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Historical Rainfall Patterns and Arroyo Activity within the Zuni River Drainage Basin, New Mexico

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Abstract. Climate change, grazing practices, timbering activities, and erosional thresholds have been proposed to explain widespread accelerated arroyo erosion near the turn of the century in the southwestern United States. We analyze the morphology and potential causes of arroyo activity in the Zuni River drainage basin of New Mexico; our analyses illustrate the linkage between arroyos and changes that occurred through time in local precipitation patterns. Substantial archival and geological evidence confirms dominant downcutting in the intermediate and small-size arroyos within the basin for a 20- to 30-year period beginning near 1905. Historical climatic records reveal a long and severe drought from 1898–1904; this drought ended abruptly with three years dominated by unusually frequent high-intensity summer rainfall events. Daily weather records show the following two to three decades had a high number of intense summer storms, large rainfall totals, and few precipitation days. The results add support for the climate change explanation of periods dominated by arroyo incision and infilling in the southwestern U.S.

Key Words: arroyo cutting and filling, climatic change, Zuni River.

THE causes of arroyos in the southwestern United States continue to be vigorously debated in the geomorphological community (Graf 1983). Some investigators believe that these incised stream channels are caused by human impacts on vegetation associated with timbering and grazing activities (e.g., Rich 1911; Bailey 1935). Their arguments are based upon a coincidence in time (late 1800s, early 1900s) of Spanish and Anglo settlement in the Southwest and accelerated arroyo development in the region. Other researchers focus on the role of climatic variations, particularly fluctuations in precipitation intensities, in explaining periods of arroyo entrenchment (e.g., Bryan 1925; Leopold 1951; Miller and Wendorf 1958; Bull 1964; Tuan 1966; Cooke and Reeves 1976; Hereford 1984; Hereford and Webb 1989). Frequent, intense, summer storms and infrequent light winter rains may act to weaken vegetative cover and encourage arroyo erosion. More recent work on intermittent and ephemeral streams led some researchers to conclude that arroyo development is more related to geological erosional thresholds than to changes in climate (Schumm and Hadley 1957; Schumm 1973, 1976; Patton and Schumm 1975, 1981). Any fundamental cause of historic arroyo cutting must explain (a) prehistoric cycles of arroyo cutting and filling which have produced arroyos with dimensions similar to current ones (Wells 1988) and (b) valleys subjected to similar conditions where certain portions have arroyo cutting (Peterson 1950).

The arroyos in the Zuni River drainage basin of New Mexico (Fig. 1) provide an excellent opportunity for disentangling the various potential causes of arroyo activity near the turn of the century in the Southwest. These arroyos are known to have existed in the area before Spanish or Anglo intervention; timbering began in the headwaters before widespread arroyo development (Resource Consultants 1987); valley floors were overgrazed by the 1880s with little change in grazing practices into the early decades of the twentieth century; and excel-

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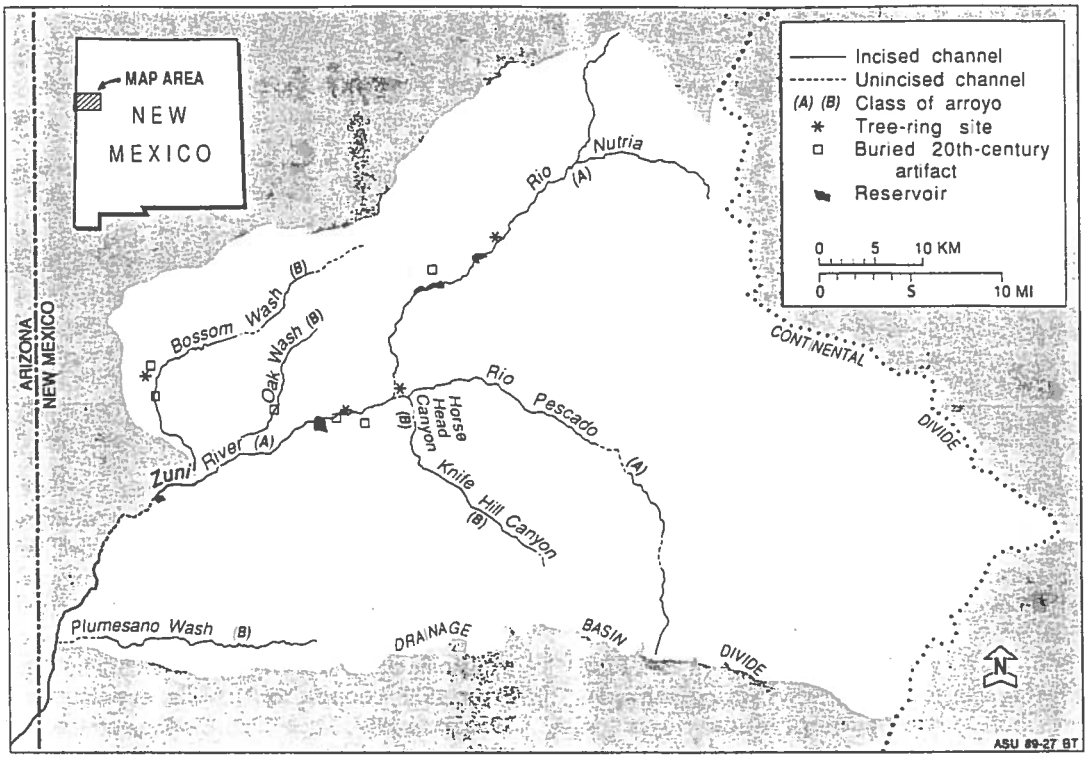

Figure 1. Zuni River watershed features.

lent, long-term daily weather records exist for the area. Given these conditions, our purpose is to analyze the nature of arroyo activity within the past hundred years, examine the potential role of land-use and/or geological erosional thresholds, and analyze climatic variations that may be linked to changes in the arroyos. We believe that our interdisciplinary analyses demonstrate that arroyo activity in the Zuni River drainage basin is linked, through time, to changes in precipitation patterns in the area, and in particular, to precipitation intensities.

Historical Arroyo Conditions

Arroyos in the Zuni area are classified into three groups based upon the hydrogeologic conditions, length of continuity and associated drainage basin size, and geographic position in the drainage network. The largest arroyos (Zuni, Nutria, Pescado) are classified as *A-scale*, which drain areas exceeding 500 km² and receive snowmelt runoff from the Zuni Mountains. Intermediate size arroyos, *B-scale*, drain areas between 500 and 20 km² and primarily receive runoff from thunderstorm activity. The smallest C-scale arroyos typically drain bedrock uplands and terminate prior to reaching the B-scale arroyos. This classification of arroyos in the Zuni area is critical because the arroyos of these three scales respond to different hydrologic conditions and may operate at different rates (Wells 1988).

A characteristic of all sizes of arroyos in the Zuni River drainage basin is that the channels are discontinuous (incised channel reaches are separated by unincised reaches along the valley floors). Geomorphic changes in the arroyos of smaller sizes occur because they are more proximal to bedrock upland areas of greater natural runoff and sediment yield (Wells 1987, 1988; Yair and Wells 1989; Lagasse et al. 1990). Photogrammetric measurements indicate that

Table 1. C-Scale Arroyo Changes from 1934–74 in Bossom Wash

Tributary no.	Extension (m)[a]
1	120
2	+
3	745
4	n.c.
5	n.c.
6	+
7	+
8	288
9	344
10	89

[a] N.c. indicates no measurable change in channel length over time, and '+' indicates a loss of arroyo length by net aggradation in distal reaches. All tributaries are C-scale while the main channel is B-scale.

many of the C-scale arroyos eroded and increased by 90–750 m in length during a 50-year period (Table 1); during an overlapping 10-year period, A-scale arroyos remained stable with respect to channel depth (Table 2).

A summary of selected archival literature, maps, and photographs provides a chronology of A- and B-scale arroyo activity in the Zuni River drainage basin over the past two hundred years (Fig. 2). In addition, analyses of aerial photographs and cultural and radiometric dating provide controls for reconstructing historic arroyo activity in the C-scale class. The following chronology summarizes the conditions and timing of arroyo cutting and infilling since the arrival of the early Spanish explorers in the eighteenth century.

Arroyo incision predates the arrival of Spanish/Anglo settlers in the Zuni area (Fig. 2) indicating that incision occurred by natural processes operating outside the realm of Spanish/Anglo intervention. Germination dates A.D. 1680 and 1752 have been obtained from Gambel oaks presently living within a few feet of the active Zuni River channel. These and other tree-ring dates (Jacoby 1987) from two major tributaries of the Zuni River (Rios Pescado and Nutria) establish that the Zuni River had eroded to its present level by A.D. 1776 when Fray A. Dominguez observed that the Zuni Pueblo was located by an arroyo and that arroyos existed upstream of the Pueblo (Adams and Chavez 1956) and by A.D. 1849 when Lt. J. H. Simpson of the U.S. Army described incised channels in both the tributaries and the main valley of the Zuni River (McNitt 1964). Detailed descriptions

Table 2. A-Scale Arroyo Depth Changes in the Zuni River Watershed

Location	Change (m)[a]	Time
Rio Pescado (near Ramah)	−0.5	1967–77
Rio Pescado (below Pescado Dam)	n.c.	1967–77
Zuni River (near Zuni)	n.c.	1966–77
Rio Nutria	n.c.	1969–71
Rio Nutria	n.c.	1971–77

[a] N.c. indicates no measurable change in channel depth over time; data obtained from M. E. Cooley (1980).

of Baxter (1882) "plunging down a deep arroyo" near Zuni Pueblo and an 1883 letter by F. H. Cushing warning that several deep arroyos pose a threat to irrigation canal construction immediately north of Zuni Pueblo provide details on the geomorphic conditions of incised channels. Between 1884 and 1907, sketches, topographic maps, and photographs support written records of Simpson, Baxter, and Cushing (Fig. 2). By ca. 1890, arroyo development was areally extensive over a large area of the Zuni River drainage basin, and A-scale arroyos were incised to levels similar to the present channels.

Photographs, surveyors' notes, tree-ring dates, and buried cultural artifacts, all dating between 1890–1986, are used in conjunction with correspondence from various government officials associated with the Zuni Pueblo to assess the timing of arroyo cutting and filling over the duration of instrumental climatic records (Fig. 2). These data demonstrate that A-scale arroyos have been relatively stable and, more specifically, have not changed depth substantially since the late 1800s. Analysis of photographs indicates that the only major changes in the geomorphology of the large arroyos appear to be local aggradation between 1890–1911 and lateral widening at point bars and eroding at cut banks between 1912 and the 1930s. Widespread invasion of riparian vegetation on the arroyo floors occurred after ca. 1940. These observations are supported by U.S. Geological Survey field measurements which illustrate little change in A-scale arroyo depth during the instrumental time of 1966–77 (Table 2).

Historical documents (Fig. 2) and tree-ring data (Jacoby 1987) indicate that many of the intermediate and small arroyo channels were unstable between 1905 and the mid-1920s. Be-

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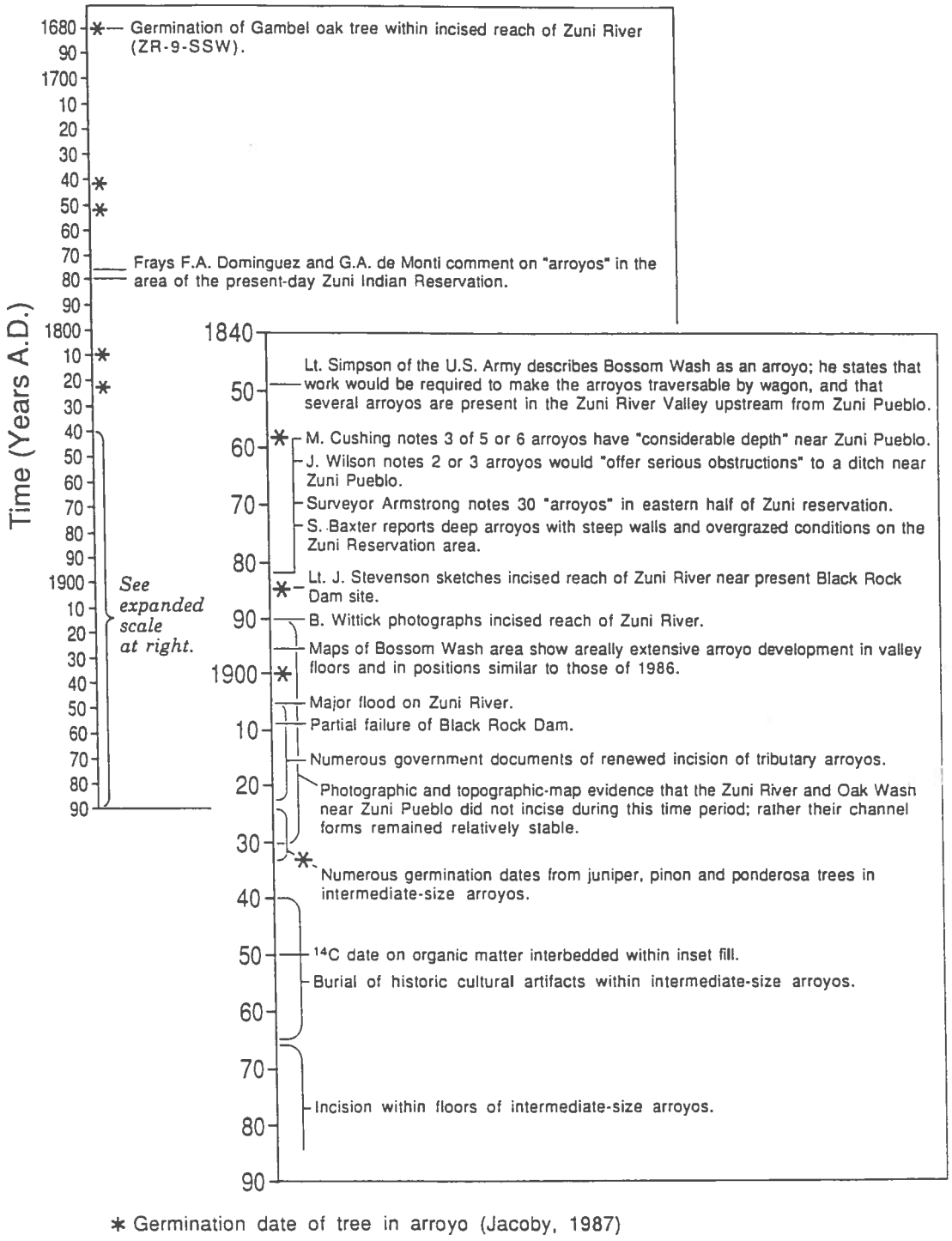

Figure 2. Summary of selected historically-documented events related to arroyo development in the Zuni area (Wells 1987).

tween 1909–19, letters from government officials at the Zuni Pueblo to staff in Washington, DC record discussions of active runoff in small arroyos. For example, on 7 August 1919, B. H. Pilcher submitted a letter to W. M. Reed discussing the record rainfall and the work required to maintain irrigation canals from arroyo erosion. The higher frequency of runoff during this time period destabilized arroyos and inhibited the germination of trees. Increased runoff would also kill trees such as juniper that are sensitive to flooding (Potter 1987). B- and C-scale arroyos apparently do not have very old trees growing within the arroyo walls as a result of the arroyo erosion early in this century. Widespread germination of trees presently living in arroyos occurred after the early 1920s (Jacoby 1987), indicating a decrease in arroyo erosion.

Buried cultural artifacts and tree trunks indicate arroyo infilling was a dominant process between the 1940s–70s. Many buried artifacts include glass and plastic bottles as well as automobiles, all which can be seen in the inset fills at numerous locations within the Zuni area. These observations coupled with a modern radiocarbon date on organics (A.D. 1950; lab sample #DIC-3332) within historical arroyos indicate aggradation of 1 to 2 m during the mid-twentieth century. During the past decade, many of the B-scale arroyos incised 1 to 2 m through this fill to produce the inset terraces visible in the arroyos today (Fig. 3). Many of the C-scale arroyos remained relatively stable in the upper reaches, but experienced aggradation in the distal reaches.

These archival, geomorphic, and tree-ring results are used to quantify the timing of A-, B-, and C-scale arroyo activity within the Zuni River watershed and to demonstrate that arroyo activity has varied spatially and temporally during the past hundred years. Larger arroyos are more stable than intermediate and small ones. This spatial difference in channel stability reflects the more erosive runoff and larger volumes of sediment movement and storage in C- and B-scale arroyos. Data indicate that over the past two to three hundred years, A-scale arroyos have been relatively stable, with local infilling occurring between 1890–1910 and channel widening between the 1920s–60s. Between approximately 1905–30, C- and B-scale arroyos were eroding. By ca. 1940 stability and infilling were dominant processes on both C- and B-scale arroyos. Significant variations over time, when arroyo cutting dominates infilling (and vice versa), must be tied to some external forcing function. The presence of arroyos in the landscape of the Zuni area by the time of Spanish and Anglo explorations indicates that widespread arroyo initiation cannot be attributed to nineteenth and twentieth century land-management practices. Relatively long-term precipitation records within and near the Zuni River watershed provide an excellent opportunity for assessing the potential role of climate in explaining the temporal variations in B- and C-scale arroyo erosion and infilling in the area.

Climatic Databases

The role of climate in Southwestern arroyo activity near the turn of the century has been difficult to assess due, in part, to the lack of reliable instrumental climatic data. We selected eight stations (Table 3, Fig. 4) for analysis based upon their location within 120 km of the center of the basin, exceptional length of the daily precipitation record, and relatively low number of missing data. We determine for each station the monthly total precipitation, number of precipitation days, and the number of days with rainfall equaling or exceeding 12.7 mm (0.5″), 19.1 mm (0.75″), and 25.4 mm (1.00″). If any part of the monthly record is missing, all precipitation data for the entire month are considered missing.

We extracted Palmer Drought Severity Index (PDSI) data from a two-volume atlas (Karl and Knight 1985a, b) to further characterize the moisture conditions in the Zuni River drainage basin. The index is a widely-used water-budgeting scheme utilizing precipitation, evapotranspiration, and soil moisture conditions to arrive at a relative index of drought (Palmer 1965). The values range from near −4.5 for "extreme drought" to near +4.5 for "extreme wetness"; a PDSI near 0.0 indicates "near normal" conditions. We use the monthly data for the Northwestern Plateau climate division of New Mexico to construct a time series of PDSI values.

Homogeneity Tests

The reliability of a long-term precipitation record can be jeopardized by the relocation of

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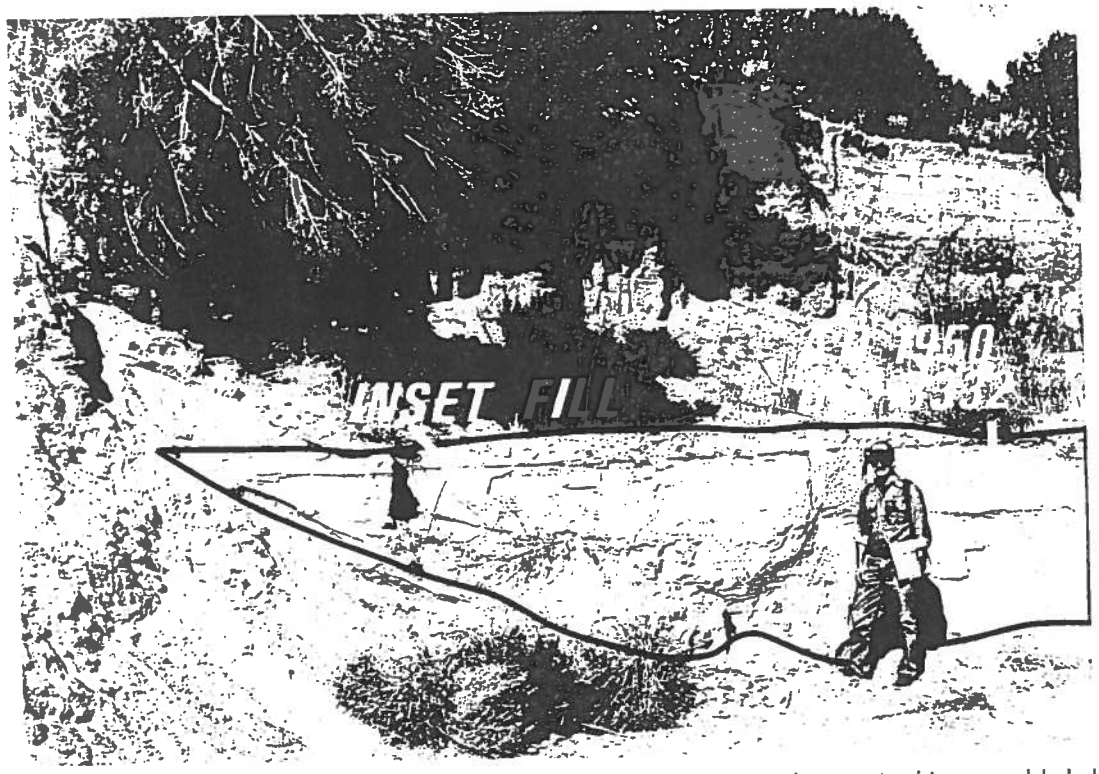

Figure 3. Solid line outlines the historic inset fill within Bossom Wash (B-scale arroyo); white arrow labeled A.D. 1950 marks the layer of a modern radiocarbon date and buried cultural features.

the rain gauge, environmental changes near the equipment, and/or changes in the observers. These and other potential problems in the collection of precipitation data can result in relative inhomogeneities in the long-term record. Such relative inhomogeneities appear in climatic records as discontinuities or unusual trends with respect to the measurements at other nearby stations. We selected June, July, and August rainfall totals for objective testing of relative inhomogeneities because summer convective storms produce the high-intensity events of interest in arroyo cutting (Leopold et al. 1966; Tuan 1966; Cooke and Reeves 1976) and the localized nature of the convective storms accentuates the effects of station movements (Mitchell et al. 1966). The objective tests include the intercorrelations among the stations and the von Neumann ratio, V, calculated as:

$$V = \frac{N}{N-1} \frac{\sum_{i=1}^{N-1} (x_i - x_{i+1})^2}{\sum_{i=1}^{N} x_i^2 - \frac{1}{N}\left(\sum_{i=1}^{N} x_i\right)^2} \qquad (1)$$

where x is the difference between a station's summer precipitation total (in z-score form) and the corresponding average z-score of the remaining stations, and N is the number of years of record (Table 4). The value of V is evaluated against a test parameter calculated as:

$$(V)_t = \frac{2N \pm 2t_s\sqrt{N-2}}{N-1} \qquad (2)$$

where t_s is the area under a normal curve corresponding to a one-tailed test at the 0.95 level of confidence used. If V is less than $(V)_t$, the array of z-score differences is non-random, and

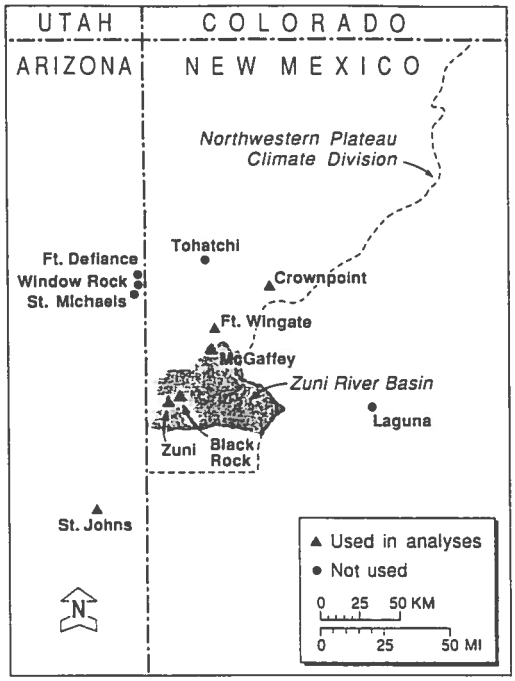

Figure 4. Location of climate stations near the Zuni River drainage basin.

a relative inhomogeneity is assumed to exist (Mitchell et al. 1966).

Laguna was eliminated from further analyses due to intercorrelations as low as 0.23 with the other seven stations. This finding is most likely associated with Laguna's long distance from the center of the study area and its location on the opposite side of the continental divide. Tohatchi was eliminated based upon the results

Table 4. Homogeneity Test Results

Station	N	V	$(V)_t$	Outcome
Black Rock-Zuni	70	1.68	1.64	Random
Crownpoint	44	2.16	1.55	Random
Fort Wingate	39	2.01	1.53	Random
McGaffey	56	1.96	1.60	Random
Tohatchi	49	1.39	1.57	Not random
Ft. D.-St. M.-W.R.	76	1.59	1.65	Not random
St. Johns	75	1.87	1.64	Random

from the von Neumann ratios (Table 4); the relocation of the instruments in 1979 may have caused the inhomogeneity in the data. The von Neumann ratio also indicates a problem with the Fort Defiance, St. Michaels, and Window Rock, AZ data assemblage. Given the number of instrument relocations, the inhomogeneity was somewhat expected, so the station was eliminated.

With three stations eliminated, the remaining analyses are conducted on the precipitation data from the Black Rock and Zuni combined record, Crownpoint, Fort Wingate, McGaffey, and St. Johns. These five stations do not have significant relative inhomogeneities; all have high intercorrelations (0.54 to 0.78) in their summer rainfall totals. The precipitation patterns from these five stations are assumed to be representative of rainfall variations existing within the historical period over the Zuni River drainage basin.

Areal Climatic Data

At each of the five stations, a monthly value for total rainfall, precipitation days, and num-

Table 3. Station Network in the Zuni Area

Station	Latitude (N)	Longitude (W)	Elevation (m)	Precipitation records
Laguna, NM	35-02	107-24	1769	1905–32, 1936–40, 1948–85
Black Rock, NM	35-06	108-47	1967	1908–49
Zuni, NM	35-04	108-50	1925	1949–85
Crownpoint, NM	35-41	108-09	2128	1914–69
Fort Wingate, NM	35-28	108-23	2135	1897–1911, 1940–66
McGaffey, NM	35-21	108-27	2379	1923–85
Tohatchi, NM	35-51	108-44	1958	1914–20, 1923–79
Tohatchi, NM	35-54	108-39	1827	1980–85
Ft. Defiance, AZ	35-45	109-05	2104	1897–1905, 1929–36
St. Michaels, AZ	35-40	109-12	2196	1906–27
Window Rock, AZ	35-41	109-03	2058	1937–85
St. Johns, AZ	34-30	109-22	1748	1901–85

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ber of days with rainfall above the three selected thresholds (12.7, 19.0, and 25.4 mm) is determined. Each time series is converted to z-scores before an area-averaged value could be calculated. This conversion is necessary because one or more of the stations did not record daily precipitation in some years between 1897 and 1985 (Table 4). If the raw data are averaged, the inclusion or deletion of a station with a mean substantially different from the mean of the remaining four stations could dominate the area-averaged value. The averaging of the z-scores minimizes this potential problem arising from the missing data. Once the area-averaged z-scores are determined, the original means and standard deviations can be used to generate area-averaged precipitation values in their original units of measure. These procedures produced an 89-year by 12-month matrix for each of the five precipitation variables.

Annual (January–December), summer (April–September), and winter (October–March) totals of each precipitation variable further condensed the information in the data matrices. These annual and seasonal values, which are assumed to be representative of the conditions over the Zuni River drainage basin from 1897–1985, are used in the analyses.

Analyses and Results

The means of the precipitation variables (Table 5) show the tendency for rainfall in the study area to occur during the summer season. This tendency is directly related to the intensity level of the precipitation event. The standardized coefficients of skewness and kurtosis indicated a lack of normality in the variables associated with the large-intensity rain events; square root transformations largely correct the skewness and kurtosis problems in the variables (Table 5). Pearson product-moment correlations between each variable and the year of record (e.g., 1897, 1898, . . . , 1985) indicate several significant linear trends including (a) a decline in summer rainfall amounts, (b) a decline in the frequency of intense summer storms, and (c) an increase in the number of precipitation days (Table 5).

Principal components analysis with varimax rotation reveals three underlying variance patterns explaining nearly 80 percent of the total variance in the 15 interrelated precipitation variables. The first rotated component explains 36 percent of the total variance and is strongly related to the variables associated with the intense summer rainfall events (Table 5). A second component is related to the amount and frequency of high-intensity winter precipitation events and explains an additional 26 percent of the total variance. The third component shows highest loadings on summer, winter, and annual precipitation days and small loadings on the variables associated with the more intense summer storms. This third component explains 18 percent of the total variance and is interpreted as the temporal variance pattern associated with the frequency of low-intensity rainfall. A sharp drop in the eigenvalues occurs between the third and fourth component; therefore, these three orthogonal patterns are used to represent the temporal variance structures in the matrix of area-averaged precipitation data.

Temporal Precipitation Patterns

Plots of the three eigenvector scores reveal the magnitude of long-term and interannual variations occurring in the precipitation patterns of the Zuni area. The plot for the first eigenvector shows a period of above-normal intense summer storm activity from the beginning of the instrumental record to about 1920 (Fig. 5). Years of particularly large positive scores (>2.0) on this composite summer storm index include 1898, 1911, and 1919. Also noteworthy are the three consecutive years from 1905–07 when the standardized scores remain above 1.0; the 89-year record shows no other occurrence of as few as two consecutive years with scores above 1.0. The early 1930s show a secondary maximum in the 11-year running averages, followed by a long period of below-normal summertime storminess levels.

The plot of the scores for the second eigenvector (Fig. 6) reveals high interannual variance, but the 11-year running averages appear to oscillate around zero. Winters of high precipitation include 1897–98, 1972–73, and 1979–80. The winters of 1904–05 and 1905–06 show large positive values on this wintertime rainfall index; both wet winters were followed by summers of above-normal storminess levels.

The eigenvector related to the frequency of

Table 5. Selected Statistics for Zuni Precipitation Data[a]

Variable	N	Mean (mm)	Std. dev. (mm)	z_1	z_2	r	Loadings for components 1	2	3
Total									
Annual	89	336.0	76.7	1.15	−0.29	−0.13	0.69	0.29	0.54
Summer	89	194.6	54.1	0.56	−1.22	−0.22	0.81	−0.11	0.46
Winter	88	141.0	50.8	2.06	0.37	0.07	0.13	0.89	0.21
Prec. Days									
Annual	89	63.0	12.8	0.44	2.03	0.23	0.11	−0.00	0.95
Summer	89	35.6	8.5	−0.10	−1.00	0.18	0.16	−0.18	0.89
Winter	88	27.4	8.2	1.36	1.12	0.19	−0.06	−0.51	0.60
Days ≥ 12.7									
Annual	89	6.6	2.3	1.58	−0.34	−0.26	0.76	0.42	0.05
Summer	89	4.1	1.7	1.84	−0.29	−0.20	0.89	−0.00	0.10
Winter	88	2.6	1.5	*0.60*	*−0.42*	*0.02*	*0.15*	*0.89*	*−0.11*
Days ≥ 19.0									
Annual	89	2.8	1.3	*0.88*	*1.66*	*−0.23*	*0.84*	*0.41*	*0.01*
Summer	89	1.8	1.1	*−1.25*	*1.80*	*−0.25*	*0.88*	*−0.08*	*0.05*
Winter	88	0.9	0.8	*−0.09*	*−0.33*	*0.13*	*0.05*	*0.88*	*−0.05*
Days ≥ 25.4									
Annual	89	1.3	0.9	*1.81*	*0.49*	*−0.22*	*0.79*	*0.34*	*0.01*
Summer	89	0.8	0.7	*−0.21*	*−0.45*	*−0.27*	*0.83*	*0.81*	*−0.02*
Winter	88	0.4	0.5	*2.07*	*−0.96*	*0.10*	*0.07*	*0.81*	*−0.02*

[a] All italicized values are associated with the square root transformations. z_1 and z_2 are the standardized coefficients of skewness and kurtosis; absolute values above 1.99 indicate a significant departure from normality at the 0.95 confidence level. Absolute values of r, the Pearson product-moment correlation coefficient with the year of record, above 0.21 are significant.

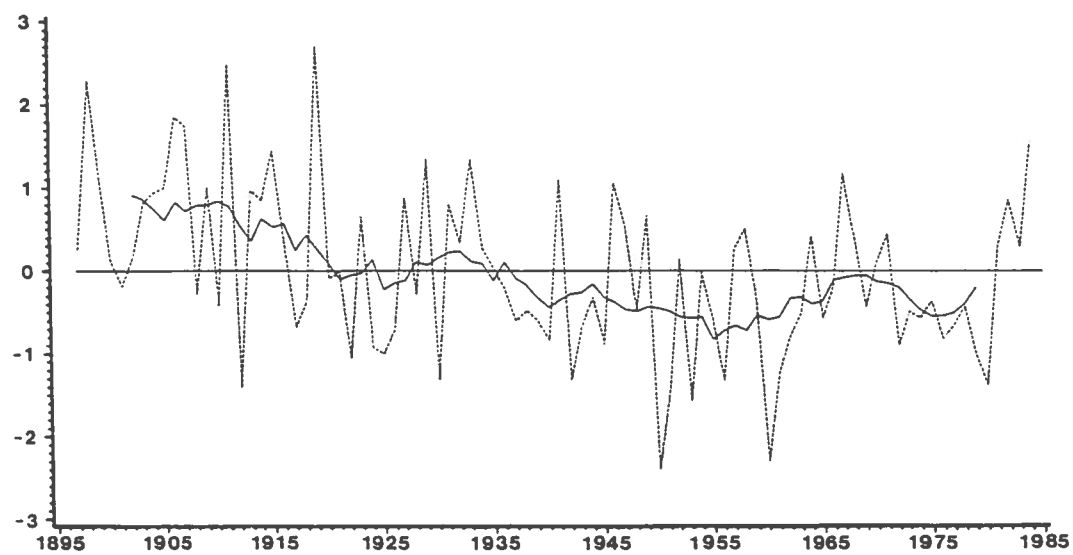

Figure 5. Raw standardized scores and 11-year running means for the first component (intense summer rain events).

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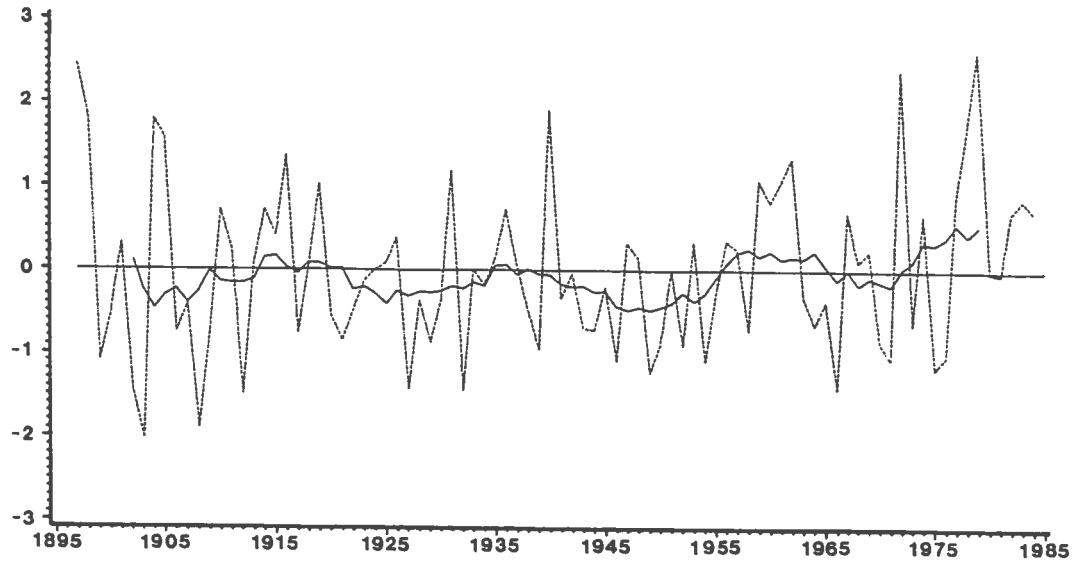

Figure 6. Raw standardized scores and 11-year running means for the second component (winter precipitation).

light rains shows a striking increase from the late 1890s to the mid-1920s (Fig. 7). After the peak in the 1920s, the 11-year running means decline slowly and remain near the zero level. The plots associated with the first and third eigenvectors strongly suggest that significant differences exist between the precipitation patterns in the early part of the study period and those from the more recent subperiod. Accordingly, a Student's *t*-test (Mitchell et al.

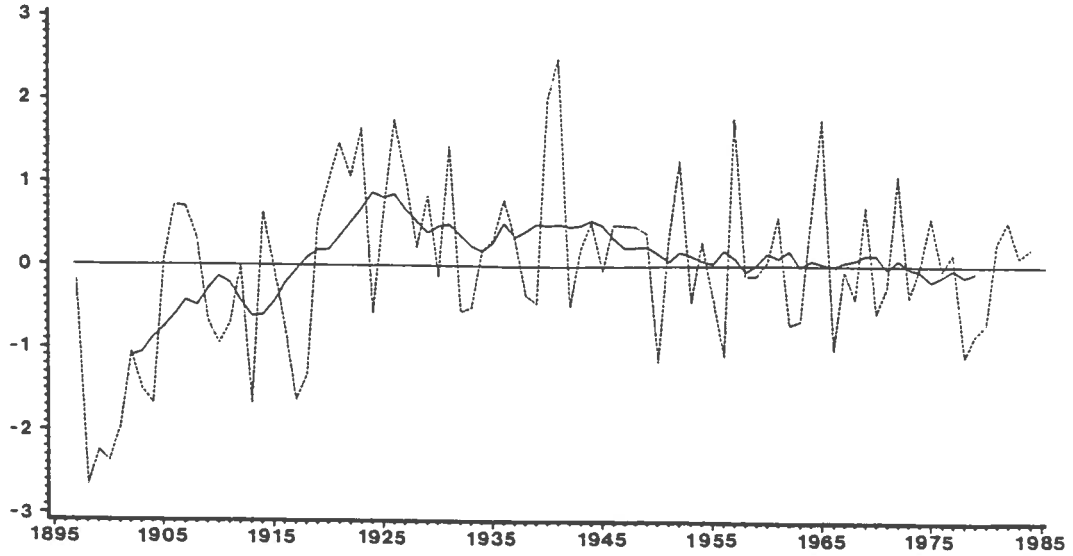

Figure 7. Raw standardized scores and 11-year running means for the third component (low-intensity rainfall).

Table 6. Student's *t*-Test Results[a]

Variable	Subperiod Means 1897–1920	Subperiod Means 1921–85	*t*	Subperiod Means 1897–1939	Subperiod Means 1940–85	*t*
Total						
Annual	355.4	327.6	*−2.44*	351.4	319.6	*−2.83*
Summer	211.1	187.9	*−2.86*	209.3	179.7	*−3.72*
Winter	141.3	140.7	−0.07	142.4	139.4	−0.39
Prec. Days						
Annual	55.2	66.0	*6.01*	60.9	64.9	*2.10*
Summer	31.5	37.2	*4.64*	34.7	36.4	1.40
Winter	23.7	28.8	*4.28*	26.5	28.2	1.35
Days ≥ 12.7						
Annual	8.0	6.1	*−5.98*	7.3	6.0	*−3.87*
Summer	4.9	3.7	*−4.92*	4.6	3.5	*−4.54*
Winter	1.6	1.5	−1.73	1.5	1.5	−0.40
Days ≥ 19.0						
Annual	1.8	1.5	*−5.00*	1.7	1.5	*−2.67*
Summer	1.4	1.2	*−3.95*	1.3	1.1	*−3.18*
Winter	0.8	0.9	0.47	0.8	0.9	0.93
Days ≥ 25.4						
Annual	1.3	1.0	*−4.98*	1.1	1.0	*−2.42*
Summer	1.0	0.7	*−4.65*	0.9	0.7	*−2.67*
Winter	0.5	0.4	−0.33	0.4	0.5	0.65
Component						
#1	0.7	−0.3	*−6.65*	0.3	−0.3	*−4.45*
#2	0.0	−0.0	−0.05	−0.0	0.0	0.57
#3	−0.6	0.2	*6.35*	−0.1	0.1	1.79

[a] Italicized values *t*-test values are significant at the 0.95 level.

1966) is used to determine the magnitude and statistical significance of the differences in the mean conditions of selected subperiods.

Several schemes are used to subdivide the 89-year study period. Jacoby (1987) found many trees in the arroyos of the Zuni River drainage basin dating back to about 1920. His dendrochronological evidence along with historical data from the area suggest an end to a period of accelerated arroyo activity and the beginning of a more stable period near 1920. Therefore, one scheme uses 1920 as the break year for subdividing the study period. Another scheme subdivides the study period into two near-equal halves with a 1939 break year.

The results of the Student's *t*-tests (Table 6) are similar for both of the subdivision schemes. The Student's *t*-tests show: (1) Total annual precipitation amounts have dropped significantly into the more recent period. Both sets of analyses suggest a statistically significant decline of more than 25 mm per year in the subperiod means. Most of this decline appears to be associated with a drop in the summer rainfall totals. (2) The number of precipitation days is significantly higher in the recent subperiod. (3) The intensity of the summertime rain events significantly decreases into the more recent subperiod. This pattern is reflected in the sharp decline in the principal component scores of the first eigenvector. The early part of this century appears to be a time when a large number of high-intensity summer rain events occurred across the Zuni River drainage basin.

Drought Patterns

The most striking pattern in the plot of PDSI values from the Northwestern Plateau climate division is the existence of a long and severe drought extending from the summer of 1898 to December 1904 (Fig. 8). The drought ended abruptly in the first few months of 1905 when conditions became unusually wet for several years. The PDSI in December of 1904 was within the −3 to −4 range, indicating "severe drought"; by April 1905, the values were be-

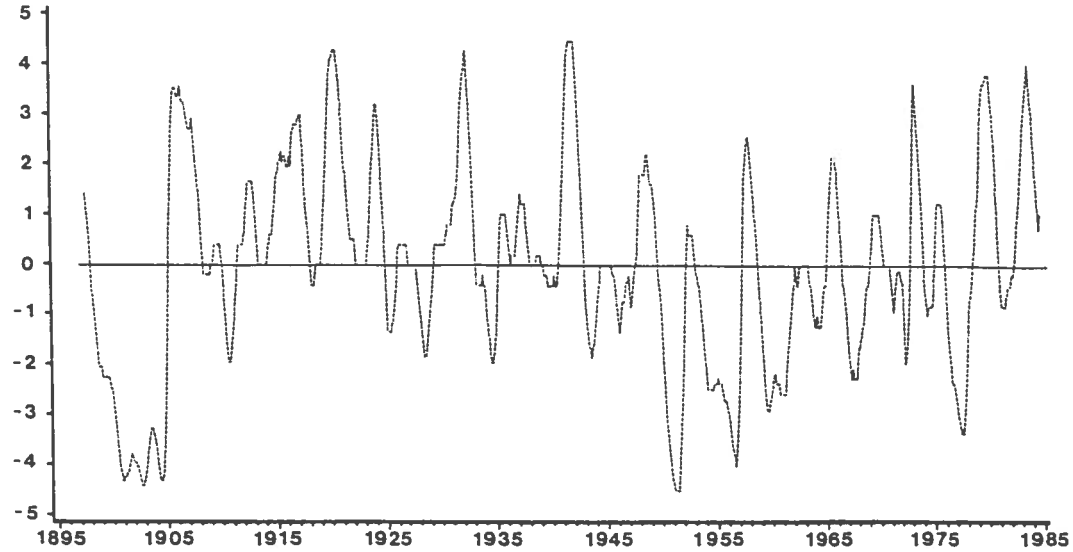

Figure 8. Plot of the PDSI values for the Northwestern Plateau Climate Division of New Mexico.

tween +3 and +4, indicating "severe wetness." Following this abrupt change came three consecutive summers of far-above-normal frequencies of the intense storms. Jacoby (1987) found the three-year period beginning in 1905 to be the wettest period in the area over the past thousand years. The drought preceding the wet period was exceeded in prolonged intensity only in the 1500s. Jacoby (1987, 45) concludes, "Nowhere in the thousand-year record is there an immediate juxtaposition of such severe sustained drought followed by an extreme high-precipitation period from the 1890s to the early 1900s."

Arroyo Activity and Climate Change

Cooke and Reeves (1976, 9–10) point out that "many investigators have been impressed by the fact that arroyo cutting occurred in prehistoric times—before man could have caused the necessary changes—and found climatic changes adequate" to induce arroyo cutting and filling. Historic discharge records of the Zuni River since 1904 show changes in runoff characteristics associated with the observed changes in precipitation. The period between 1905–30 had high-intensity storms which declined after 1930 and stabilized after the mid-1940s. More frequent flood events and significantly higher average discharge occurred between 1905–30 compared to the 1970–84 instrumental record (Fig. 9). A yearly average of mean annual discharge of 30 ft^3/sec (0.85 m^3/sec) for 1905–30 is nearly two times the 1970–84 yearly average. Similar trends between discharge and precipitation have been observed in the Little Colorado River downstream from the Zuni River and for the entire Colorado River drainage basin for approximately the same time periods (Hereford 1984).

The relation between Zuni River runoff and climatic changes provides the hydrophysical link between arroyo activity and precipitation patterns. Data indicate that B-scale and C-scale arroyos display greater magnitudes of cutting and erosion during increased high-intensity rainfall events (Fig. 9). Increased precipitation and erosion of inset deposits within intermediate and small arroyos during the period 1970–84 support the observation that arroyo erosion is linked to periods of increased effective precipitation. Periods dominated by arroyo infilling appear to coincide with a long period of below-normal summertime storminess levels (Fig. 9). Comparison of photographs from the archives with modern photographs suggests lo-

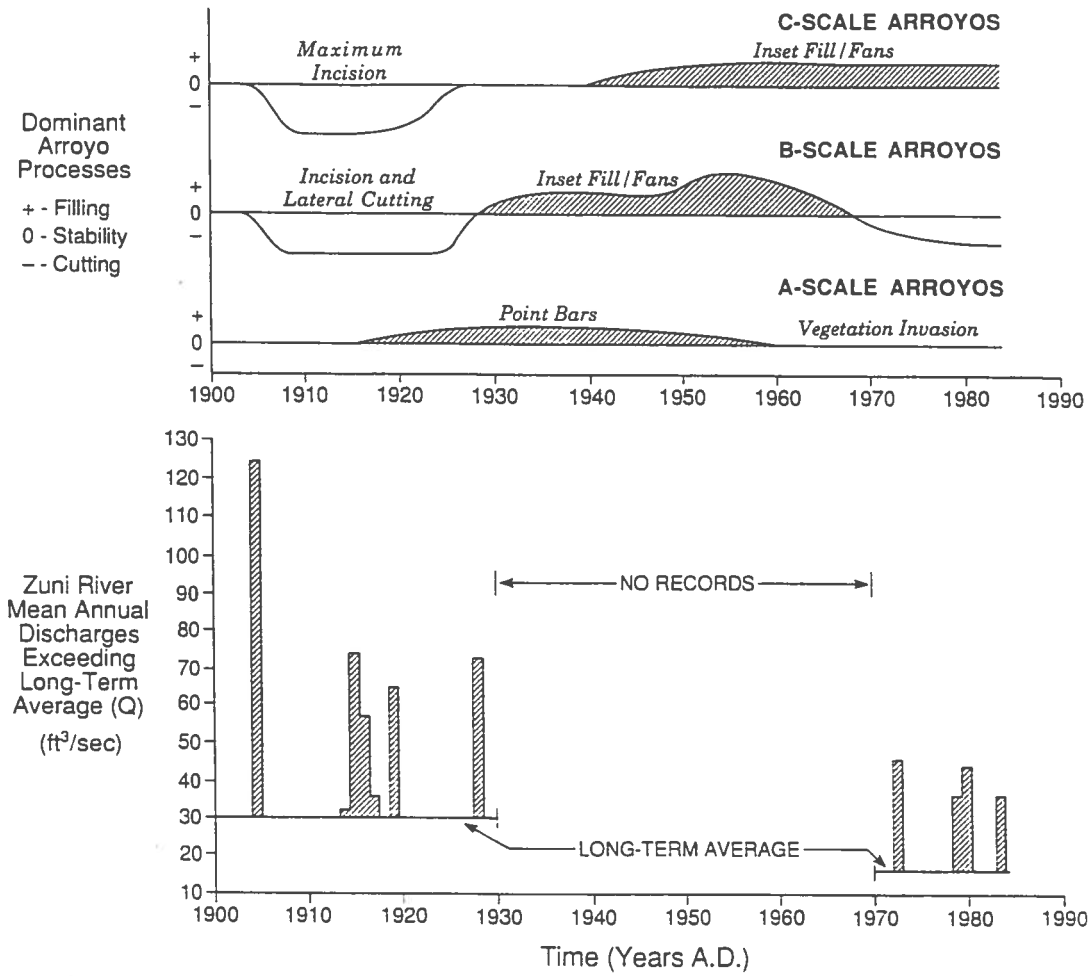

Figure 9. Summary diagram of geomorphic and hydrologic behavior of arroyos of different sizes in the Zuni area.

cal infilling of A-scale arroyos during the drought of 1898–1904. The transition of a period with exceptional drought with a period of extremely high precipitation apparently exceeded the erosional threshold of arroyos in the Zuni area, causing both small and intermediate arroyos to erode simultaneously (Fig. 9).

Conclusions

Our goal was to analyze the basic morphology and potential causes of the modern arroyos of the Zuni River. Geomorphic evidence suggests that during the early part of this century (ca. 1910), the large arroyos were undergoing aggradation of point bars, active floodplain accretion, increased lateral migration of meanders, and lateral cutting of arroyo walls. Intermediate- and small-size arroyos showed increased erosion during the period 1905–30. The 1930–70 period saw the establishment of riparian vegetation in the stabilized large arroyos, while the small and intermediate arroyos underwent a period of stability followed by channel infilling and deposition of alluvial fans at the arroyo mouths. Since ca. 1970, the large

arroyos have remained stable, but the intermediate arroyos have incised from one to two meters.

During the past century, evolution of theories of arroyo incision demonstrates that research and proposed models of arroyo formation have shifted from those solely pertaining to land use cause to those involving numerous natural hydrologic and geologic causes and have recognized numerous difficulties in assuming land-use practices are the primary cause of arroyo development. In many locations in the Southwest, arroyo incision was contemporaneous with changes in livestock populations, grazing conditions, or timbering activity, thereby creating difficulty in distinguishing the major mechanisms for incision (Peterson 1950). The Zuni area represents a unique opportunity to illustrate the relative role of climatic changes on arroyo processes because (a) arroyos existed prior to any Spanish or Anglo intervention, and large arroyos had eroded to approximately their present level by two to three hundred years ago; (b) tree-ring dates within the headwaters and middle reaches of the Zuni River indicate long-term channel stability before and after the time of timber harvesting (Resource Consultants 1987); and (c) the degree of soil development on the valley floors of the Zuni area indicates that overgrazing did not increase the erodibility of the valley bottoms (Wells 1988).

Observed changes in arroyo activity in the Zuni River drainage basin appear to be synchronous with statistically significant changes that occurred in the local and regional climate. These relations imply periods of arroyo incision are triggered by changes in precipitation patterns involving increased precipitation amounts and the number of high-intensity summer storms. Under these conditions, increased runoff enhances channel erosion, as suggested by Leopold in 1951. In the Zuni area, arroyo infilling and stability occur as precipitation patterns change to fewer intense summer storms and less annual rainfall.

Recent decades have seen a deemphasis of climate as a mechanism responsible for arroyo activity in the past (Patton and Schumm 1981). The identification of pronounced changes in precipitation patterns of the Zuni area should reestablish climatic change as a significant variable responsible for changing erosional thresholds of arroyos and valley floors in the early part of this century.

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References

Adams, E. D., and Chavez, A. 1956. *The missions of New Mexico, 1776.* Albuquerque: University of New Mexico Press.

Bailey, R. W. 1935. Epicycles of erosion in the valleys of the Colorado Province. *Journal of Geology* 43:337–55.

Baxter, S. 1882. The father of the pueblos. *Harper's New Monthly Magazine* 65:72–91.

Bryan, K. 1925. Date of channel trenching (arroyo cutting) in the arid Southwest. *Science* 62:338–44.

Bull, W. B. 1964. History and causes of channel trenching in western Fresno County, California. *American Journal of Science* 262:249–58.

Cooke, R. U., and Reeves, R. W. 1976. *Arroyos and environmental change in the American South-West.* Oxford: Clarendon Press.

Cooley, M. E. 1980. Geologist, U.S. Geological Survey, Albuquerque. Personal communication.

Graf, W. L. 1983. The arroyo problem—Paleohydrology and paleohydraulics in the short term. In *Background to paleohydrology,* ed. G. K. Gregory, pp. 262–303. London: John Wiley and Sons.

Hereford, R. 1984. Climate and ephemeral-stream processes: Twentieth-century geomorphology and alluvial stratigraphy of the Little Colorado River, Arizona. *Geological Society of America Bulletin* 95:654–68.

———, **and Webb, R. H.** 1989. Timing and possible causes of late Holocene erosion and aggradation southwestern Colorado Plateau, USA. *EOS, Transactions, American Geophysical Union* 70:1124.

Jacoby, G. C. 1987. Dendrochronological investigation of the Zuni Indian Reservation. U.S. Department of Justice Technical Report, Claims Court No. 327-81L, Exhibit 14000. Washington.

Karl, T. R., and Knight, R. W. 1985a. *Atlas of monthly Palmer Drought Severity Index (1895–1930) for the contiguous United States.* Asheville, NC: National Climatic Data Center.

———, **and** ———. 1985b. *Atlas of monthly Palmer Drought Severity Index (1931–1983) for the contiguous United States.* Asheville, NC: National Climatic Data Center.

Lagasse, P. F.; Schall, J. D.; and Wells, S. G. 1990. Runoff and erosional processes in an arid watershed. American Society of Civil Engineers *Pro-*

ceedings, International Symposium on Hydraulics/Hydrology of Arid Lands.

Leopold, L. B. 1951. Rainfall frequency: An aspect of climatic variation. *Transactions, American Geophysical Union* 32:347–57.

———; Emmett, W. E.; and Myrick, R. M. 1966. Channel and hillslope processes in a semiarid area, New Mexico. *U.S. Geological Survey Professional Paper* 352-G:193–253.

McNitt, F. 1964. *Navajo expedition—Journal of military reconnaissance from Santa Fe, New Mexico to the Navajo Country made in 1849 by Lieutenant James H. Simpson.* Norman: University of Oklahoma Press.

Miller, J. P., and Wendorf, F. 1958. Alluvial chronology of the Tesuque Valley, New Mexico. *Journal of Geology* 66:177–94.

Mitchell, J. M., Jr. et al. 1966. *Climatic change.* World Meteorological Organization, Technical Note No. 79. Geneva.

Palmer, W. C. 1965. *Meteorological drought research paper no. 45.* Washington: U.S. Weather Bureau.

Patton, P. C., and Schumm, S. A. 1975. Gully erosion, northwestern Colorado: A threshold phenomenon. *Geology* 3:88–90.

———, and ———. 1981. Ephemeral-stream process: Implications for studies of Quaternary valley fills. *Quaternary Research* 15:24–43.

Peterson, H. V. 1950. The problem of gullying in Western valleys. In *Applied sedimentation,* ed. P. D. Trask, pp. 407–34. New York: John Wiley and Sons.

Potter, L. D. 1987. Ecological interpretations of the Zuni Indian Reservation, New Mexico. U.S. Department of Justice Letter Report, Claims Court No. 327-81L, Exhibit 17000. Washington.

Resource Consultants, Inc. 1987. Analysis of changes in hydrology, hydraulics, and sediment transport, Zuni Indian Reservation, New Mexico. U.S. Department of Justice Technical Report, Claims Court No. 327-81L, Exhibit 13000. Washington.

Rich, J. L. 1911. Recent stream trenching in the semi-arid portion of southwestern New Mexico, a result of removal of vegetation cover. *American Journal of Science* 32:237–45.

Schumm, S. A. 1973. Geomorphic thresholds and complex response of drainage systems. In *Fluvial geomorphology,* ed. M. Morisawa, pp. 299–310. Binghamton, NY: State University of New York.

———. 1976. Episodic erosion, a modification of the geomorphic cycle. In *Theories of landform development,* ed. W. N. Melhorn and R. C. Flemal, pp. 69–86. Binghamton, NY: State University of New York.

———, and Hadley, R. F. 1957. Arroyos and the semi-arid cycle of erosion. *American Journal of Science* 255:161–74.

Tuan, Y-F. 1966. New Mexican gullies: A critical review and some observations. *Annals of the Association of American Geographers* 56:573–97.

Wells, S. G. 1987. A quantitative analysis of arroyo development and geomorphic processes in the Zuni River drainage basin, west-central New Mexico. U.S. Department of Justice Technical Report, Claims Court No. 327-81L, Exhibit 12000. Washington.

———. 1988. Holocene and historic arroyo evolution in the Zuni River watershed, western New Mexico. *Geological Society of America Abstracts with Programs* 20:A361.

Yair, A., and Wells, S. G. 1989. Ratio of rock surfaces and surficial deposits as a control of fluvial processes and landscape evolution in semiarid and arid regions. *Geological Society of America Abstracts with Programs* 21:A38.