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PRECIPITATION CHANGES FROM 1956 TO 1996 ON THE WALNUT GULCH EXPERIMENTAL WATERSHED[1]

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ABSTRACT: The climate of Southern Arizona is dominated by summer precipitation, which accounts for over 60 percent of the annual total. Summer and non-summer precipitation data from the USDA-ARS Walnut Gulch Experimental Watershed are analyzed to identify trends in precipitation characteristics from 1956 to 1996. During this period, annual precipitation increased. The annual precipitation increase can be attributed to an increase in precipitation during non-summer months, and is paralleled by an increase in the proportion of annual precipitation contributed during non-summer months. This finding is consistent with previously reported increases in non-summer precipitation in the southwestern United States. Detailed event data were analyzed to provide insight into the characteristics of precipitation events during this time period. Precipitation event data were characterized based on the number of events, event precipitation amount, 30-minute event intensity, and event duration. The trend in non-summer precipitation appears to be a result of increased event frequency since the number of events increased during nonsummer months, although the average amount per event, average event intensity, and average event duration did not. During the summer "monsoon" season, the frequency of recorded precipitation events increased but the average precipitation amount per event decreased. Knowledge of precipitation trends and the characteristics of events that make up a precipitation time series is a critical first step in understanding and managing water resources in semiarid ecosystems.

(KEY TERMS: precipitation; statistical analysis; semiarid rangeland; surface water hydrology; meteorology/climatology.)

INTRODUCTION

The climate of semiarid rangelands in the southwestern United States is characterized by seasonal differences in moisture sources and amount of precipitation. Increased precipitation during July, August, and September characterize the Arizona "monsoon" season. Researchers recognize the Arizona "monsoon" as an expression of a larger scale North American monsoon (Douglas *et al.,* 1993; Adams and Comrie, 1997). The North American monsoon provides a large-scale influence on resulting summer precipitation, particularly with respect to atmospheric conditions (Carleton, 1985; Higgins *et al.,* 1997, 1998). Thunderstorm precipitation dominates the "monsoon" season in the southwestern United States. Airmass thunderstorms characterized by extreme spatial variability, limited areal extent, and short durations dominate precipitation-runoff relationships during July, August, and September in southern Arizona (Osborn, 1982). These storms result from convection currents that lift moist southerly air masses to produce summer thunderstorms. Summer thunderstorms in the Southwestern U.S. have a strong spatial dependence in association with topography. Convective currents are enhanced in areas of marked topographic relief (Carleton, 1986). Although annual precipitation volume is dominated by summer thunderstorm rainfall, the general precipitation pattern in southeastern Arizona is characterized by a bimodal precipitation distribution pattern that provides both winter and summer rain. Winter precipitation results from storms characterized by long duration, low intensity, and large areal coverage (Sellers, 1960). These precipitation events generally result from airmass lift caused by slow moving storm fronts emerging from the Pacific Ocean into and across California and Arizona.

The importance of summer precipitation is reflected in the research conducted during the past 46 years at the USDA-ARS Southwest Watershed Research Center. Precipitation during the summer "monsoon" season provides a major contribution to annual water yields and causes most of the surface runoff. The

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intense thunderstorms that dominate summer precipitation typically produce large peak discharges (Lane, 1983; Boughton *et al.,* 1987; Goodrich *et al.,* 1997). Flooding, replenishing of water supplies, erosion, and sediment transport are some of the obvious results of intense summer rains. Because thunderstorm precipitation is so important to water supply and water resource system design, precipitation research and analyses have focused on quantifying and characterizing the precipitation that falls during the summer "monsoon" season (Osborn, 1983a, 1983b). Runoff producing precipitation is of primary interest to engineers and hydrologists concerned with the consequences of extreme events.

In contrast to thunderstorm generated runoff and water yield, the consequences of precipitation during nonsummer months are less dramatic, but are still important to semiarid ecosystems. Infiltration and soil moisture distribution dominate the hydrologic cycle from October through May. Precipitation during nonsummer months is more likely to be gentle, long duration, soaking rain that produces very little runoff. Conditions during these months are more favorable for soil moisture storage because during the summer months, high temperatures result in large evaporation losses. Vegetation in semiarid ecosystems has evolved to make efficient use of this temporally distributed precipitation. Land use (primarily grazing) and management strategies have been developed to accommodate dry periods and the subsequent "monsoons."

Vegetation on the semiarid rangelands of southeastern Arizona is generally described by the broad classes of shrubs and grasses, but there is great variety in the species across the region. Sorting out the effects of temporal precipitation pattern changes on vegetation is a complex challenge. Shrubs and grasses coexist, but their relative abundances often shift in response to changes in seasonal precipitation, among other factors (McClaran and Van Devender, 1995). The amount and timing of germination, establishment, and growth are controlled in part by precipitation and the soil moisture availability. The seasonal distribution of precipitation plays a role in plant response (Burgess, 1995). Climate variability over decadal time scale has been shown to affect large scale ecological response (Swetnam and Betancourt, 1998). At smaller scales, the response of vegetation to wet or dry years can be seen in plant cover, density, and abundance (Goldberg and Turner, 1986; Neilson, 1986; Burgess, 1995).

During the last century there has been a general change from grasslands to shrublands in the southwestern United States (Hastings and Turner, 1980; Humphrey, 1987). Observations and limited published information indicates that there has been a change in vegetation on the Walnut Gulch Experimental Watershed during the past 40 years. Knowledge of precipitation trends and the characteristics of events that make up precipitation time series may be a critical first step in understanding ecosystem response and managing water resources in semiarid watersheds.

Within the last decade, connections between climate and larger scale atmospheric phenomenon have been the subject of scientific interest and research. Seasonal, annual, interannual, and decadal variability result in a complex precipitation regime in southeastern Arizona (Sheppard *et al.,* 2001; Cayan *et al.,* 1998). The amount of precipitation received in any given year is highly variable. Periods of drought and above average precipitation can be identified in precipitation records. Although not conclusive, research conducted during the past decade has suggested a connection between interannual variation in precipitation and variations in larger scale atmospheric circulation patterns. Quantifying this variability is part of a larger complex climate regime that has been the subject of increasing scientific interest and research during the past decade. Characterizing the climate of the southwestern U.S. has revealed connections between increasing sea surface temperatures in the eastern Pacific Ocean that results in increased amounts of winter precipitation (El Niño) and the related atmospheric component that includes barometric pressure variations that drive air flow patterns (Southern Oscillation). On an interannual time scale El Niño has been identified as a cause of quasi-periodic climate variability. El Niño episodes, which are associated with wetter winters and dryer summers in the southwest, have been identified as a major source of variability in precipitation (Woolhiser *et al.,* 1993; Andrade and Sellers, 1988; Carleton, *et al.,* 1990; Redmond and Koch, 1991). A series of wetter winters since the 1970s in the southwest has been linked to the more frequent occurrence of El Niño episodes, especially in the decade from 1980 to 1990 (Trenberth and Hoar, 1996).

Much of the recent research to determine physical causes of variations in climate and precipitation in the Southwestern U.S. has been based on precipitation records complied on daily, monthly, or annual time scales. Unfortunately, detailed long-term precipitation records are rare in the Southwestern U.S. with the longest records generally restricted to the 100 most recent years of time. The lack of long-term event based precipitation data has limited detailed characterization of precipitation events. Data collected over sufficient spatial and temporal coverage is still an expressed need to further the understanding of connections between the atmosphere, oceans, and land (Higgins *et al.,* 1997).

As previously described, a large body of research exists to understand and explain connections between large-scale atmospheric circulation patterns and precipitation on a daily, monthly, or annual time scale. Quantifying the characteristics of individual events will add to that understanding. The detailed precipitation records collected on the Walnut Gulch Experimental Watershed offer the opportunity to quantify precipitation events during summer "monsoon" and other seasons to provide information on the character of precipitation events as well as general trends in precipitation amounts. The goal of this paper is to provide insight into the characteristics of summer and non-summer precipitation events in southeastern Arizona based on detailed event data collected on the USDA-ARS Walnut Gulch experimental Watershed from 1956 to 1996.

The USDA-ARS Walnut Gulch Experimental Watershed

The USDA-ARS Walnut Gulch Experimental Watershed (Figure 1) is located in the transition zone between the Sonoran and Chihuahuan Deserts. In general, the distinction between vegetation in the Sonoran and Chihuahuan ecosystems is related to precipitation regime. Precipitation in the Chihuahuan desert is concentrated in the summer months while the Sonoran desert receives both winter and summer precipitation.

The watershed comprises 150 square kilometers in the San Pedro River Valley in southern Arizona and is representative of approximately 60 million hectares of brush and grass covered rangeland found throughout the semiarid southwestern U.S. (Renard *et al.,* 1993). Beginning in 1953 the watershed was instrumented with weighing raingages. By 1956, a raingage

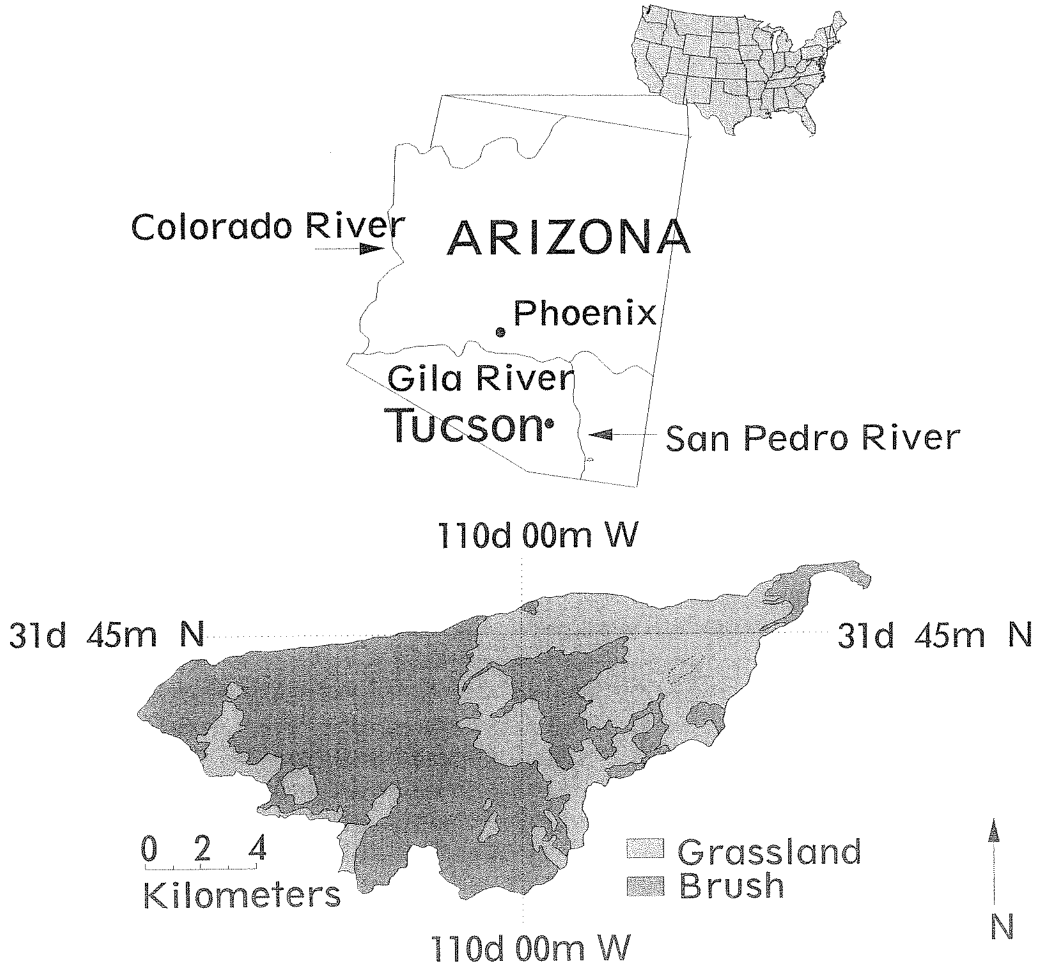

Figure 1. USDA-ARS Walnut Gulch Experimental Watershed Location Map.

network consisting of 40 gages was recording precipitation on the watershed. Over time raingages were added to the network; however, there are few continuous records spanning the entire time period from 1954 to 1996. Currently, the 93 raingages make up the densest raingage network in the semiarid southwestern United States.

METHODS OF ANALYSIS

Changes in summer and non-summer precipitation were assessed based on six spatially distributed gages with continuous records from 1956 to 1996 (Table 1). This time period spans the longest available recordings for which there is spatially distributed coverage of the watershed. Gages 4, 13, 42, 44, 60, and 68 (Figure 2) were chosen to represent the entire period.

Linear regression of various seasonal precipitation statistics was performed to determine if temporal changes in precipitation patterns on the Walnut Gulch Experimental Watershed are significant. For the purpose of this analysis, summer is defined as July, August, and September; nonsummer includes all other months. Descriptive statistics of annual precipitation (January to December), summer, and non-summer precipitation are presented in Table 2. Average annual precipitation on the watershed ranged from 303 mm at the lower end of the watershed to 339 mm near the upper end. Summer precipitation dominates the contribution to total annual volume and exhibits a more consistent seasonal average than the nonsummer precipitation.

TABLE 1. Characteristics of Six Raingages Used in Subsequent Analyses.

Gage	Easting	Northing	Elevation (m) msl	Number of Events 1956 to 1996
4	583035	3512291	1275	2630
13	586181	3509986	1327	2670
42	592741	3504730	1433	2564
44	595013	3511431	1443	2381
60	599722	3512251	1524	2638
68	603116	3512988	1585	2560

RESULTS

Linear regression equations and statistical significance, as indicated by P-values less than 0.05, for annual precipitation for the six gages are listed in Table 3. The annual precipitation and linear trends for Gages 4 and 60 are shown graphically in Figure 3. Gages 4 (located at the lower end of the watershed) and 60 (located near the upper end of the watershed) represent the range in mean annual precipitation from 1956 to 1996.

Linear regression of total annual precipitation revealed significant increasing trends (95 percent

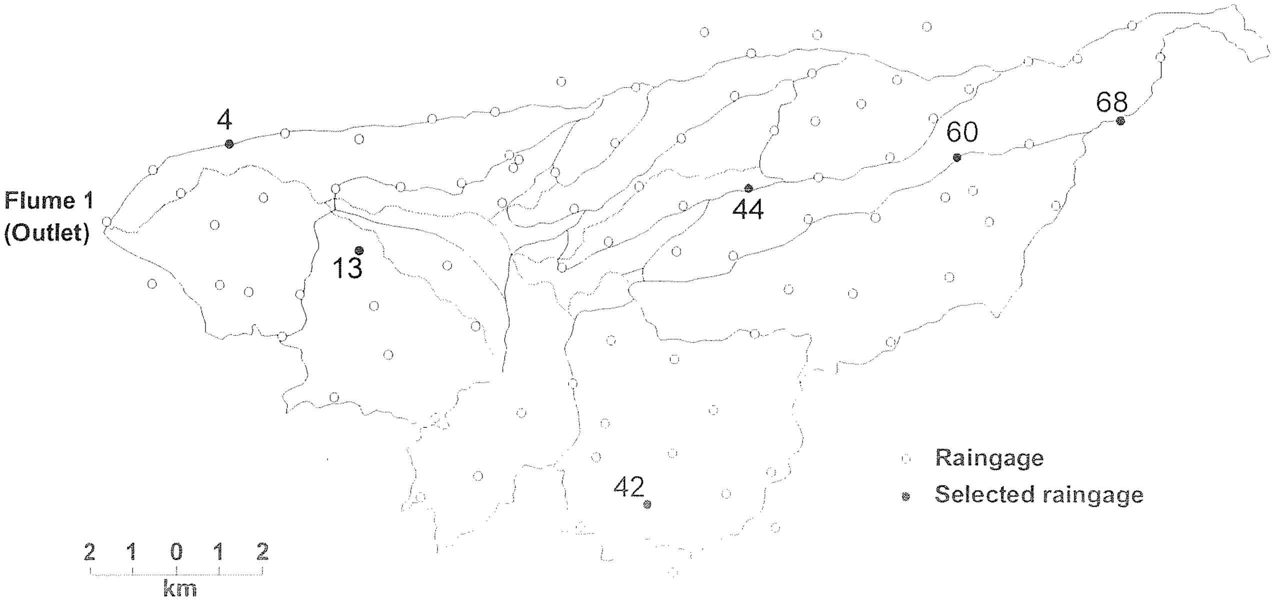

Figure 2. USDA-ARS Walnut Gulch Experimental Watershed Raingage Network With Selected Raingages Indicated.

TABLE 2. Characteristics of Precipitation at Six Gages Based on Data Collected From 1956 to 1996.

Gage	Minimum	Maximum	Mean	Variance
Annual Precipitation (mm)				
4	136	519	303	6230
13	171	574	312	7601
42	121	517	317	8413
44	103	537	304	7063
60	170	542	339	8200
68	141	507	330	6631
Summer Precipitation (mm)				
4	100	338	184	3283
13	72	336	182	3128
42	50	305	185	3991
44	28	302	181	3282
60	93	378	199	3886
68	74	377	191	3384
Nonsummer Precipitation (mm)				
4	37	257	119	2634
13	43	266	129	3065
42	46	300	132	4069
44	40	277	122	3205
60	52	309	140	4088
68	46	322	139	3786

confidence level) in total annual precipitation with time, with the exception of Gage 4. It should be pointed out that although the range of slopes in the linear trend of 2.5 to 3.8 mm per year may seem small, this amounts to increases in mean annual precipitation of between 102.5 and 155.8 mm during the 41-year record. This is considerable with respect to mean annual precipitation on the order of 300 to 330 mm.

TABLE 3. Linear Trend in Annual Precipitation Recorded at Six Gages During the Time Period 1956 to 1996.

Gage	Regression Equation	P-Value (x-coefficient)
4	$y = 1.44x - 2551.4$	0.17
13	$y = 2.52x - 4666.7$	0.03
42	$y = 2.50x - 4618.3$	0.04
44	$y = 2.78x - 5190.0$	0.01
60	$y = 3.79x - 7160.0$	0.001
68	$y = 3.26x - 6118.9$	0.001

The semiarid environment of southeastern Arizona is characterized by a high degree of temporal variability in precipitation, both from season to season and from year to year. Yearly variability in precipitation can be seen clearly in Figure 3. Periods of above and

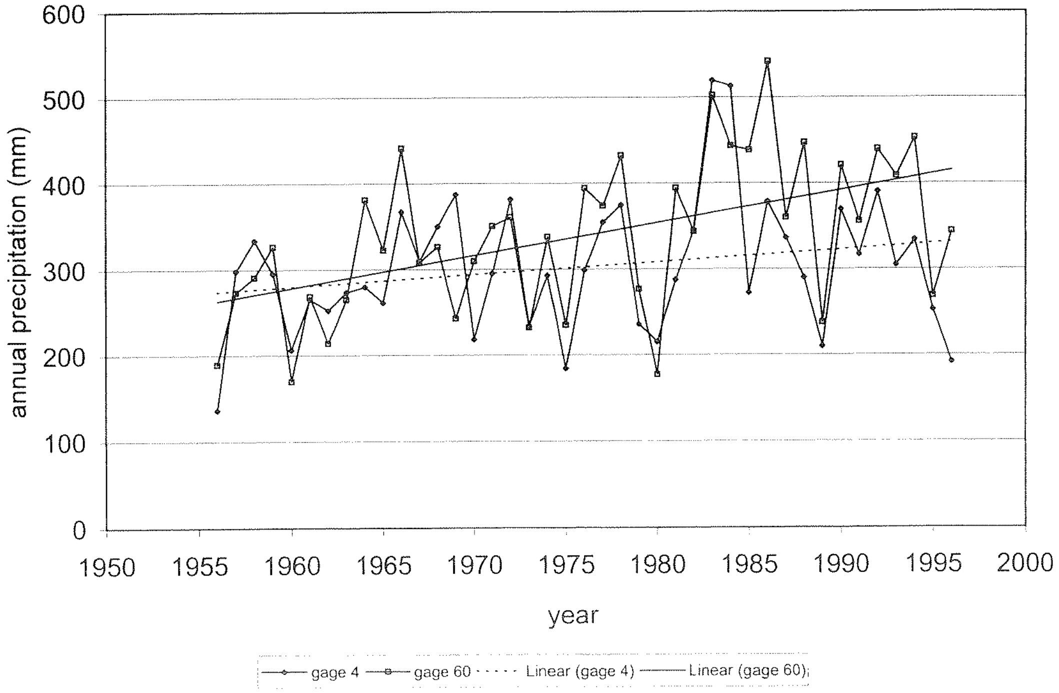

Figure 3. Annual Precipitation From 1956 to 1996 at Gages 4 and 60 With Linear Trend Indicated.

below average precipitation are common. So, a summary of annual trends in precipitation does not provide sufficient information to directly infer impacts of temporal changes on the fragile semiarid ecosystem. To understand the possible implications of this precipitation increase, an analysis of trends in summer and non-summer precipitation was conducted.

The summer air mass thunderstorms are the dominant precipitation producer in the semiarid southwest. Summer season precipitation on the Walnut Gulch Watershed contributes nearly two-thirds of the total annual precipitation (Table 2). But, despite the increasing trend in annual totals, linear regression of summer precipitation does not indicate a statistically significant trend at any of the six gages (Figure 4 and Table 4).

As the increasing trend in annual precipitation and the lack of a trend in the summer record would suggest, there is a significant linear relationship between time and non-summer precipitation. For each gage, linear regression revealed a highly significant positive trend in annual nonsummer precipitation (Figure 5 and Table 5). This result is consistent with previously reported increases in nonsummer precipitation in the southwestern U.S. Although the 41-year record is probably not sufficient to provide reliable statistical interpretations of trends over the decadal timescale, Figure 5 suggests that interannual variability in nonsummer precipitation is increasing. The average nonsummer precipitation from 1956 to 1975 was 91.6 mm (variance = 1006 mm, minimum = 36.8 mm, and maximum = 150.9 mm) in contrast to the average for the 1976 to 1996 time period, which was 140.7 mm (variance = 3104 mm, minimum = 42.7 mm, maximum = 256.8 mm).

TABLE 4. Linear Trend in Summer Precipitation Recorded at Six Gages During the Time Period 1956 to 1996.

Gage	Regression Equation	P-Value (for x-coefficient)
4	y = -0.35x + 875.1	0.65
13	y = 0.29x - 387.0	0.702
42	y = -0.24x + 649.5	0.782
44	y = 0.33x - 462.9	0.672
60	y = 0.65x - 1091.2	0.434
68	y = 0.59x - 968.7	0.452

Although average summer seasonal precipitation accounts for approximately 60 percent of the annual precipitation on the watershed over the study period, this analysis indicates there is an increase in the proportion of the nonsummer contribution to the total with time. Linear regression revealed a positive linear trend in the proportion of precipitation accounted for

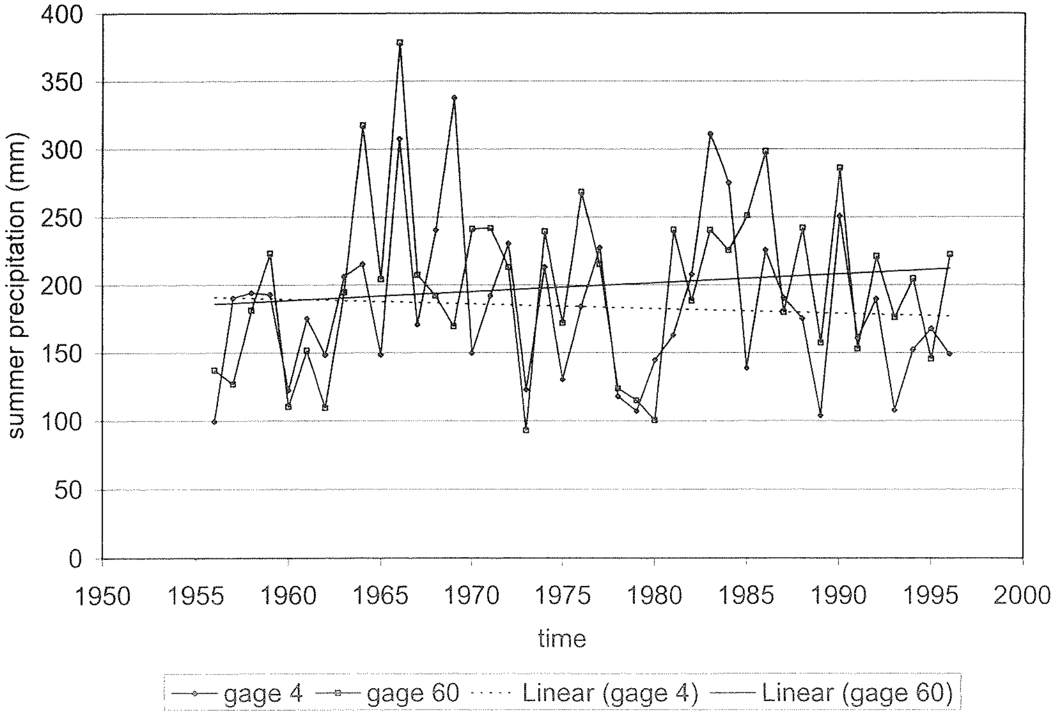

Figure 4. Summer Precipitation From 1956 to 1996 at Gages 4 and 60 With Linear Trend Indicated.

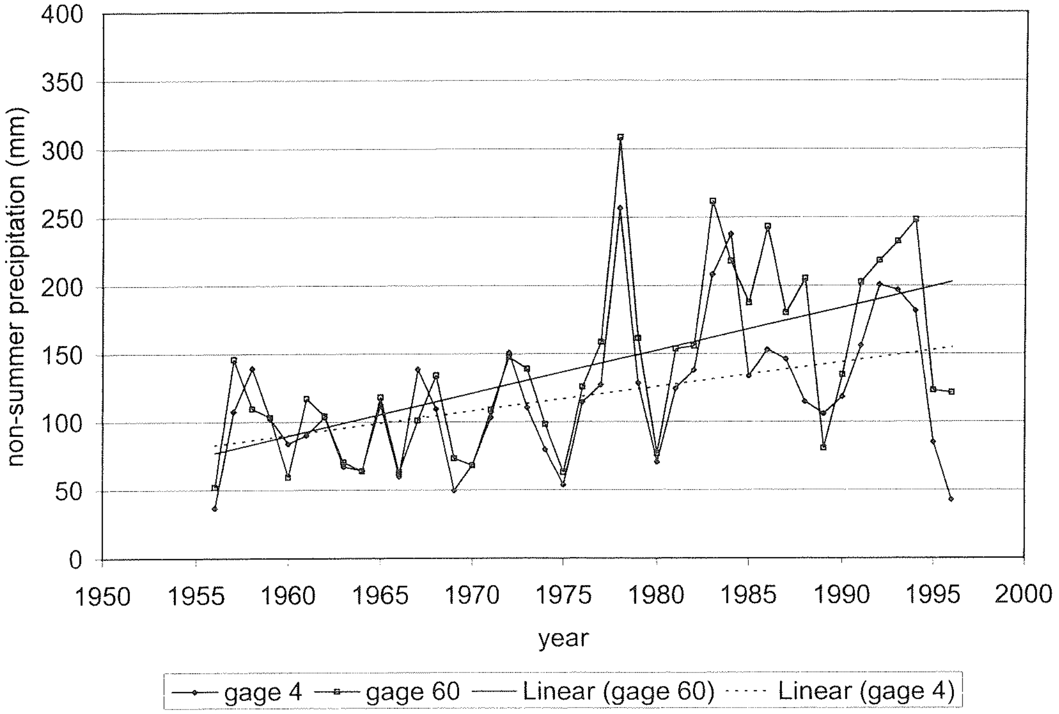

Figure 5. Nonsummer Precipitation From 1956 to 1996 at Gages 4 and 60 With Linear Trend Indicated.

by nonsummer storms with the trend line indicating slightly more than 30 percent in 1956 and just below 50 percent in 1996.

TABLE 5. Linear Trend in Nonsummer Precipitation Recorded at Six Gages During the Time Period 1956 to 1996.

Gage	Regression Equation	P-Value (for x-coefficient)
4	y = 1.79x - 3426.5	0.006
13	y = 2.23x - 4279.7	0.001
42	y = 2.74x - 5277.7	0.0006
44	y = 2.45x - 4727.1	0.0005
60	y = 3.14x - 6068.8	0.00005
68	y = 2.68x - 5150.2	0.0005

Long term historic precipitation records are rare in southeastern Arizona, and detailed event rainfall records that include time and intensity values are even rarer. Precipitation data collected on the Walnut Gulch Experimental Watershed consists of detailed storm event information that can be used to characterize precipitation event duration, intensity, and amount.

Further insight into the character of precipitation during summer and nonsummer was gained by evaluating event data for trends in: (1) the number of events per year for each of the seasons; (2) the average yearly precipitation amount recorded per event for each of the two seasons; (3) the average event duration per year for each season; and (4) the average 30 minute event maximum intensity per year for each season

A general summary of event characteristics for both summer and nonsummer months is presented in Table 6 and Figure 6. The number of precipitation events recorded at the six raingages increased from 1956 to 1996 during both the summer and nonsummer months (Table 7 and Figures 7 and 8), with the exception of the number of summer events recorded at Gage 4. However, there was no statistically significant change in the average precipitation amount recorded per event during the nonsummer months. This stands in contrast with the decrease in the average precipitation amount recorded per event during the summer months (Table 8 and Figures 9 and 10). There was no statistically significant change in average event duration or in average 30-minute event intensity, although during the summer months, three of the gages showed a decrease in average 30-minute event intensity for the 41-year precipitation record.

TABLE 6. General Summary of Event Characteristics From 1956 to 1996.

Season	Number of Events/Year	Average 30-Minute Event Intensity	Average Event Amount	Average Event Duration
Summer (July, August, September)	Increasing, except Gage 4	Decreasing at Gages 4, 13, 42 No change at Gages 44, 60, 68	Decreasing, except Gage 44	No change
Nonsummer (all other months)	Increasing	No change	No change	No change

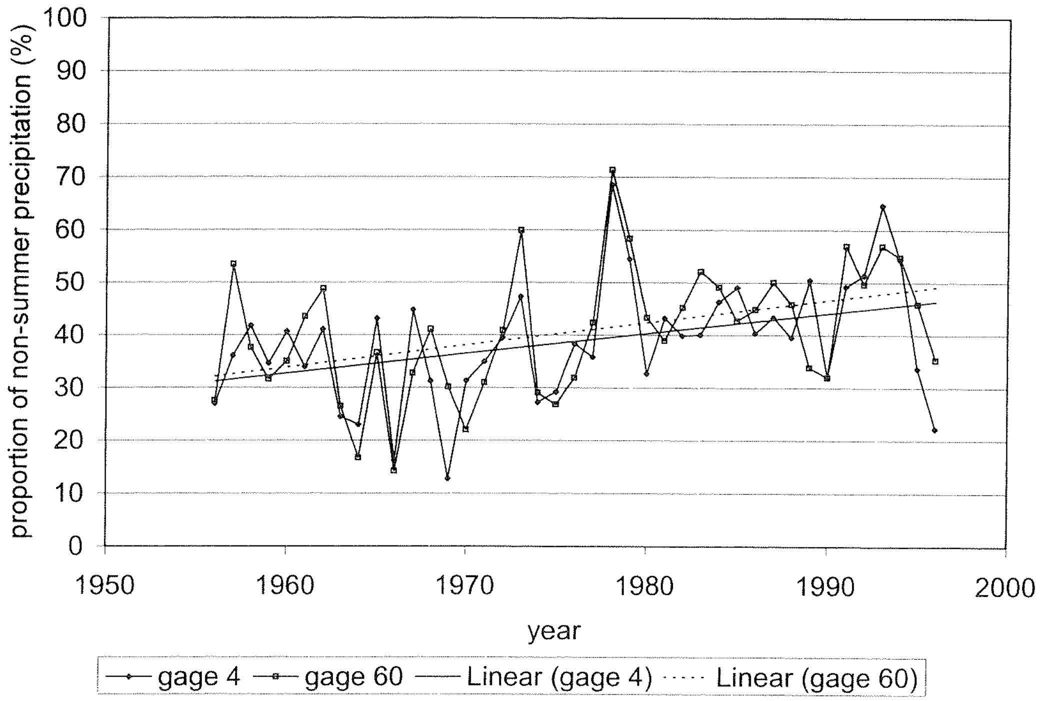

Figure 6. Proportion of Annual Precipitation Contributed by Nonsummer Precipitation at Gages 4 and 60 With Linear Trend Indicated.

TABLE 7. Linear Trend in the Number of Precipitation Events From 1956 to 1996.

Gage	Summer Regression Equation	Summer P-Value (for x-coefficient)	Nonsummer Regression Equation	Nonsummer P-Value (for x-coefficient)
4	y = 0.13x + 23.5	0.24	y = 0.40x + 0.01	0.005
13	y = 0.30x + 10.8	0.004	y = 0.45x - 2.8	0.003
42	y = 0.27x + 11.9	0.008	y = 0.49x - 7.2	0.001
44	y = 0.19x + 15.5	0.03	y = 0.56x - 14.3	0.0005
60	y = 0.39x + 3.06	0.0003	y = 0.69x - 20.6	0.00003
68	y = 0.28x + 10.8	0.01	y = 0.61x - 15.5	0.0002

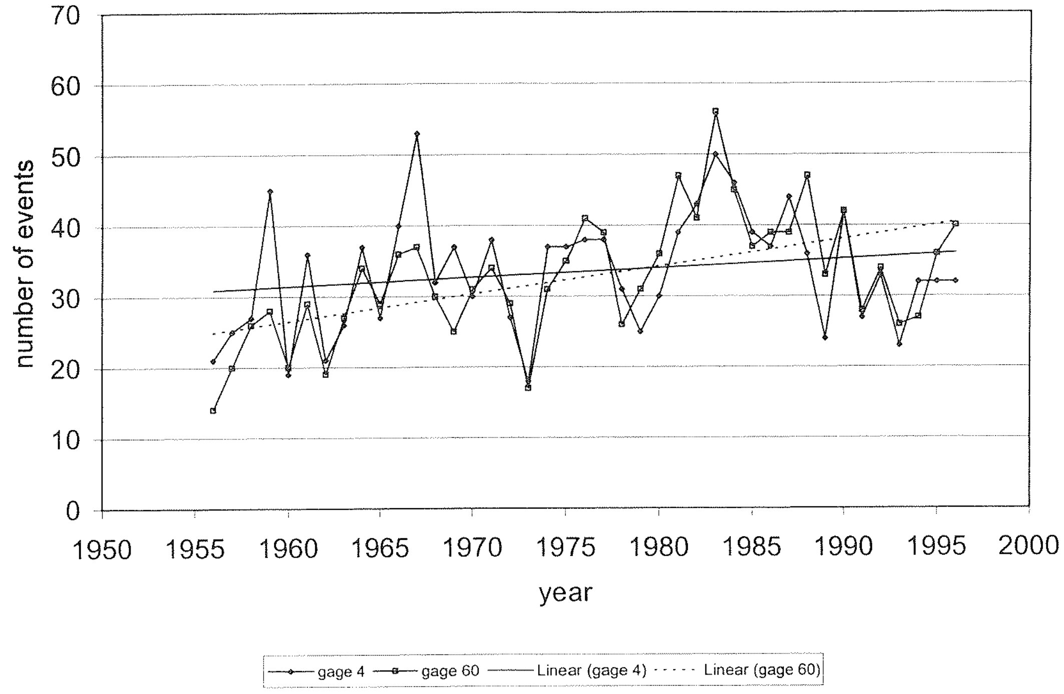

Figure 7. Number of Precipitation Events During Summer Months.

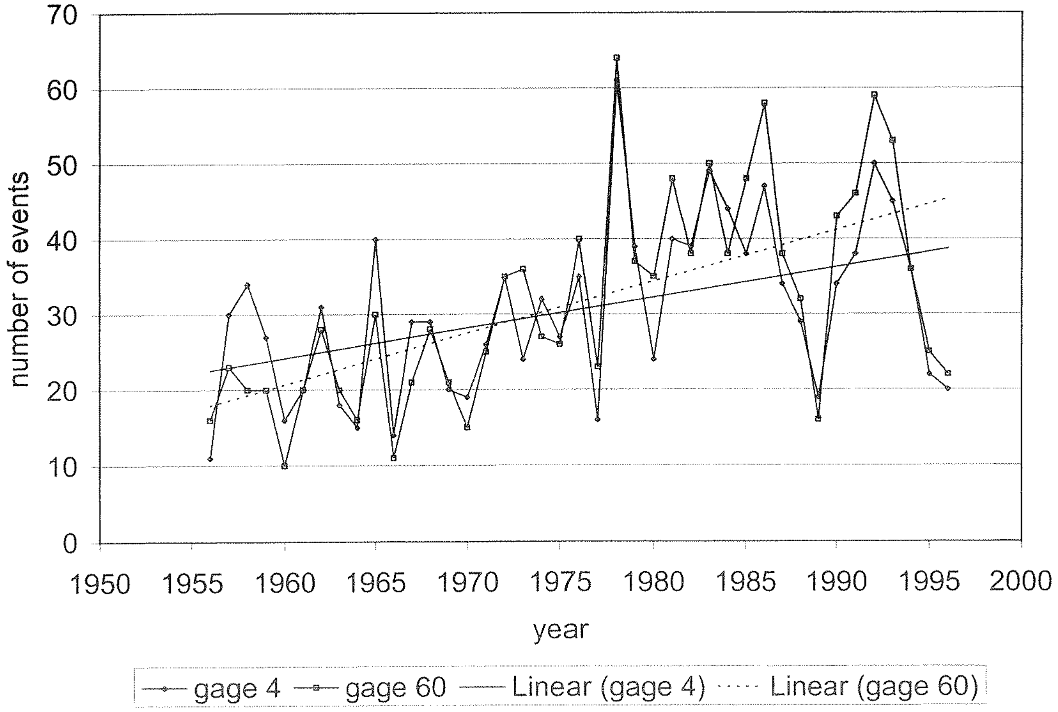

Figure 8. Number of Precipitation Events During Nonsummer Months.

TABLE 8. Linear Trend in Average Amount of Precipitation Per Event From 1956 to 1996.

	Summer		Nonsummer	
Gage	Regression Equation	P-Value (for x-coefficient)	Regression Equation	P-Value (for x-coefficient)
4	$y = -0.04x + 8.8$	0.02	$y = 0.003x + 3.7$	0.81
13	$y = -0.05x + 9.1$	0.004	$y = 0.008x + 3.6$	0.56
42	$y = -0.06x + 9.9$	0.004	$y = 0.019x + 3.1$	0.39
44	$y = -0.03x + 8.3$	0.17	$y = -0.004x + 4.9$	0.83
60	$y = -0.05x + 10.4$	0.008	$y = 0.002x + 4.4$	0.90
68	$y = -0.03x + 8.4$	0.08	$y = -0.003x + 5.0$	0.85

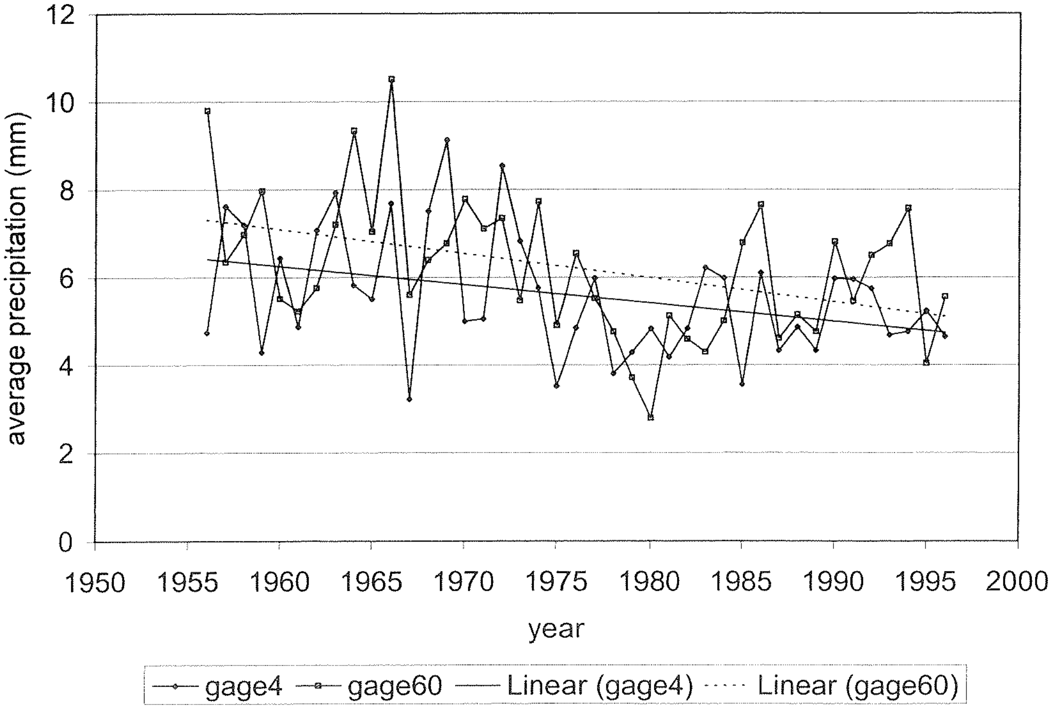

Figure 9. Average Event Depth During Summer Months.

DISCUSSION AND CONCLUSIONS

The analysis presented in this paper is based on the finite time period from 1956 to 1996. During this period there was an increase in total annual precipitation on the Walnut Gulch Experimental Watershed. In the context of longer term trends in precipitation in southeastern Arizona, the time period from 1956 to 1996 follows one of the most severe droughts on record since the end of the 1800s. The drought period in the 1950s was followed by a period of increasing precipitation. The trends identified in this paper are part of longer term precipitation patterns that cannot be adequately quantified based on limited periods of record. They do, however, indicate that within the fluctuations of large scale precipitation patterns there are changes in the precipitation patterns which may be consequential. The increase of annual precipitation totals coincides with observations that vegetation is changing on the Walnut Gulch Experimental Watershed. It is uncertain and difficult to quantify the

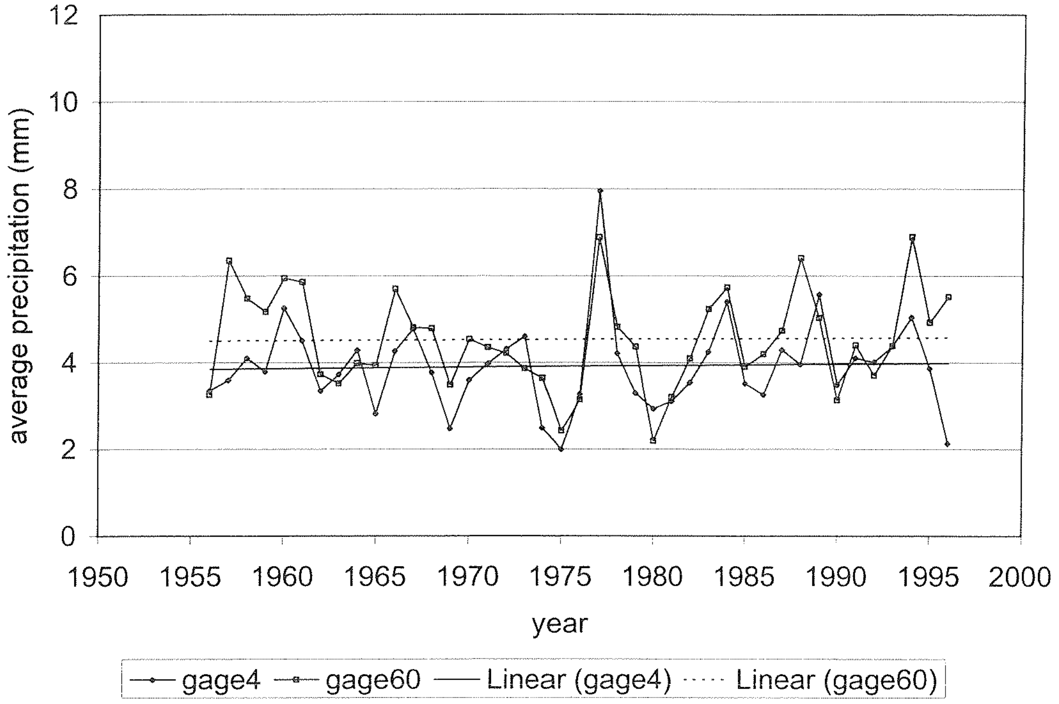

Figure 10. Average Event Depth During Nonsummer Months.

contributing factors of this change. Quantifying trends in event precipitation characteristics and the temporal distribution of events is a first step in understanding the connection between precipitation patterns and ecological response.

Precipitation event data were characterized based on the number of events, amount of event precipitation, 30-minute event intensity, and event duration. Evaluation of the trends in summer and nonsummer precipitation characteristics reveals that the increase in total annual precipitation is not simply a case of more precipitation. The seasonal distribution of events and the character of individual events within each season have changed during this period. Based on an evaluation of event frequency, duration and intensity we conclude that:

1. The increase in annual precipitation totals can be attributed nearly entirely to an increase in precipitation during nonsummer months and consequently by an increase in the proportion of annual precipitation occurring during the non-summer months.

2. The increasing trend in nonsummer precipitation appears to be a result of increased event frequency rather than a change in the character of individual events. The number of events increased during nonsummer months, but the average amount per event, average event intensity, and average event duration did not. The precipitation amount recorded during the summer "monsoon" season shows no trend during the study period, but the frequency of recorded precipitation events increased, and the average amount of precipitation per event decreased. Thus the impacts of the increase in total annual precipitation during this period may be driven substantially by the underlying change in precipitation event characteristics and a change in precipitation seasonality.

3. The precipitation characterization needs to be coupled with vegetation data to assess the ecological impact of changes in the character of precipitation events on the Walnut Gulch Experimental Watershed. The relationships between the physiologic and morphologic characteristics of individual species and changes in precipitation distribution patterns are a subject for further research.

4. Where available, additional long-term event precipitation records from the southwestern U.S. should be evaluated to determine whether the trends reported herein persist over large distances and from one mountain basin to another.

Of all the factors contributing to range condition (e.g., climate, soils, vegetation) vegetation is the one most easily influenced by management activities. However, vegetation depends on precipitation, the characteristics of which may be changing with time. One of the great difficulties in management of semiarid desert vegetation is climate variability. Quantifying precipitation variability is a critical need for understanding the relationships between precipitation and semiarid ecosystem response. Ultimately, the goal of continued research to determine the significance of the identified precipitation trends relative to trends in vegetation is the development of improved semiarid rangeland management practices.

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