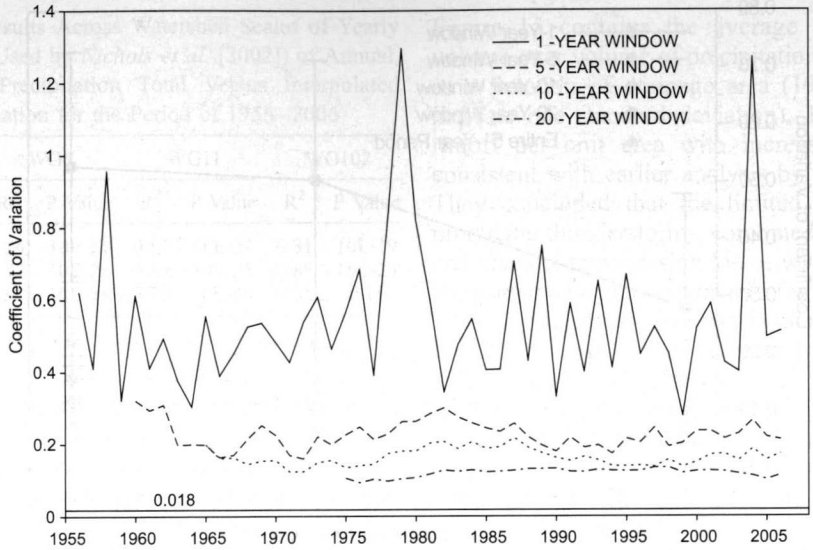

Figure 9. Spatial coefficient of variation (CV) of annual volumes of rainfall with daily I30 $\geq$ 25 mm h^{-1} over the WGEW as a function of time for 1, 5, 10, and 20 year moving windows. Horizontal line indicates estimated level of variability due to intergauge measurement bias.

for annual and cumulative precipitation over the 51-year period (Figure 3). It is apparent from these plots that starting about 1970, nonsummer precipitation is consistently greater in the eastern and southern areas of the WGEW. Summer precipitation is more variable and generally has an easterly increasing trend as well, but the monsoon southerly trend shifts to a northerly trend around 1985. The polar plots show the net trend direction for each year. The direction of rain gauge elevation trend is also indicated. There is no evident alignment between the precipitation trend points and elevation trend line. Like precipitation depth, the overall spatial trends for I30 $\geq$ 25 mm h^{-1} show greater volumes toward the east (Figure 4) but also consistently increase toward the north rather than south (Figure 4). Only summer data are shown, as occurrences of I30 $\geq$ 25 mm h^{-1} are rare otherwise. These trends were removed from the gridded data before computing the spatial CV for both precipitation depth and depth of I30 $\geq$ 25 mm h^{-1}.

[22] When comparing the four sets of paired close-proximity gauges, the slopes of the regression lines in all cases were significantly different than one, with R^2 values greater than 0.98 and an average bias of 4%. This bias will be used as an estimate of the spatial variation that can be attributed to measurement errors; therefore CV values less than 0.04 would indicate that precipitation depth is essentially uniform. For I30 $\geq$ 25 mm h^{-1}, the average bias was 1.8%.

[23] The CV of accumulated rainfall over the WGEW as a function of time for 1, 5, 10, and 20-year moving windows is plotted in Figure 5. In Figure 6 the mean CV for each temporal window size over the 1956–2006 period is plotted for annual, summer, and nonsummer rainfall totals over the entire WGEW, along with fitted power law relationships. These data are summarized across watershed scales in Figure 7 with the mean CV and standard deviation for each temporal window size for watersheds WG11, WG6, and WG1. WG102 is approximately equal in size to one 100 × 100 m grid square, so a spatial CV for this watershed cannot be computed. Also indicated is the CV for the entire 51-year period of record.

[24] It is apparent from Figure 5 that the interannual variability is relatively large for annual rainfall and that most of the reduction in mean CV occurs before reaching the 20-year accumulation. This behavior is again seen in Figure 6, which also shows the expected result that nonmonsoon rainfall tends to be more uniform (lower CV). The annual and nonmonsoon mean CV crosses the 4% threshold after 10 years of accumulation, whereas for summer the threshold is crossed after 20 years. Figure 7 illustrates the well-known principle that smaller watersheds experience more uniform rainfall.

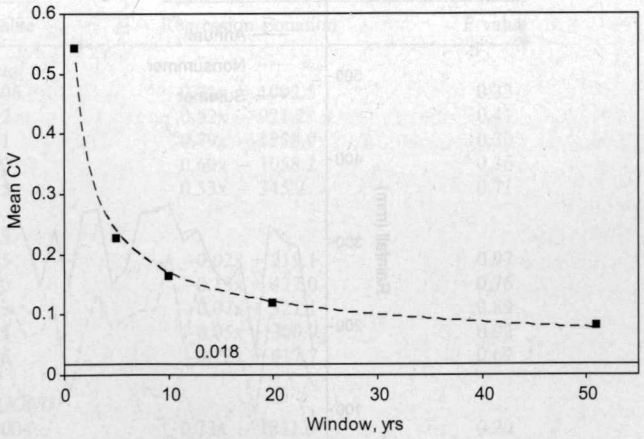

Figure 10. Mean spatial CV and fitted power law relationship between the total volume of I30 $\geq$ 25 mm/hr for the entire WGEW as a function of moving window size for 1956–2006.

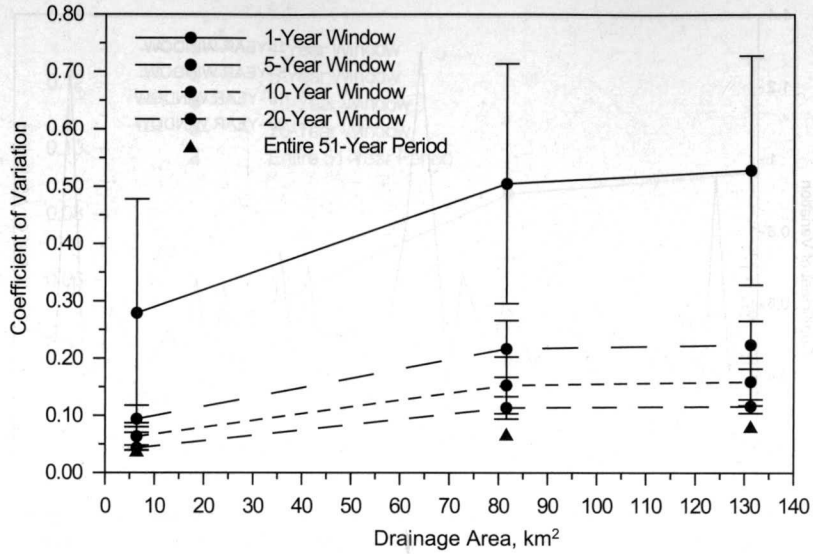

Figure 11. Mean spatial CV of accumulated I30 $\geq$ mm/hr volume for each window size as a function of drainage area. Vertical bars indicate one standard deviation.

[25] The behavior of the spatial CV for I30 $\geq$ 25 mm h^{-1} is illustrated in Figures 8 through 11. The behavior is similar to that of precipitation depth but with much higher mean CV values. In Figure 8, CV is not distinguished by season as contributions during the nonsummer period are negligible.

4.2. Trends

[26] The spatially interpolated summer (July, August, September), nonsummer, and annual precipitation for 1956–2006 are plotted in Figure 12. Since an objective herein is to compare and extend the finding of *Nichols et al.* [2002] we assessed how the six-gauge average compares with interpolated averages across watershed scales (Table 4). Correlation for the overall WGEW (WG1) are quite high as would be expected given that the six gauges (4, 13, 42, 44, 60, 68; see Figure 1) were selected to be well distributed within the WGEW. The correlation decreases as watershed size decreases and fewer of the six gauges are included in the average. In Table 4, the regressions for each of the six gauges and their average include an additional 10 years of observations (1997–2006) beyond those of *Nichols et al.* [2002].

[27] Table 5 contains the annual, summer, and nonsummer precipitation linear trend and statistical significance ($p < 0.05$ is considered significant) for various watershed scales using the average of six rain gauges (AVG6), and interpolated from 88 rain gauges over the entire watershed (WG1), WG6, WG11, and WG102 for 1956–1996 and 1956–2006. In all cases, the significant increasing trends for annual and

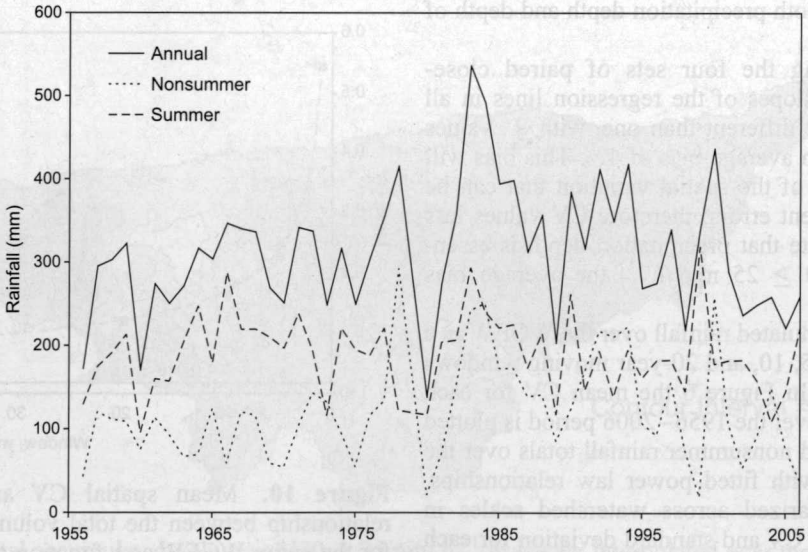

Figure 12. Annual, summer, and nonsummer WGEW yearly rainfall totals for 1956–2006.

Table 4. Regression Results Across Watershed Scales of Yearly Six-Gauge Average (as Used by *Nichols et al.* [2002]) of Annual, Winter, and Summer Precipitation Total Versus Interpolated Watershed Scale Precipitation for the Period of 1956–2006

	WG1		WG6		WG11		WG102	
	R^2	P Value	R^2	P Value	R^2	P Value	R^2	P Value
Annual	0.95	10E-33	0.94	10E-31	0.84	10E-21	0.81	10E-19
JFM	0.92	10E-28	0.92	10E-28	0.89	10E-25	0.88	10E-24
JAS	0.94	10E-32	0.92	10E-28	0.75	10E-16	0.05	0.11

nonsummer precipitation total found for 1956–1996 are no longer significant when the additional 10 years of observations are added. This was also the case for the regressions of the individual gauges used by *Nichols et al.* [2002]. In Figure 12, it is fairly apparent that the increasing trend from 1956 to 1996 is due to a consistently wetter period from 1983 to 1997. Average nonsummer rainfall during this period was 167 mm/a compared to 102 mm/a from 1956 to 1982 and 96 mm/a from 1998 to 2006.

[28] Figures 13a and 13b attempt to examine trends in precipitation relative to storm size and the volume of I30 $\geq$ 25 mm h^{-1} on an annual basis from 1956 to 2006 across watershed scales. Tests revealed no significant linear trends in either volume or areal coverage over the 1956–1996 and 1956–2006 periods.

4.3. Precipitation and Runoff

[29] As expected, the large interannual variability in precipitation described above translates directly into comparable variability in runoff. These data are summarized as a function of drainage area (ponds excluded) in Figure 14, for the 41-year period from 1966 to 2006. In a similar format, Figure 15 contains the average annual ratio of runoff volume over volume of precipitation with I30 $\geq$ 25 mm h^{-1} as a function of drainage area (1966–2006; vertical bars indicate one standard deviation). The decreasing trend of runoff per unit area with increasing watershed area is consistent with earlier analysis by *Goodrich et al.* [1997]. They concluded that the limited spatial scale of runoff producing thunderstorms, combined with increasing ephemeral channel transmission losses with increasing scale, were the primary factors responsible for this trend.

[30] A significant ($p < 0.05$) linear decreasing trend was found for annual runoff volumes from WG1 over the 1966 to 1998 period (Figure 16). This period was selected to further explore the conclusions of *Thomas and Pool* [2006], who noted a decrease in runoff in the San Pedro beyond what could be explained by decreasing trends in precipitation. In the work of *Thomas and Pool* [2006], a sharper downward trend in summer precipitation and summer streamflow began in the early to mid-1960s and continued through the last year of the record they considered (2002). The period we selected began in 1966 as this is when high confidence was achieved in runoff observations. The year 1998 was selected as the end date to exclude the large monsoon events in 1999 and 2000. The point being, we wanted to isolate a period of significantly decreasing runoff and examine whether or not precipitation or other watershed factors might influence this trend (e.g., vegetation, geomorphic change, etc.) with supporting observations in the WGEW.

[31] Since virtually all runoff from WG1 occurs during the summer, this is consistent with *Thomas and Pool* [2006], who found a significant decreasing trend in annual summer streamflow for 1961–2002. To more directly compare these trends, a linear trend analysis was conducted

Table 5. Annual, Summer (JAS), and Nonsummer (JFMAMJOND) Precipitation Linear Trend and P Value (<0.05 is Significant) for Various Watershed Scales Using the Average of Six Rain Gauges (AVG6) and Interpolated From 88 Rain Gauges Over the Entire Watershed (WG1), WG6, WG11, and WG102 for 1956–1996 and 1956–2006[a]

	1956–1996		1956–2006	
WS Scale	Regression Equation	P value	Regression Equation	P value
		Annual		
AVG6	2.72x − 5052.8	0.006	0.71x − 1092.5	0.33
WG1	2.46x − 4540.5	0.02	0.62x − 921.2	0.41
WG6	2.69x − 4999.4	0.01	0.79x − 1258.9	0.30
WG11	2.43x − 4484.0	0.02	0.69x − 1058.2	0.36
WG102	2.39x − 4407.4	0.05	0.33x − 345.2	0.71
		JAS		
AVG6	0.21x − 230.8	0.75	−0.02x + 219.1	0.97
WG1	0.08x + 38.8	0.90	−0.15x + 477.0	0.76
WG6	0.13x − 75.0	0.83	−0.07x + 321.1	0.89
WG11	0.14x − 80.0	0.85	−0.05x + 300.9	0.92
WG102	0.35x − 495.0	0.65	−0.22x + 617.7	0.69
		JFMAMJOND		
AVG6	2.51x − 4821.9	0.0004	0.73x − 1311.6	0.20
WG1	2.38x − 4579.3	0.002	0.77x − 1398.2	0.20
WG6	2.56x − 4924.4	0.001	0.86x − 1579.9	0.17
WG11	2.29x − 4403.8	0.003	0.75x − 1359.1	0.22
WG102	2.04x − 3912.5	0.006	0.54x − 962.8	0.35

[a]The precipitation units are in average depth of the drainage area in mm and "x" is time in years.

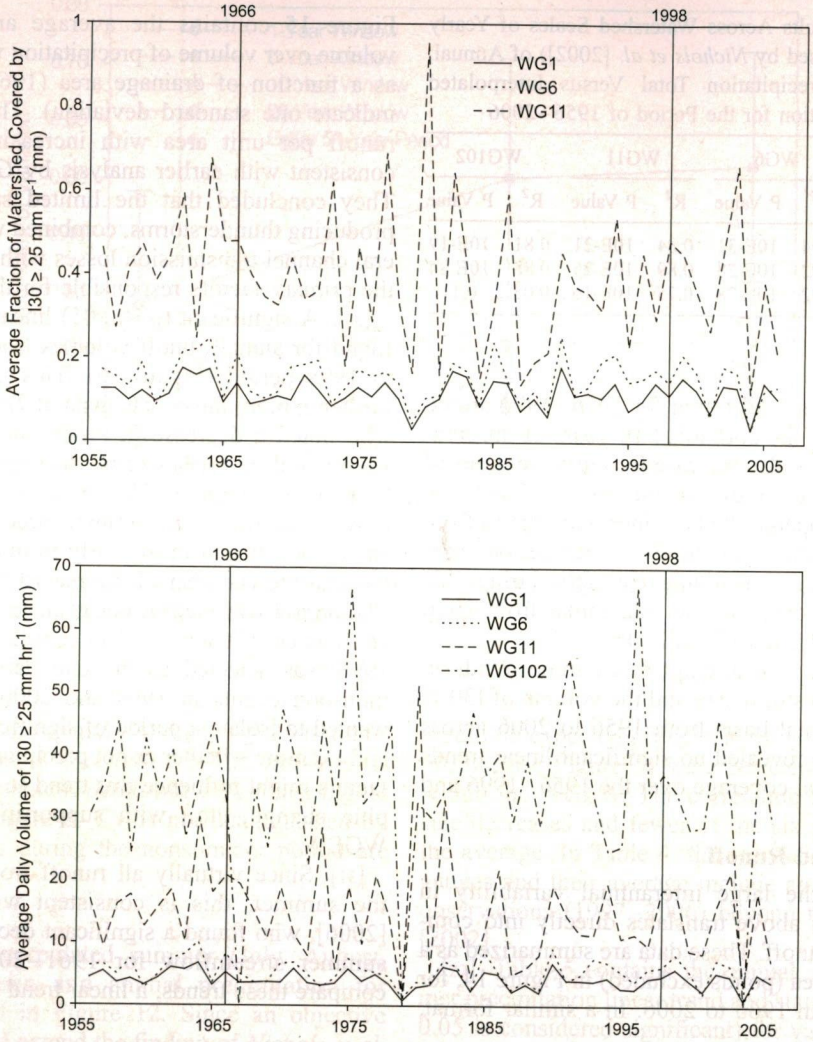

Figure 13. (a) Daily average fraction of watershed area covered by I30 $\geq$ 25 mm h^{-1} on an annual basis for WG1, WG6, and WG11; (b) daily average I30 $\geq$ 25 mm h^{-1} volume on an annual basis for WG1, WG6, WG11, and WG102.

for the 1966 to 1998 period using data from *Thomas and Pool* [2006]. The corresponding decreases in summer streamflow from the Charleston stream gauge and runoff from WG1 were 74% and 69%, respectively. The similarity in these percentages suggests that the decrease in summer flows in the San Pedro might be the result of the decreasing ephemeral tributary inflow.

[32] For WG1, the volume of annual I30 $\geq$ 25 mm h^{-1} was found to correlate relatively well with annual runoff volume (R^2 = 0.70) compared to the correlation of summer rainfall with runoff (R^2 = 0.43) using a power law relationship (Figure 17). The power law equation was used to capture the highly nonlinear nature of runoff generation in the WGEW [*Goodrich et al.*, 1997]. Residuals from this regression showed no significant trend with time (Figure 18) indicating that the trend in runoff may be explained by a nonlinear response to random variations in higher-intensity precipitation. However, the correlation between rainfall and runoff is not high enough to exclude other potential causative factors, such as changes in vegetation and channel morphology.

[33] For the case of vegetation, *Thomas and Pool* [2006] cite the large changes in land cover over time noted by *Kepner et al.* [2000]. In that study they analyzed and classified Landsat imagery over the San Pedro Basin for imagery from 1973, 1986, 1992, and 1997. The 1973 image was from a 60 × 60 m pixel resolution multispectral scanner (MSS) instrument and the latter images were from the 30 × 30 m thematic mapper (TM) instrument. However, all of the TM imagery was degraded to 60 × 60 m resolution to allow comparisons from 1973 onward. They detected a 415% increase in the mesquite (i.e., shrub) and a 15% decrease in grass cover from 1973 to 1986. *Kincaid et al.* [1966] noted that lower intensities of precipitation are required to produce runoff in the shrub-covered subwatersheds of the WGEW than in the grass-covered subwatersheds but in either cover type, runoff was far more dominated by rainfall characteristics. If mesquite behaves more like the common desert shrubs on the WGEW in terms of its partitioning of precipitation into runoff, this would imply an increase in runoff as vegetation changes from grass to mesquite. However, this is the opposite trend

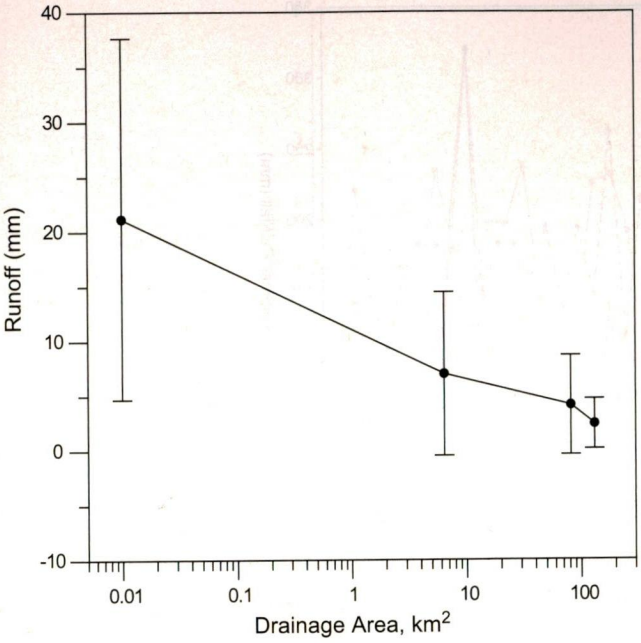

Figure 14. Average annual runoff volume for 1966–2006 as a function of drainage area; vertical bars indicate one standard deviation.

in runoff observed both herein and by *Thomas and Pool* [2006] for the 1966–1998 period.

[34] The land cover changes within the WGEW were examined more closely using the same classified land cover data layers analyzed by *Kepner et al.* [2000]. Table 6 contains the respective areas for the four imagery dates. The mesquite woodland class dramatically increased in area from roughly 20 to 1900 ha from the 1973 to 1986 imagery. However, it should be noted that roughly 1620 ha of the increase was due to conversion out of the desert scrub class. Thus most of the change is from one woody land cover type to another. In this case, one would expect a less dramatic change in runoff production than from a grassland cover to a woody cover. Care must also be taken in interpretation of these land cover changes. In the accuracy assessment of the classified cover maps by *Skirvin et al.* [2004] they noted that both the producer and user accuracies for the mesquite woodland class were low for all four dates (80% and 30%, respectively, for 1973, and 65% and 40% for the other dates). In addition, they noted particular problems with the mesquite woodland class by noting, "it was likely that neither the spectral nor the spatial resolution of MSS imagery was adequate to distinguish the mesquite woodland class in a heterogeneous semiarid environment, where most pixels are mixtures of green and woody vegetation, standing litter, and soils of varying brightness" [*Skirvin et al.*, 2004, p. 127].

[35] Visual examination of multidate low-level aerial photography, closely matching the date of the 1973 and 1986 imagery, also supported this point. For several areas in which the classified imagery indicated a change from desert scrub to mesquite woodland, what had actually taken place, as judged from the aerial photographs, was not a change in vegetation type but growth of the woody desert scrubs. Ground survey data presented by *King et al.* [2008] also does not support any significant changes in vegetation type from 1967 to 2005.

[36] Larger plants of the same species will likely have larger roots and a larger canopy which could possibly lead to greater interception and decreased soil moisture storage and thus a larger initial rainfall abstraction via higher soil suction. These factors could lead to a decrease in runoff but *Wilcox* [2007] noted that no such decline in streamflow was observed in conjunction with increases in woody shrub cover over the last century on the Edwards Plateau of Texas. In an earlier paper, *Wilcox* [2002] concluded that on mesquite and shrub dominated Texas rangelands, shrub control is unlikely to affect streamflow significantly because of (1) high ET; (2) deep soils with no groundwater interaction; (3) runoff is primarily Horton flow; and (4) most runoff is generated by flood producing precipitation events "...so overwhelming as to render insignificant other factors, such as interception by vegetation and even soil moisture storage." *Hibbert* [1983] also noted there was no potential to increase streamflow by shrub removal if precipitation is less than 500 mm/year (WGEW average precipitation is ~310 mm/a). If we view shrub growth as the converse of shrub removal, this also implies that shrub growth will have little or no impact on streamflow within the WGEW. These results discount vegetation change within the WGEW as a major agent of change in the hydrologic response of the watershed. Many of the above points would also discount reductions in runoff due to increased ET resulting from higher potential ET due to positive temperature trends with time.

[37] To further evaluate whether changes in the main channel may have been a causative factor in reducing runoff

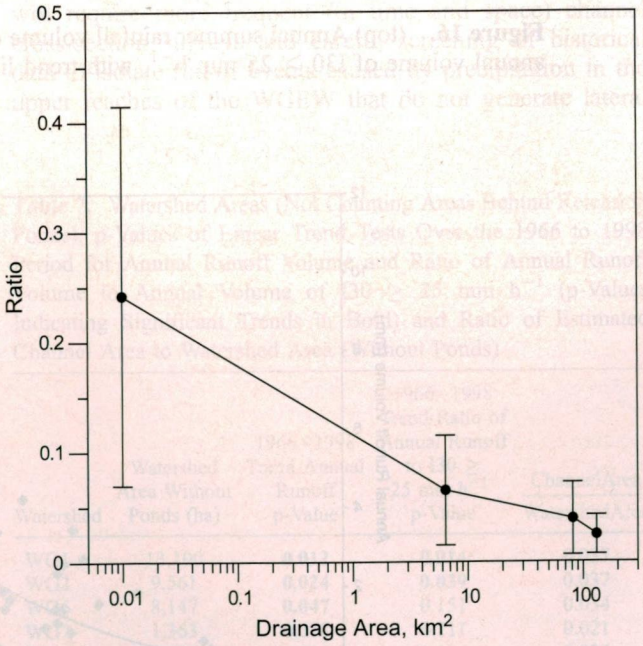

Figure 15. Average annual ratio of runoff volume to volume of I30 $\geq$ 25 mm h^{-1} for 1966–2006 as a function of drainage area; vertical bars indicate one standard deviation.

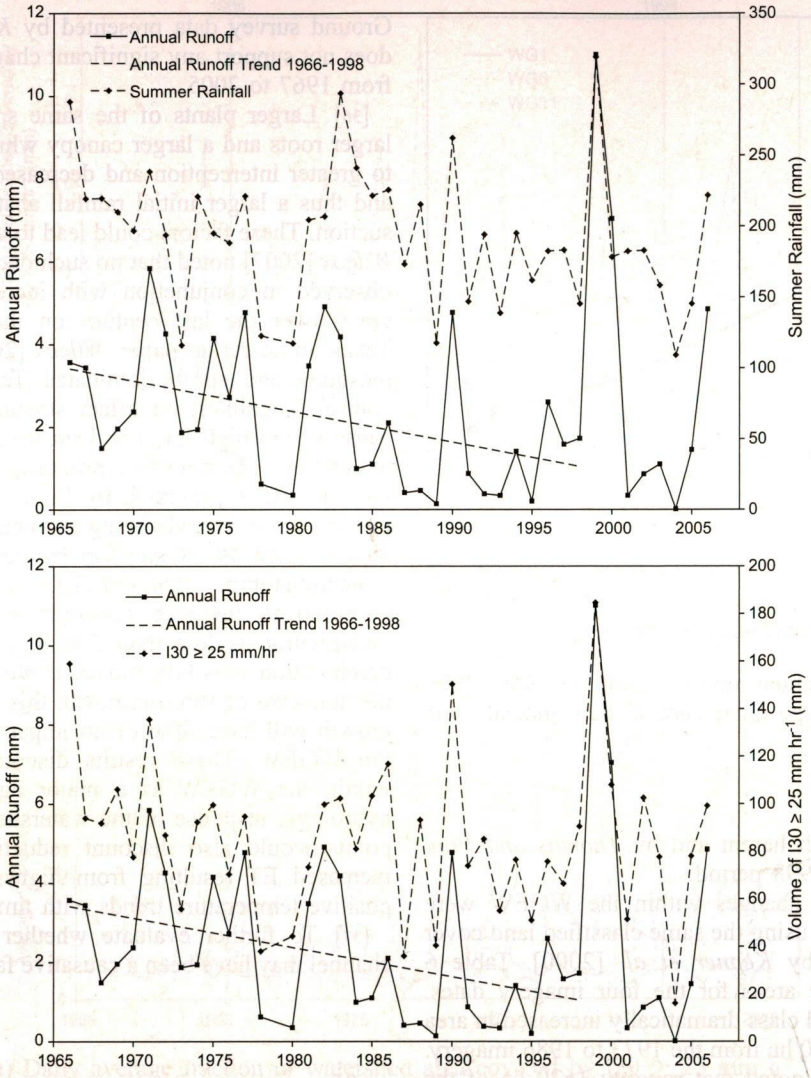

Figure 16. (top) Annual summer rainfall volume over WG1. (bottom) Annual WG1 runoff volume and annual volume of I30 $\geq$ 25 mm h^{-1}, with trend lines for the 1966–1998 period.

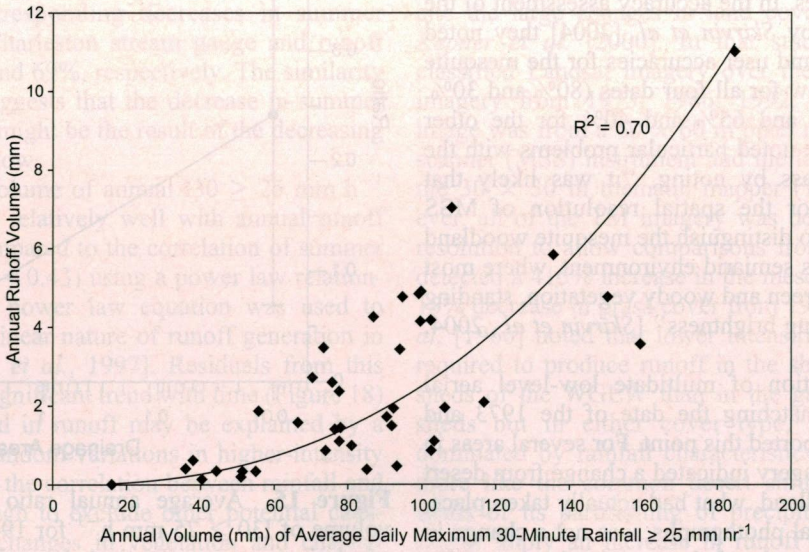

Figure 17. Annual WG1 runoff volume regressed against annual volume of I30 $\geq$ 25 mm h^{-1}.

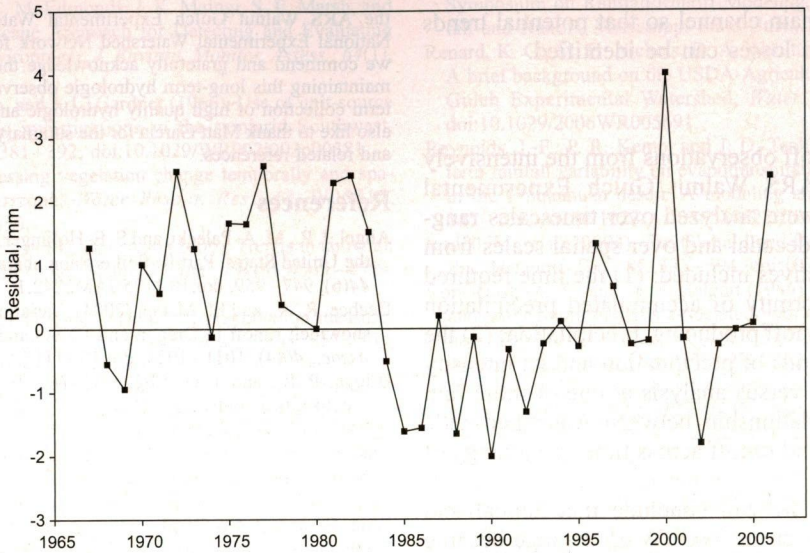

Figure 18. Residuals from regression of WG1 annual runoff volume against annual volume of I30 $\geq$ 25 mm h^{-1}.

from WG1 over the 1966–1998 period, runoff data from eight subwatersheds over a range of scales were also tested for trends (Table 7, Figure 1). For this period there were no significant trends in summer rainfall or in the annual volume of precipitation with I30 $\geq$ 25 mm h^{-1}. The second and third largest watersheds (WG2, WG6), both of which include sections of the main channel showed significant decreasing linear trends in annual runoff. Data from the smaller watersheds, except for WG11, did not have significant trends. The exception, WG11, has an uncharacteristically high ratio of channel to watershed area (Table 7) due to a large percentage of area lying behind two retention ponds. Discounting WG11, these results support the notion that the main channel has evolved over the 1966–1998 period in a way that increased transmission losses.

[38] *Goodrich et al.* [1997, 2004] discussed, in detail, the importance of channel transmission losses in watershed response in the ephemeral, influent WGEW. Data presented by *Nichols et al.* [2005] document the accumulation of sediment and large increases in vegetation within the main channel. Accumulation of sandy alluvium sediment in the main channels would provide additional storage to accommodate increased channel transmission losses. However, *Nichols et al.* [2005] also describe the formation of inset channels in an initially wide sand bed, with increasingly larger flows contained within the inset channels as they continued to develop. In contrast to our hypothesis, the reduced wetted perimeter and increased hydraulic efficiency of the inset channels would tend to decrease, rather than increase the amount of transmission losses leading to increased runoff. This contradictory finding requires further analyses which are being initiated. One line of thought is that in a regime of relatively small flood flows in which channel sediment aggrades and vegetation colonizes, that a positive feedback would develop with increasing channel transmission losses for a given flow level, resulting in a further decline of annual runoff. This will require more frequent (in time and space) channel cross-section surveys and careful screening of historical data to isolate runoff events caused by precipitation in the upper reaches of the WGEW that do not generate lateral

Table 6. Land Cover Areas for Each 1973, 1986, 1992, and 1997 Classified North American Land Cover Data Layers of the WGEW

	Area (ha)			
	1973	1986	1992	1997
Oak woodland	10.4	10.4	5.4	5.4
Mesquite woodland	19.4	1882	1890	1874
Grassland	4148	3866	3844	3817
Desert scrub	10,480	8574	8531	8438
Urban	139	292	328	479
Barren/clouds	-	173	198	183

Table 7. Watershed Areas (Not Counting Areas Behind Retention Ponds), p-Values of Linear Trend Tests Over the 1966 to 1998 Period for Annual Runoff Volume and Ratio of Annual Runoff Volume to Annual Volume of I30 $\geq$ 25 mm h^{-1} (p-Values Indicating Significant Trends in Bold) and Ratio of Estimated Channel Area to Watershed Area (Without Ponds)

Watershed	Watershed Area Without Ponds (ha)	1966–1998 Trend Annual Runoff p-Value	1966–1998 Trend Ratio of Annual Runoff to I30 $\geq$ 25 mm h^{-1} p-Value	ChannelArea / WatershedArea
WG1	13,100	**0.012**	**0.014**	0.037
WG2	9,561	**0.024**	**0.039**	0.037
WG6	8,147	**0.047**	0.151	0.034
WG7	1,363	0.078	0.211	0.021
WG9	2,076	0.804	0.186	0.034
WG10	1,478	0.468	0.244	0.041
WG11	635	**0.031**	**0.022**	0.062
WG15	1,640	0.506	0.166	0.041
WG102	1.46	0.750	0.107	0.006

inflow into the lower main channel so that potential trends in channel transmission losses can be identified.

5. Conclusions

[39] Rainfall and runoff observations from the intensively instrumented USDA-ARS Walnut Gulch Experimental Watersheds (WGEW) were analyzed over timescales ranging from event to multidecadal and over spatial scales from 1.5 to 15,000 ha. Objectives included: (1) the time required to achieve spatial uniformity of accumulated precipitation and of high-intensity, runoff producing, precipitation; (2) the temporal and spatial trends of precipitation and its intensity over the entire WGEW versus analysis at one or more rain gauges; and (3) the relationship between watershed-wide precipitation variation and runoff across time and a range of watershed scales.

[40] For objective 1 we can conclude that annual and seasonal precipitation over the WGEW on average became spatially uniform after 20 years of accumulation, as indicated by a spatial variability (CV) below the estimated variation due to measurement errors. Although the spatial variability of runoff-producing precipitation intensity ($I30 \geq 25$ mm h^{-1}) declined exponentially over the time periods of accumulation considered, it was still well above estimated measurement error after 51 years.

[41] In regards to the second objective we conclude that for every year from 1956 to 2006, annual precipitation exhibited a significant spatial trend. Owing to consistent trend directions mostly during the nonsummer season, accumulations since 1970 show an increasing trend to the southeast. This trend direction does not coincide with the direction of elevation trend for the rain gauge network, suggesting it is caused by larger-scale climatic or orographic features. While *Nichols et al.* [2002] found significant positive temporal trends for precipitation over the period of 1956 to 1996 for annual and nonsummer periods, with the addition of 10 years of observations, we found no significant trends in annual, summer, and nonsummer precipitation over the WGEW and three smaller internal subwatersheds. The trends computed from the average of six well-distributed rain gauges as employed by *Nichols et al.* [2002] were consistent with interpolated, basin-scale observations, derived in this study.

[42] For the third objective we conclude that only four of the nine subwatersheds of the WGEW had a significant decrease in runoff from 1966 to 1998. The volume of precipitation within a contiguous 30 min block of intensity greater or equal to 25 mm h^{-1} was a relatively good predictor of annual runoff volume for the overall watershed ($R^2 = 0.70$). A long-term decrease in runoff from ephemeral tributaries like the WGEW may be the primary cause of decreasing summer flows in the San Pedro. And it is likely that changes in higher-intensity, runoff-producing rainfall is a major factor responsible for the decreasing trend in runoff over the 1966–1998 period in the WGEW. Other factors could include changes in vegetation and increasing channel transmission losses, although the evidence for these is contradictory.

[43] **Acknowledgments.** This analysis would not have been possible without the many early Soil Conservation Service and ARS scientists and administrators who had the vision and commitment to construct and operate the ARS Walnut Gulch Experimental Watershed and the entire ARS National Experimental Watershed Network for the long-term. In addition we commend and gratefully acknowledge the dedication of ARS staff in maintaining this long-term hydrologic observatory and their diligent long-term collection of high quality hydrologic and watershed data. We would also like to thank Matt Garcia for the summary table of rain gauge densities and related references.

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D. C. Goodrich, C. L. Unkrich, T. O. Keefer, M. H. Nichols, J. J. Stone, L. R. Levick, and R. L. Scott, Southwest Watershed Research Center, Agricultural Research Service, U.S. Department of Agriculture, Tucson, AZ 85719, USA. (dave.goodrich@ars.usda.gov)