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Climatic Change and Streamflow in the Southwest

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Abstract

Extreme variability between summer rainfall seasons in the 1880's, followed by a summer drought in the 1890's and early 1900's, possibly combined with the influx of cattle to the region in the 1880's, may have significantly altered the range and basin ecosystems in southern Arizona and much of the Southwest. A small, but possibly meaningful, decline in summer rainfall, along with a more stable winter precipitation plus continued pressure from grazing, is the most likely explanation for continued deterioration of the rangelands. The large number of recent damaging floods on the Santa Cruz River is mostly the result of the greater incidence of fall storms, rather than a change in basin and channel characteristics. For the period 1956-1980, annual flood peaks for the San Pedro River were not correlated to flood peaks from the USDA-ARS Walnut Gulch Experimental Watershed, a small subdrainage of the San Pedro, suggesting that long-term streamflow records on major basins are not helpful in determining the representativeness of shorter records from southeastern Arizona.

Introduction

Two major ecosystem perturbations have been observed in the Southwest during the last 100 years. From 1880 to around 1900, many formerly perennial or intermittent streams exhibited a rapid down-cutting and subsequent entrenchment (2, 8). Many of these regime changes were observed to occur, or be initiated, within a single storm season. The rapid entrenchment process resulted in loss of riparian vegetation and associated changes in a rather short period. About the same time, and continuing to the present, profound changes in vegetation have occurred. These changes were perhaps most dramatic in the warm season grasslands. Large areas of relatively open grasslands were subjected to deterioration of soil, water, and plant resources characterized by invasion of woody vegetation, accelerated erosion, loss of water-holding capacity of the soil, and decline in grassland productivity (6. 7).

Several hypotheses, such as fire suppression, overgrazing, exploitation of woodlands, and climate change have been proposed, either singularly or in combination, to explain these changes (1, 2, 3, 6, 7). Depending upon which hypothesis is accepted, profound implications for future water resources, land use, and management result. For example, if overgrazing was the primary cause of these changes, then our future land management alternatives are of primary importance. If, on the

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other hand, these changes in the ecosystems were primarily in response to climatic changes, then historical land use patterns may have had much less influence on ecosystem changes.

Intensive range research has been concentrated in the past 30 years. It is important to researchers and others involved in water and range uses to understand how and where these relatively recent experimental records fit within the documented 100-yr period of change. Of the hypothesized mechanisms for the ecosystem changes, the climate change hypothesis is easiest to test using historical data. In this paper, we examine historical time series of precipitation and mean annual temperature as a possible empirical basis for a climate change hypothesis. Also, because increased rates of runoff (peak flows) are often cited as contributing factors in channel down-cutting, annual peak flow data from selected drainage basins in southern Arizona were examined. Finally, these analyses were interpreted in terms of hypothesized changes in streamflow in the semiarid Southwest.

Climate

Summer precipitation generally occurs as intense, short-duration thunderstorm rains of limited areal extent (13). Winter precipitation is generally wide-spread and low-intensity, although thunderstorms can occur throughout the year (15). Many range grasses depend upon summer rainfall, while the more deep-rooted shrubs are better able to take advantage of winter precipitation. The principal source of moisture for Arizona and western New Mexico is the Pacific Ocean, whereas the Gulf of Mexico supplies most of the moisture for eastern New Mexico (5, 14).

Study Watershed and River Basins

The 58-mi^2 (150-km^2) Walnut Gulch experimental rangeland watershed lies in the San Pedro basin of southeastern Arizona (Fig. 1) (16, 18). This experimental watershed is representative of semiarid rangeland in southeastern Arizona, southwestern New Mexico, and northeastern Sonora, Mexico. Precipitation is measured with a dense recording raingage network, and runoff is measured at 11 locations, including the watershed outlet 2 mi upstream from the confluence with the San Pedro River (16, 18). Rainfall and runoff data have been the basis for developing hydrologic models which represent both the extreme spatial and temporal distribution of thunderstorm rainfall and watershed characteristics for differing range uses and management practices (12, 14, 16, 17). It is important to determine how well the experimental period (1955-1980) represents the longer climatic record and the accuracy expected for prediction.

To do this, we examined long-term records from two river basins (20), the San Pedro and the Santa Cruz, and compared them with the Walnut Gulch records over the concurrent period from 1956 to 1980. The San Pedro and Santa Cruz Rivers are ephemeral to intermittent streams which flow north from Sonora, Mexico into Arizona (Fig. 1). The basins selected for analysis were the San Pedro, at Charleston (1220 mi^2, 3170 km^2), and the Santa Cruz, at Tucson (2220 mi^2, 5750 km^2). The rivers are similar, but the Santa Cruz River Basin is more heavily populated, and the

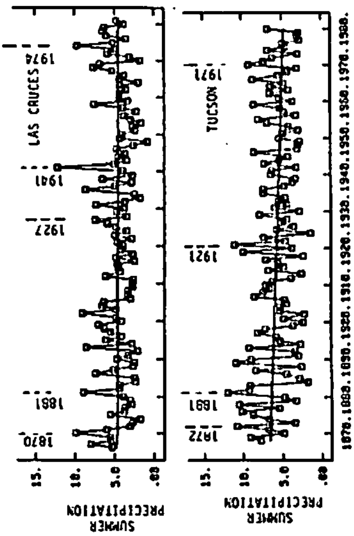

Figure 2. Summer precipitation for selected Arizona and New Mexico stations.

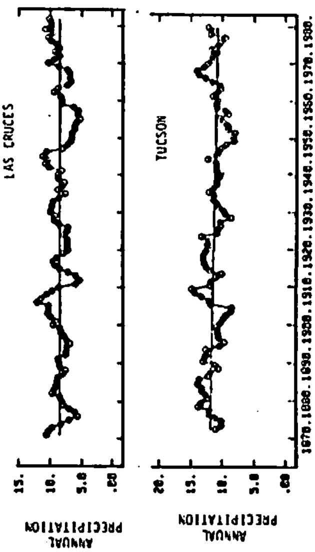

Figure 3. Five-year moving averages of annual precipitation for selected Arizona and New Mexico stations.

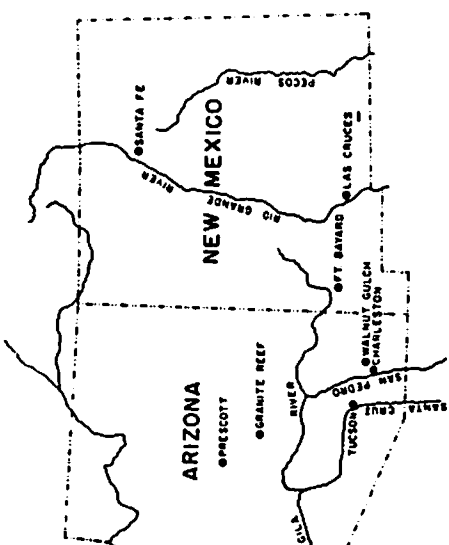

Figure 1. Location of precipitation and/or streamflow measuring stations in Arizona and New Mexico.

river channel has undergone more engineering. Both rivers were meandering, shallow, perennial streams prior to the 1880's, when the rivers probably began downcutting (1, 2, 6). Today, the rivers are characterized by intermittent flow, high vertical banks, and sandy bottoms.

Data

Studies on possible climatic and man-caused ecosystem changes in the Southwest are handicapped by the relatively short period of continously recorded climatic data (2). In climatic research, the researcher must first decide whether to emphasize a greater number of stations with shorter records or fewer stations with longer records. After studying records from a large number of precipitation stations in Arizona and New Mexico, we decided to concentrate on the few stations with long precipitation records. The two river basins chosen had runoff records from 1915. There were no official flood peak records prior to 1915.

Rainfall

Some rainfall records in the Southwest date to the late 19th century, with the Santa Fe record beginning in the 1850's. However, we could identify only three stations in Arizona and three in New Mexico with acceptable records from the 1860's to the present (Fig. 1) (4, 10, 11, 19, 21).

There were a number of stations established between 1890 and 1910, but their records began after the reported period of change in the range and streamflow characteristics in the Southwest. Therefore, we concentrated on the few long-term records which provided over 110 years of data beginning before 1870 (Table 1).

Our objective was to identify possible trends or cycles in annual and seasonal precipitation, and changes in the variability of season-to-season and year-to-year precipitation which might account for changes in the ecosystem. Four of the six stations selected suggested a decrease in average annual precipitation during the period of record, one indicated no change, and one indicated an increase (Table 1). The four stations suggesting a decrease were Tucson, Granite Reef, Ft. Bayard, and Santa Fe. There was no indicated change at Las Cruces, and there was an increase at Prescott. Shorter records at several other stations reinforced the indication of a weak negative trend in southeastern Arizona.

There were stronger indications, although not statistically significant, of negative trends in summer precipitation, particularly in southeastern Arizona (Table 1). For example, the overall decrease in summer precipitation would be about 2 in. (50 mm) for Tucson, or a decrease from 6.4 to 4.4 in. (160 to 110 mm). Fragmentary records and shorter records in southeastern Arizona, including those on Walnut Gulch, tend to support this negative trend. On the other hand, no long-term trend is apparent in winter precipitation. Such a decrease in summer rainfall could be critical for grasses dependent upon summer rainfall, particularly for grasses under continuous pressure from grazing. At the same time, conditions may have been relatively favorable for shrubs.

The 1880's and early 1890's exhibited highly variable summer rainfall in southern Arizona and New Mexico (Fig. 2) (1). The extreme range of highs and lows in southeastern Arizona occurred during the period when large herds of cattle were brought into Arizona (1, 2, 6). Also, this period of extreme variability was followed by an 8-year summer drought (1899 -1906) and an exceptionally wet year (1905) of winter, spring, and fall precipitation. Summer rainfall for Tucson, from 1878 through 1906, illustrates the extreme pressure that must have been brought on the rangeland in southeastern Arizona (Fig. 2). From 1878 through 1894, almost every summer was either considerably above or below average, with rainfall being doubled or halved in consecutive years on several occasions. Since the early 1890's, summer-to-summer variability has been considerably less.

Table 1.--Possible trends in precipitation for selected Arizona and New Mexico stations.

		Trends (in/yr)				
Arizona stations	Years of record	Annual	Winter	Spring	Summer	Fall
Granite Reef	112	-.014	-.004	0	-.010	0
Prescott	115	+.022	0	+.004	+.010	+.008
Tucson	113	-.010	0	+.003	-.017	+.004

		Trends (in/yr)				
New Mexico stations	Years of record	Annual	Winter	Spring	Summer	Fall
Ft. Bayard	115	-.006	-.006	0	0	0
Las Cruces	116	0	0	0	0	0
Santa Fe	114	-.005	0	0	-.005	0

There were no identifiable cycles in annual or seasonal precipitation for the seven stations for the period of record, but there were very definite wet and dry periods (Fig. 3 and 4). Rangeland vegetation has adapted to these irregular wet and dry periods, but the tendency to add cattle during wet periods and the reluctance to remove them during dry periods, plus the more favorable moisture conditions for encroachment of shrubs, suggests a hypothesis for continuing changes in the plant community.

Temperature

Unfortunately, few long-term climatic records in the Southwest include temperature. The records which are available indicate significant increases in mean annual and seasonal temperature for urbanized areas in both Arizona and New Mexico, but no solid evidence of increasing temperature in rural areas. Some stations suggest an increase, some a decrease, and some no change. We could not verify any significant change in temperatures in the Southwest, but temperature may have played a role during specific periods of stress. A water balance-plant growth model, which reflects grazing impacts, is needed to test this hypothesis (8, 9).

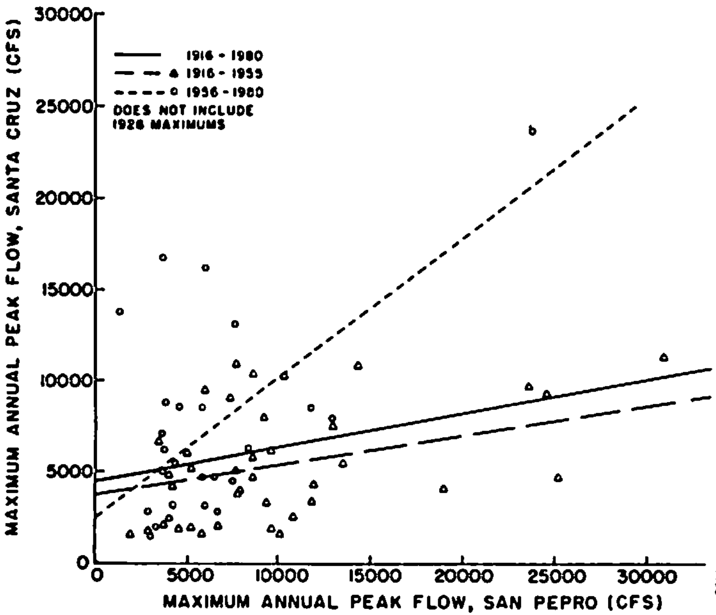

Figure 5. Comparison of maximum peak flows for the Santa Cruz River at Tucson and the San Pedro River at Charleston (1916-1980).

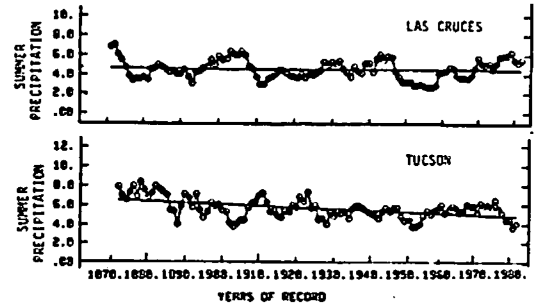

Figure 4. Five-year moving averages for summer precipitation for selected Arizona and New Mexico stations

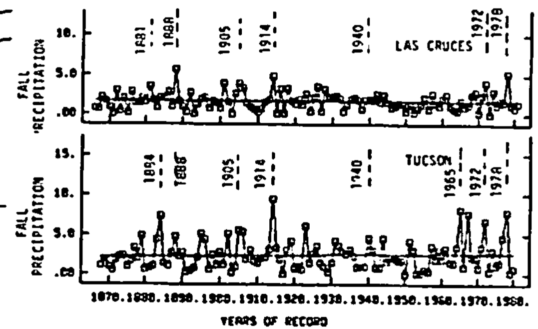

Figure 6. Fall precipitation for selected Arizona and New Mexico stations.

Peak Flows

For this study, we examined the maximum annual peak flows for the San Pedro and Santa Cruz Rivers from 1916 through 1980 (Fig. 5). We also examined flood peaks on Walnut Gulch from 1956 through 1980, and compared the Walnut Gulch record with the San Pedro record (Table 2). Comparison of maximum peak flows on the San Pedro and Santa Cruz for the period 1916-1955 indicated that flood peaks were, on the average, about twice as great on the San Pedro as on the Santa Cruz (11,100 cfs (314 cms) on the San Pedro as opposed to 5,480 cfs (155 cms) on the Santa Cruz) (Table 2, Fig 5). Based on linear regression, the Walnut Gulch and San Pedro maximum annual peak flows were not correlated. The same storm may occasionally produce the maximum for both small and large watersheds, but such occurrences do not help the correlation, because the major peak on the small watershed is most often a minor peak on the large watershed, even if it is the largest of the year. Therefore, the flood series for the San Pedro and the Santa Cruz cannot be used to determine the representativeness of the experimental period on Walnut Gulch.

Table 2.--Annual maximum peak flows (cfs) for three selected drainages in southern Arizona (1956-1980).

Station	Period of record	Mean	Std. dev.	Selected trend slope[1]	Time series serial correlation; significant lags[2]	Data spectral density; main periods[3]
		(cfs)	(cfs)	(cfs/yr)	(yrs)	(yrs)
San Pedro	1916-1980	9400.	8760.	-104.	5, 14, 28	2.4, 4.9
San Pedro	1916-1955	11000.	10300.	-69.	14	2.4, 5.0
San Pedro	1956-1980	6640.	4530.	+183.	none	none
Santa Cruz	1916-1980	6230.	4300.	+67.*	10, 16. 32	3.2, 5.3
Santa Cruz	1916-1955	5480.	3260.	+64.	5, 19	5
Santa Cruz	1956-1980	7440.	5440.	+154.	none	none
Walnut Gulch	1956-1980	2440.	2490.	-106.	none	none

[1]Linear trend analysis with time, *indicates significance at the 95% level.
[2]Time lag (K) in years when the serial correlation coefficient R(K) is outside the 95% tolerance limits.
[3]Largest spectral density values for the indicated frequency (or period) when serial correlation indicates significant dependence.

However, from 1956 through 1980 (Walnut Gulch records began in 1956), maximum annual peak flows were actually a little higher on the Santa Cruz than the San Pedro. For the full period of record (1916 - 1980), the San Pedro drainage still had greater peak flows, but records from the last 25 years suggest that the earlier imbalance may have been by chance rather than because of a different climate and/or river basin characteristics.

Time series analyses are summarized in Table 2. For the 65-year period 1916 - 1980, there was no significant linear trend in peak flows with time on the San Pedro River, but there was a statistically significant increase in annual peak flow on the Santa Cruz River (see column labeled Trend Slope in Table 2). No linear trends with time were significant for the other drainage basins or for different periods of record. The serial correlation analysis results were mixed, with three coefficients showing significance during the 65-year period (5, 14, and 28 years for the San Pedro River, and 10, 16, and 32 years for the Santa Cruz River). This is about what to expect for 95% tolerance limits, i.e., about 5% of the correlation coefficients showing significance by chance alone, even if the series is random. Similar results were otained for the 40-year period 1916 - 1955 (i.e., 1 and 2 serial correlation coefficients being judged significant). No significant serial correlation coefficients were found for the 25-year period 1956 - 1980. Results from the spectral density analysis were also mixed, with perhaps a 2- to 5-year cycle indicated for the 65-year and 40-year records, and no apparent cycles in the 25-year records. In view of the above interpretation of the serial correlation analysis, not much credence should be given these spectral density analysis results. Rather, they should be considered as tentative, perhaps suggestive of cyclical patterns, or due to chance.

Interpretation of results suggests high variability and large uncertainty in statistical estimates of means, variances, serial correlation coefficients, and spectral densities. Analysis of data from an individual station over various periods of record demonstrates marked changes in statistical results (and their interpretation) with varying record length. For example, compare the conclusions one might be tempted to reach for the San Pedro River if (1) all data from 1916 - 1980 were analyzed (e.g., perhaps decreasing annual peak flows and about 2- and 5-year cycles), (2) data only from 1956 - 1980 (e.g., no cycles and a suggestion of increasing peak discharges). Finally, there is a weak indication that annual peak flows may be increasing on the Santa Cruz River relative to the San Pedro River and Walnut Gulch. At most, we offer this as a hypothesis for further testing. Therefore, based on streamflow data from 1916 - 1980, we cannot definitely establish increased peak flows as a reason for channel down-cutting and entrenchment. Without good streamflow records extending back before 1900, direct analysis of existing peak flow data from these basins cannot be used to examine the peak flow increase hypothesis as a basis for stream channel changes.

Fall precipitation may be the cause of differences in flow characteristics between 1915 - 1955 and 1956 - 1980 (Fig. 6). Most "record" peak flows on the San Pedro and the Santa Cruz have occurred in late September or October. In most years, the maximum annual peak flow occurred in July, August, or early September. Summer thunderstorms produce the major flood peaks on small watersheds (up to 100 mi^2) (260 km^2), but these thunderstorms are generally too limited in areal extent to generate "record" peak flows on the major basins (1,000 mi^2 (2600 km^2) and larger).

For the San Pedro River, from 1916 through 1955, all but two of the maximum annual peak flows were recorded in the summer; on the Santa Cruz, all but three were summer events. One of the two fall storms on the San Pedro occurred in late September of 1926. It was by far the largest flood peak of record on either river. From 1956 through 1976, all annual maximums on the San Pedro were summer events, and all but three on the Santa Cruz were summer events. The maximums in 1977, 1978, and 1979, at both stations, were fall or winter events.

These seasonal analyses suggest an additional hypothesis that there has been a recent shift in the seasonal occurrence of flood peaks, and that perhaps similar occurrences have occurred in the past. More powerful techniques (e.g., a water balance-plant growth model) would be required to assess the significance of changes in seasonal precipitation and flood peak occurrence.

Precipitation records at Tucson suggest that major floods or periods of exceptionally heavy runoff could have occurred in southeastern Arizona before runoff-measuring stations were established on the Santa Cruz and San Pedro Rivers. The fall of 1884, the summers of 1872, 1876, 1881, 1887, 1889, and 1890, and the winter and spring of 1905 were all exceptionally wet seasons. The 1880's were exceptional in the extreme variability of summer rainfall compared to the other seasons during the same period, just as the fall storms were exceptional from 1965 through the present.

Summary

Extreme variability between summer rainfall seasons in the 1880's, followed by a summer drought in the 1890's and early 1900's, possibly combined with the influx of cattle to the region in the 1880's, may have significantly altered the range and basin ecosystems in southern Arizona and much of the Southwest. A small, but possibly meaningful, decline in summer rainfall over the past 100 years in southeastern Arizona, plus continued pressure from grazing, is the most likely explanation for the continued deterioration of the rangelands. Temperature may have played a role during specific periods of stress, but this possibility has not been established as a factor in the long-term deterioration of the rangelands. A water balance-plant growth model which reflects grazing impacts is needed to test these hypotheses. The exceptional number of recent damaging flood peaks on the Santa Cruz River is most likely the result of a large number of fall storms rather than a change in basin and channel characteristics. There is, however, a suggestion of increasing annual peak flows. Finally, long-term records of peak flows on major basins are not helpful in determing the representativeness of the 25-year record for the Walnut Gulch Experimental Watershed.

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