Allen Gellis received his M.S. in geology from Colorado State University where he studied the geomorphic evolution of arroyos in the Southwest. He joined the USGS in 1988 and was stationed in San Juan, Puerto Rico for three years. Allen has been in New Mexico since April 1991, and is currently assisting the Zuni tribe in planning for watershed rehabilitation.

DECREASING TRENDS OF SUSPENDED SEDIMENT CONCENTRATIONS AT SELECTED STREAMFLOW STATIONS IN NEW MEXICO

Allen Gellis
U.S. Geological Survey
4501 Indian School Road NE
Suite 200
Albuquerque, New Mexico 87110

INTRODUCTION

Data collected from six U.S. Geological Survey streamflow-gaging stations in New Mexico indicate a decrease in annual suspended sediment concentrations. Average annual rates of sediment accumulation in three reservoirs in New Mexico also are showing a decrease. This decrease in sediment concentrations from streamflow-gaging stations and in accumulation rates in reservoirs may reflect a change in the sediment delivery from tributary arroyos through time.

From 1880 to 1920, many arroyos in New Mexico incised and contributed large volumes of sediment to main channels, such as the Rio Grande and Pecos River. Since then many of these arroyos have been evolving. Arroyo evolution begins with channel deepening, and is followed by channel widening, floodplain formation, and the establishment of vegetation. These sequential channel changes proceed upstream through the watershed and ultimately lead to channel aggradation and reduced sediment yields.

The evolution of arroyos may be an important consideration to conservationists and erosion-control planners. In a watershed affected by channel incision, the downstream reaches of the watershed are generally aggrading, whereas upstream reaches are still eroding their bed and banks. Therefore, the stage of channel evolution in a particular reach can be an important consideration in determining the placement of erosion-control structures.

PURPOSE AND SCOPE

Suspended sediment data for selected streamflow stations in New Mexico were analyzed to show if there is a trend to the data. Stations that had at least a 20-year record were selected. Sedimentation surveys for selected reservoirs in New Mexico were analyzed to show if the accumulation rates of sediment have been changing through time. Causes for increasing or decreasing trends in either suspended sediment or reservoir sedimentation rates were examined and tested. Arroyos, which are major contributors of sediment in New Mexico, were examined for channel changes through time and their possible relation to increasing or decreasing trends in suspended sediment or reservoir sedimentation rates.

SUSPENDED SEDIMENT DATA

Suspended sediment sampling techniques used in New Mexico have varied through time and among agencies. The International Boundary and Water Commission (IBWC) collected suspended sediment at the station Rio Grande at San Marcial (Fig. 1) beginning in 1897 and was subsequently continued by the U.S. Geological Survey (USGS) in

1946. After 1950, flow at this station was divided into two channels, a floodway and a conveyance channel. Suspended sediment data for the Rio Grande at San Marcial after 1950 were reported as the sum of both channels. The IBWC collected suspended sediment using one or more of four methods described in Summary Water Bulletin Number 1 (International Boundary and Water Commission 1956). Daily, monthly, and annual totals were reported as suspended silt in acre-feet, at 1,452 tons of suspended silt per acre-foot. The USGS and the IBWC used the Rio Grande sampler for suspended sediment collection at streamflow-gaging stations in New Mexico until 1948. In 1939 an interagency committee was formed to study and develop accurate methods of suspended sediment sampling (U.S. Interagency Committee on Water Resources 1944). A standardized depth-integrated sampler, the US D-48, was developed and incorporated into use by the USGS in 1948. The USGS collects suspended sediment in accordance with guidelines presented by Guy and Norman (1970). Changes in suspended sediment concentrations as a result of sampler modifications, sampling methods, and laboratory methods are not known, but could be expected; however, whether these modifications might increase or decrease suspended sediment concentrations is unclear. Gellis and others (1991) reported that the decrease in suspended sediment loads in the 1940s in the Colorado River basin probably was not due to a change in samplers or sampling methods. Comparative laboratory tests of the Colorado River sampler and the replacement sampler, the US D-48, indicated that the US D-48 resulted in higher concentrations than did the earlier model. This increase in suspended sediment concentrations as a result of sampler changes contrasts with the lower concentrations observed in the 1940s in suspended sediment records.

Annual suspended sediment load data from eight streamflow-gaging stations in New Mexico (Fig. 1) were obtained from USGS annual data reports, IBWC Summary Water Bulletins, and the USGS hydrologic database WATSTORE. Characteristics of each station are listed in Table 1. Annual suspended sediment concentrations, in tons per acre-foot, at stations 1 through 6 (Tab. 1) were calculated by dividing annual suspended sediment

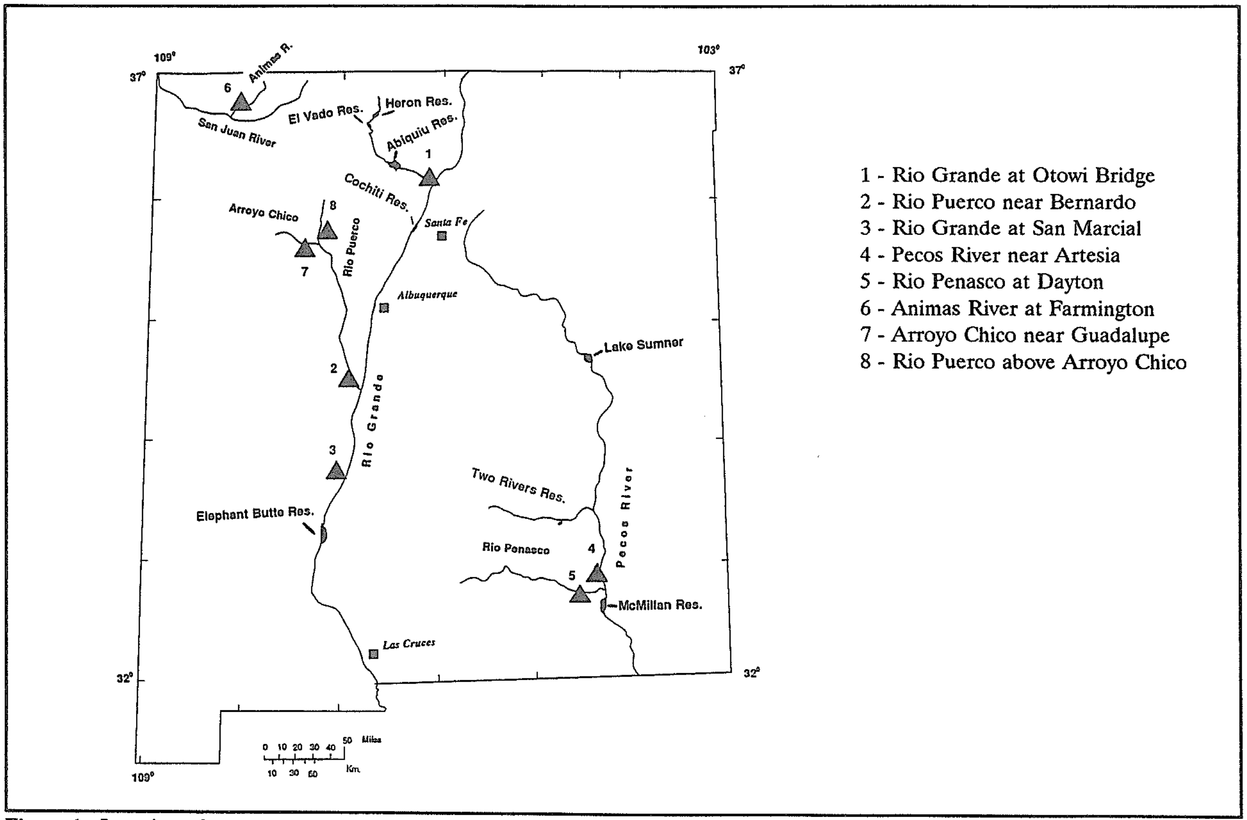

Figure 1. Location of selected streamflow-gaging stations in New Mexico.

Table 1. Characteristics of selected streamflow gaging stations.

Station name	Drainage area (mi^2)	Period of record	Average annual suspended sediment load (tons)	Upstream reservoirs & completion dates
1-Rio Grande at Otowi Bridge	14,300	1948-1990	2,046,700	El Vado - 1935 Abiqui - 1963 Heron - 1971
2-Rio Puerco near Bernardo	7,350	1948-1990	4,292,900	None
3-Rio Grande at San Marcial	27,700	1897-1990	12,100,600	El Vado - 1935 Abiqui - 1963 Heron - 1971 Cochiti - 1975
4-Pecos near Artesia	15,300	1949-1990	520,000	Lake Sumner - 1937 Two Rivers - 1963
5-Rio Penasco at Dayton	1,060	1952-1973	688,100	None
6-Animas River at Farmington	1,360	1951-1990	106,100	None
7-Arroyo Chico near Guadalupe	1,390	1949-1955 1979-1986	1,910,400	None
8-Rio Puerco above Arroyo Chico	420	1949-1955 1982-1990	867,200	None

loads, in tons, by annual runoff, in acre-feet (Figs. 2-7). As indicated by the best-fit regression lines in Figures 2-7, annual suspended sediment concentrations at all stations have decreased through time. At Rio Grande at Otowi Bridge (Fig. 2), the annual sediment concentration, as indicated by the best-fit regression line, decreased 71 percent, from 3.5 tons per acre-foot in 1948 to 1.0 ton per acre-foot in 1990. At the station Rio Grande at San Marcial (Fig. 4), annual suspended sediment concentrations decreased 85 percent, from 27.0 tons per acre-foot in 1897 to 4.0 tons per acre-foot in 1990.

Because large amounts of sediment are transported in relatively few days of high runoff, factoring out runoff on an annual basis could have some inherent errors. For example, a high runoff year might be the result of high snowmelt runoff, which does not characteristically transport large amounts of suspended sediment. A seasonal trend test might resolve some of these problems, but for the purpose of this report such a test was not performed.

Statistical analysis was performed on the data shown in Figures 2-7 to determine the significance of the trend (Table 2). Statistical analysis consisted of testing the hypothesis that fluctuations in the data are random, and testing the hypothesis that there is a trend to the data (Miller and Kahn 1962). The test for randomness involves assigning a (+) to values above the median and a (-) to values below the median. The number of runs in the data or the number of sequences of one or more like values (+ or -), preceded and followed by a different value is determined. Using a significance level of 0.025 for the lower tail, and 0.025 for the upper tail, we would reject the hypothesis of random fluctuations in the data if the probability, $P(\mu) < 0.050$.

Spearman's rank correlation method computes the correlation between an observed sequence and a regular rising or falling of variables (Miller and Kahn 1962). Spearman's rank correlation coefficient ranges from -1 to 1, so a high negative correlation would indicate the possibility of a downward trend.

Table 2. Results of statistical analysis on annual suspended sediment concentrations using data from Figures 2-7.

Station name	Test for random order, P(μ) correlation coefficient	Spearman's rank
1-Rio Grande at Otowi Bridge	0.001	-0.719
2-Rio Puerco near Bernardo	0.011	-0.668
3-Rio Grande at San Marcial	0.00002	-0.602
4-Pecos River near Artesia	0.0001	-0.736
5-Rio Penasco at Dayton	0.033	-0.319
6-Animas River at Farmington	0.124	-0.565

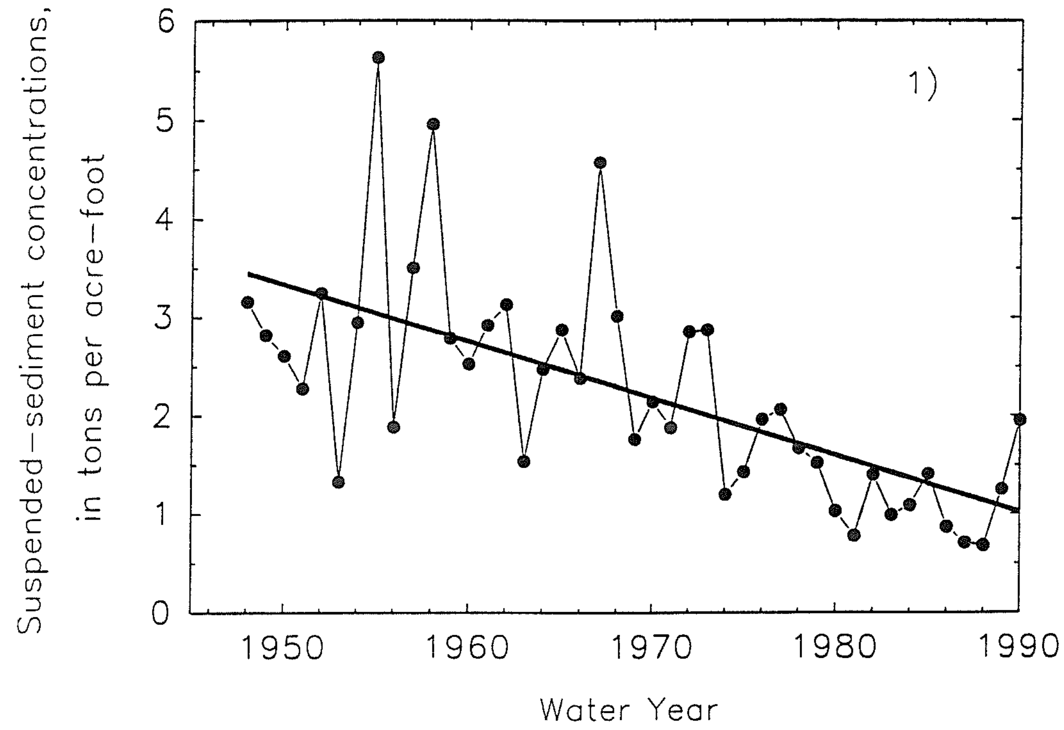

Figure 2. Annual suspended sediment concentrations through time including best-fit regression line for Rio Grande at Otowi Bridge station.

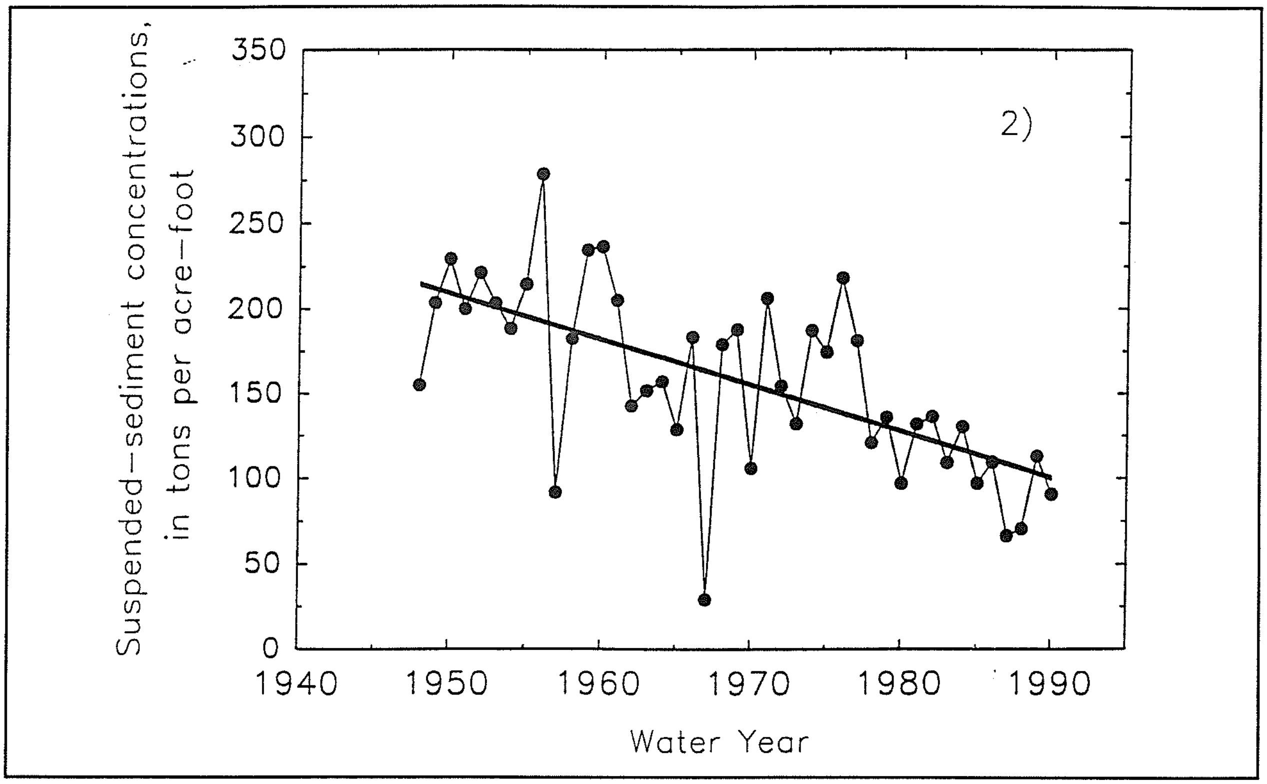

Figure 3. Annual suspended sediment concentrations through time including best-fit regression line for Rio Puerco near Bernardo station.

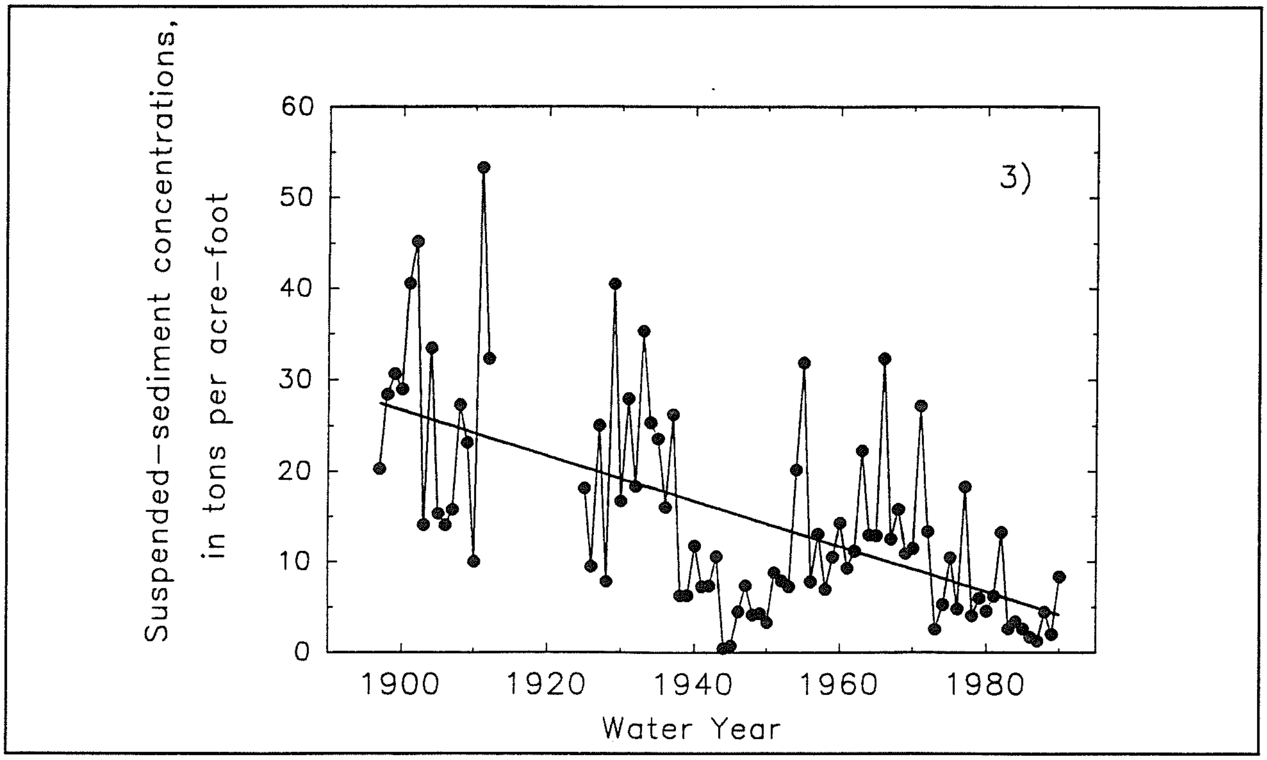

Figure 4. Annual suspended sediment concentrations through time including best-fit regression line for Rio Grande at San Marcial station.

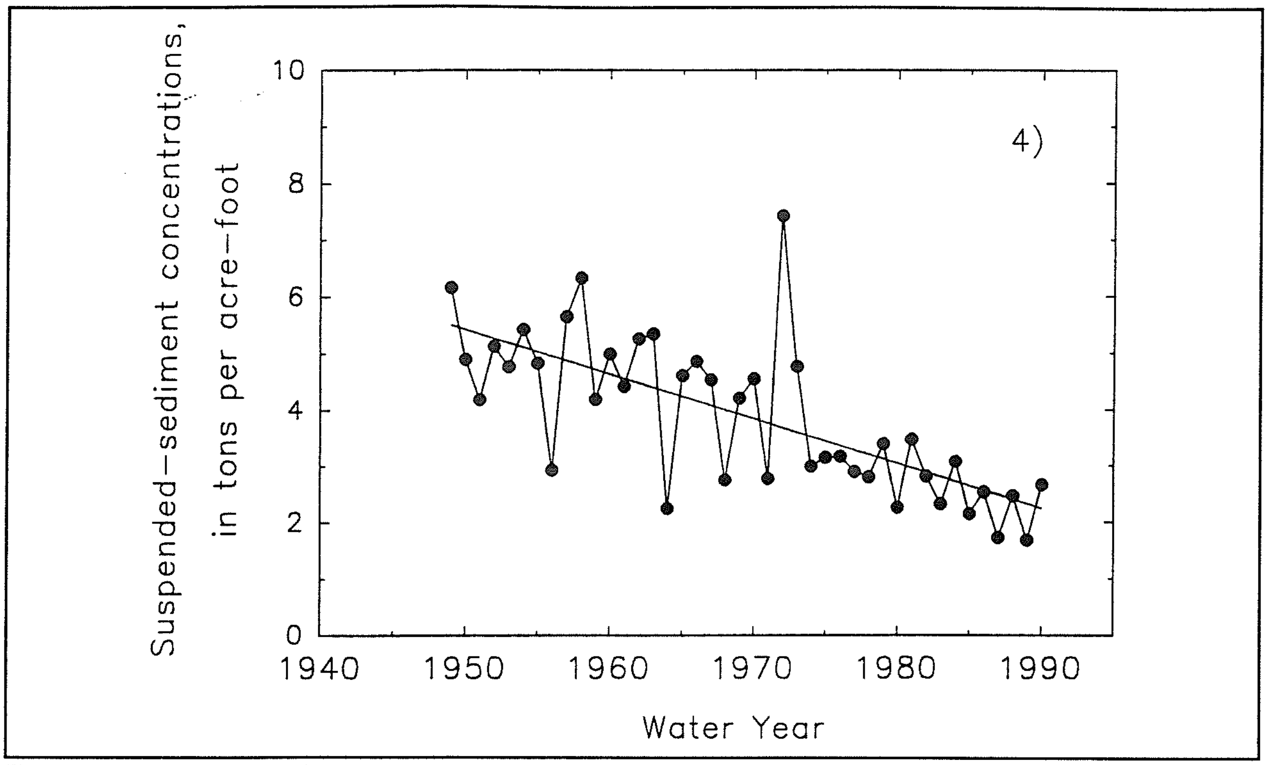

Figure 5. Annual suspended sediment concentrations through time including best-fit regression line for Pecos River near Artesia station.

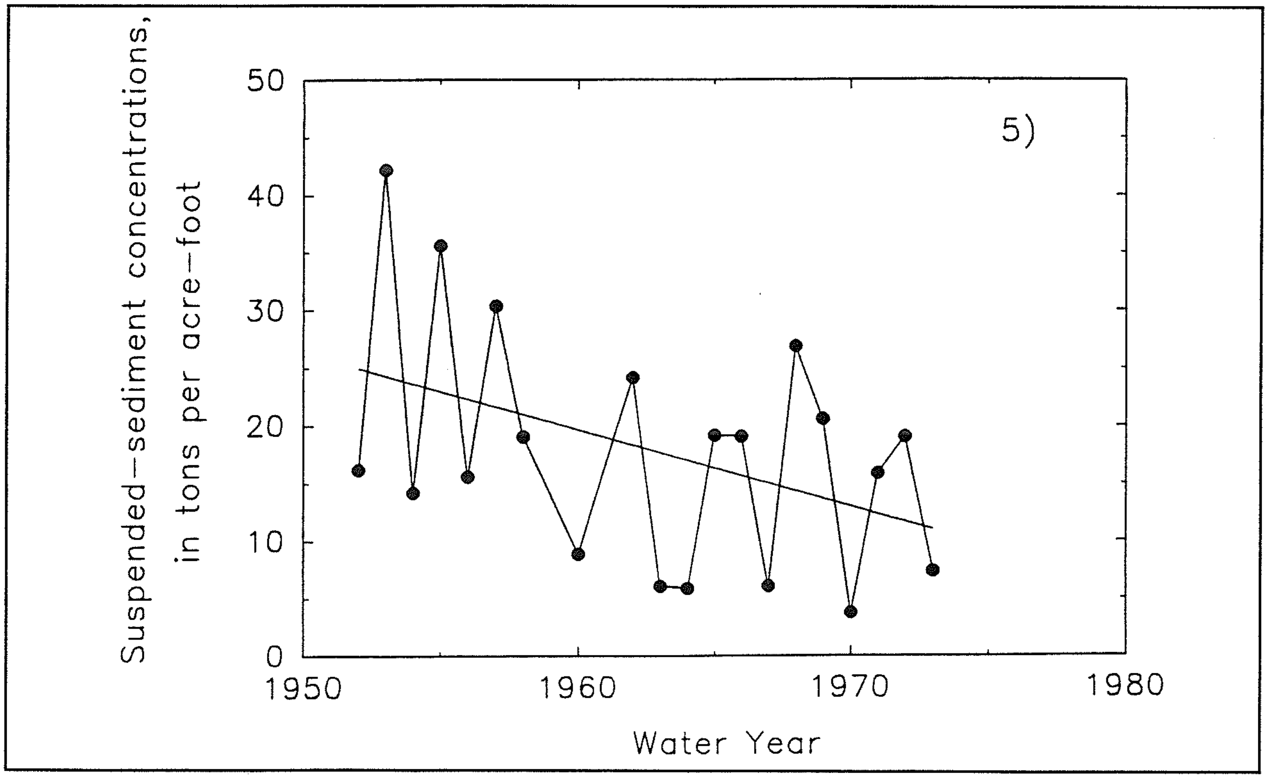

Figure 6. Annual suspended sediment concentrations through time including best-fit regression line for Rio Penasco at Dayton station.

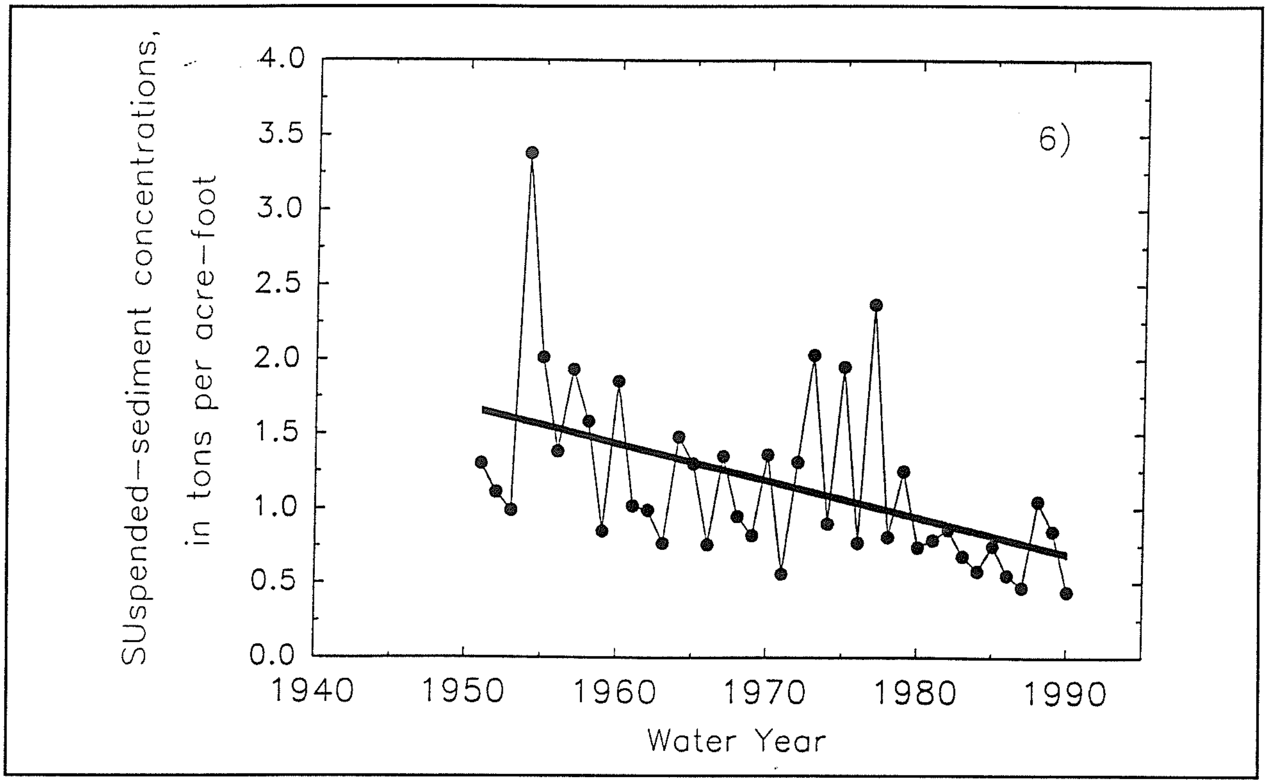

Figure 7. Annual suspended sediment concentrations through time including best-fit regression line for Animas River at Farmington station.

Of the six stations in Figure 1 tested for random order, all except the Animas River at Farmington indicate that fluctuations in the data are not random (Table 2). A Spearman rank correlation coefficient less than -0.5 was interpreted as being significant. Results of Spearman's rank correlation test indicate a strong possibility of a downward trend at all stations except for Rio Penasco at Dayton (Table 2). Although the Rio Penasco station shows a decrease in the best-fit regression line in Figure 6, this decrease may not be statistically significant. Therefore, the hypothesis that fluctuations in the data are not random and indicate a decreasing trend is supported for the stations Rio Grande at Otowi Bridge, Rio Puerco near Bernardo, Rio Grande at San Marcial, and Pecos River near Artesia.

CAUSES FOR THE DECREASE IN SEDIMENT

The causes for the decrease in annual suspended sediment concentrations could include the following: upstream reservoir closures, change in sediment-sampling procedures, or arroyo evolution.

Reservoirs generally have little impact on annual runoff, but affect peak flow and trap substantial quantities of suspended sediment. A change in sediment-sampling procedures might have affected suspended sediment concentrations. To test the hypothesis that reservoirs and a change in sediment samplers affected annual suspended sediment loads, double-mass curves were constructed for all the stations shown in Table 1 (Figs. 8-13). In double-mass curve analysis, cumulative annual suspended sediment load is plotted against cumulative annual runoff (Searcy and Hardison 1960). A break in the slope of the double-mass curve in any direction means that a change has occurred in the constant of proportionality between runoff and suspended sediment load. The effects of a reservoir on reducing sediment loads should appear as a downward break in slope in a double-mass curve. A change in sediment samplers might also appear as a break in slope of the relation between suspended sediment loads and runoff. Thompson (1984a,b) used the double-mass curve to analyze changes in suspended sediment characteristics for the Utah stations, Colorado River near Cisco and

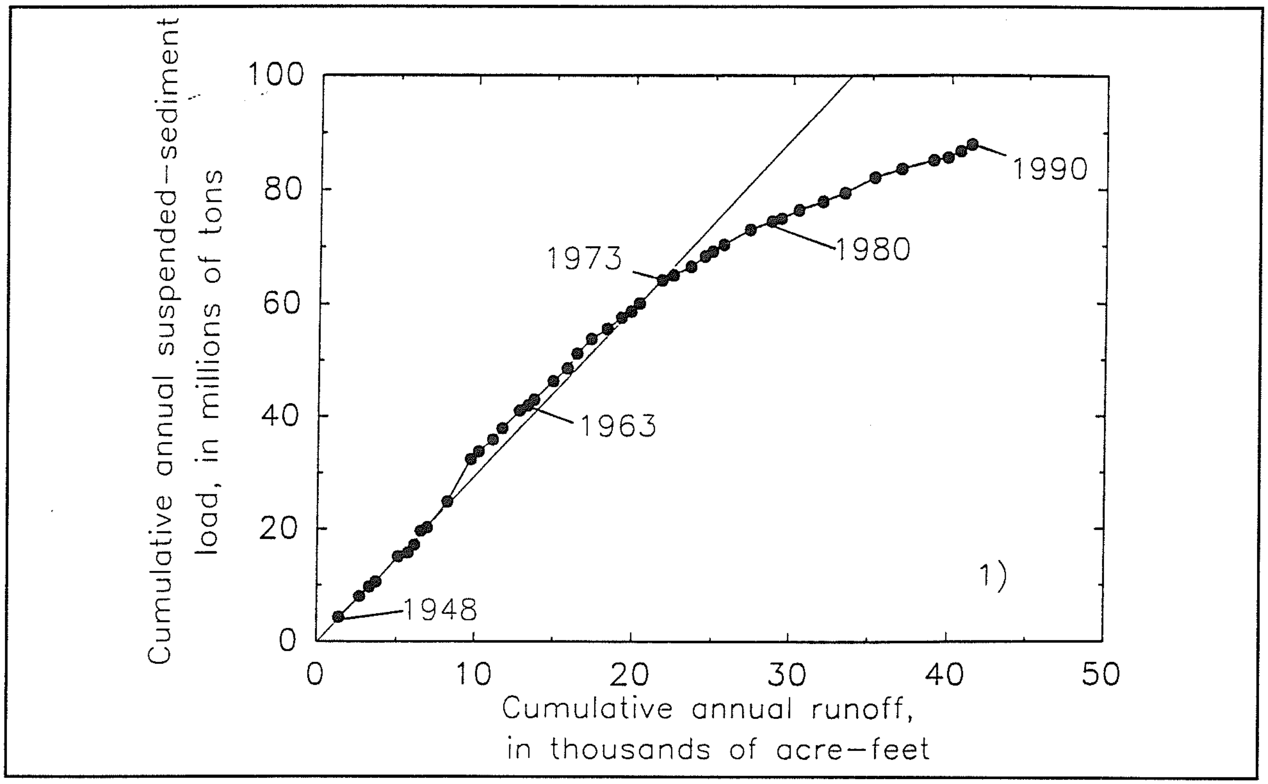

Figure 8. Double-mass curves showing relation between annual suspended sediment load and annual runoff for Rio Grande at Otowi Bridge station.

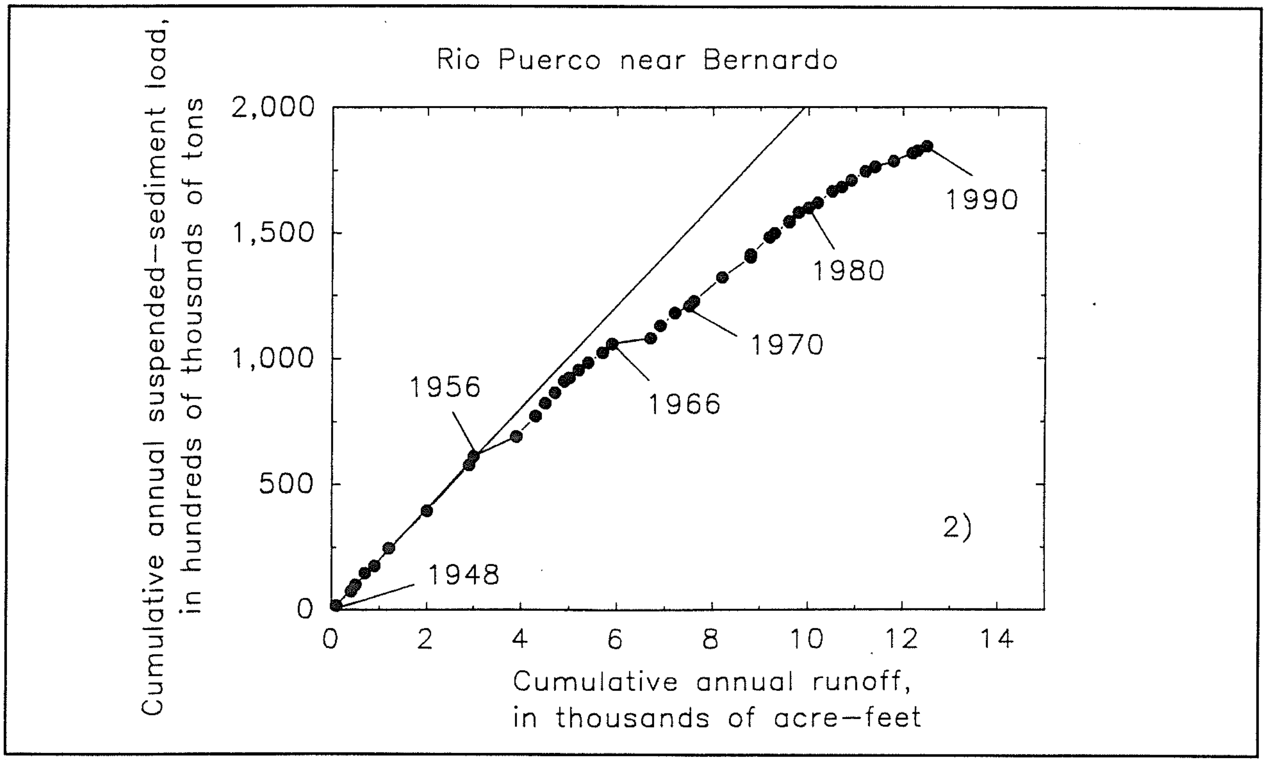

Figure 9. Double-mass curves showing relation between annual suspended sediment load and annual runoff for Rio Puerco near Bernardo station.

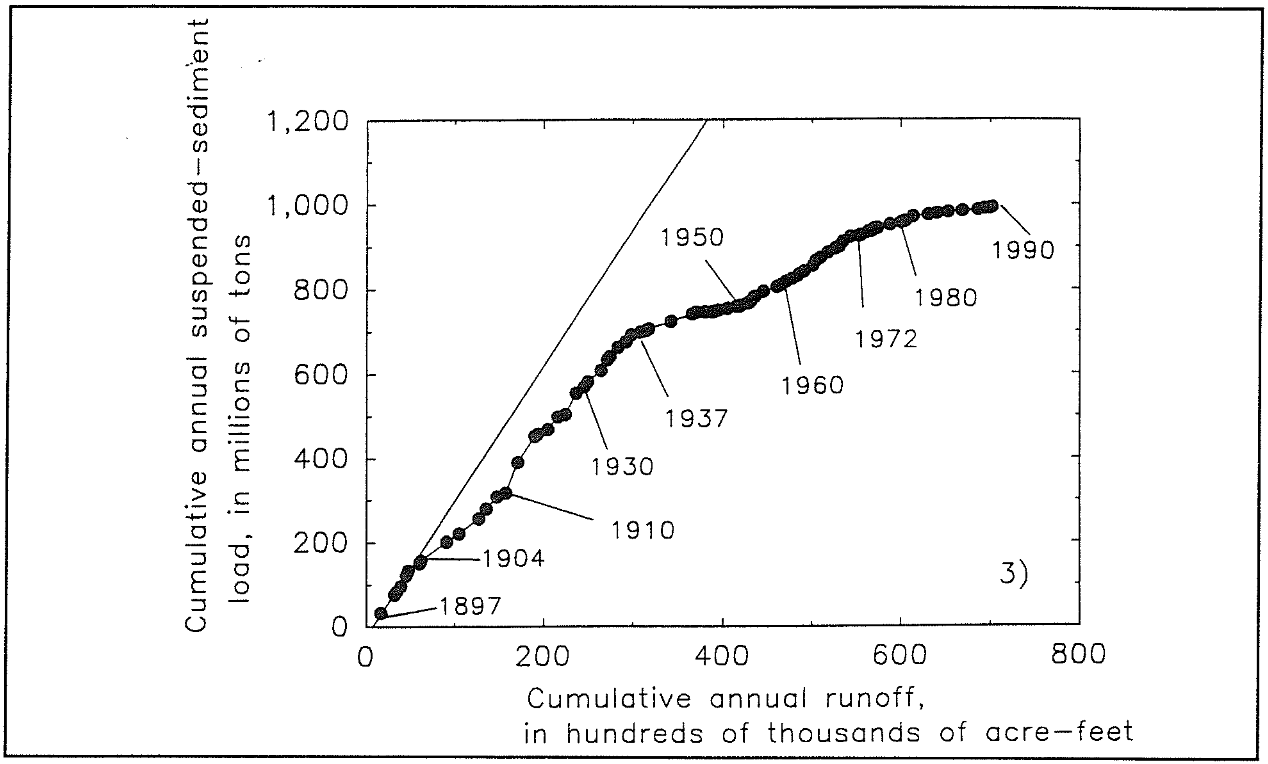

Figure 10. Double-mass curves showing relation between annual suspended sediment load and annual runoff for Rio Grande at San Marcial station.

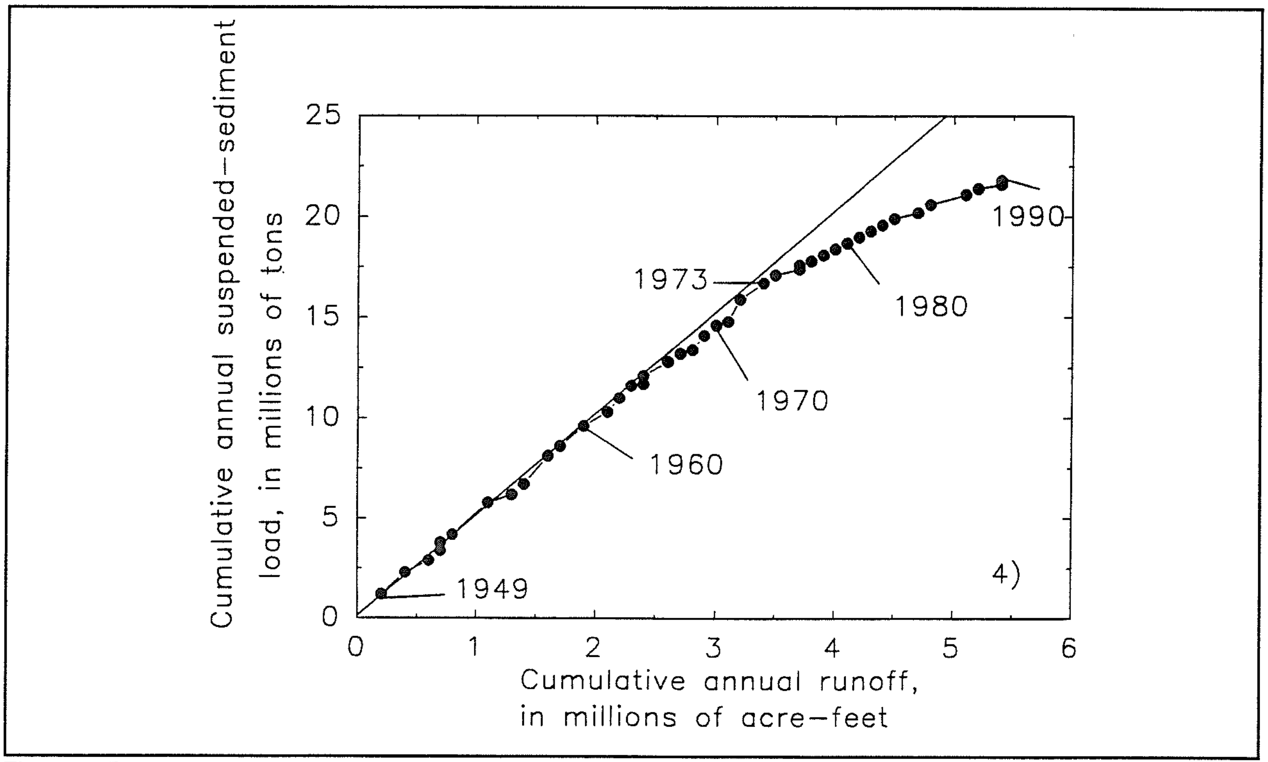

Figure 11. Double-mass curves showing relation between annual suspended sediment load and annual runoff for Pecos River near Artesia station.

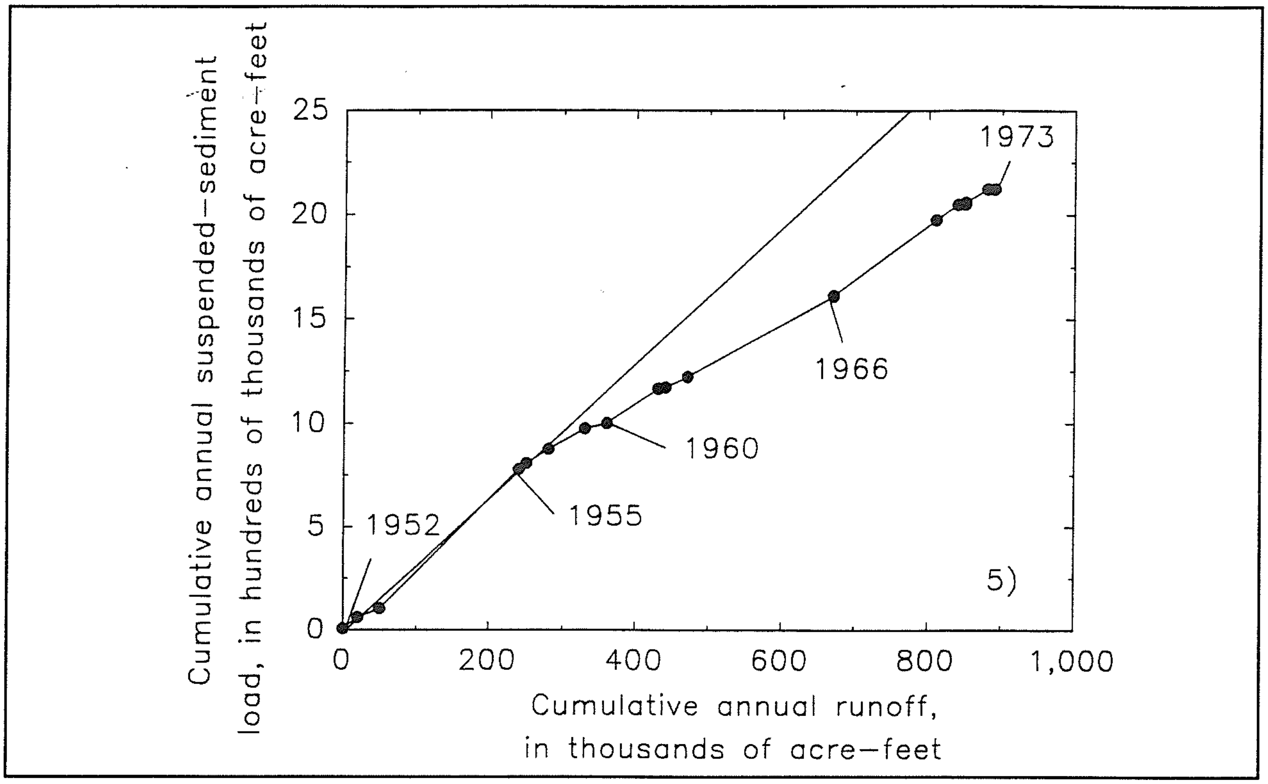

Figure 12. Double-mass curves showing relation between annual suspended sediment load and annual runoff for Rio Penasco at Dayton station.

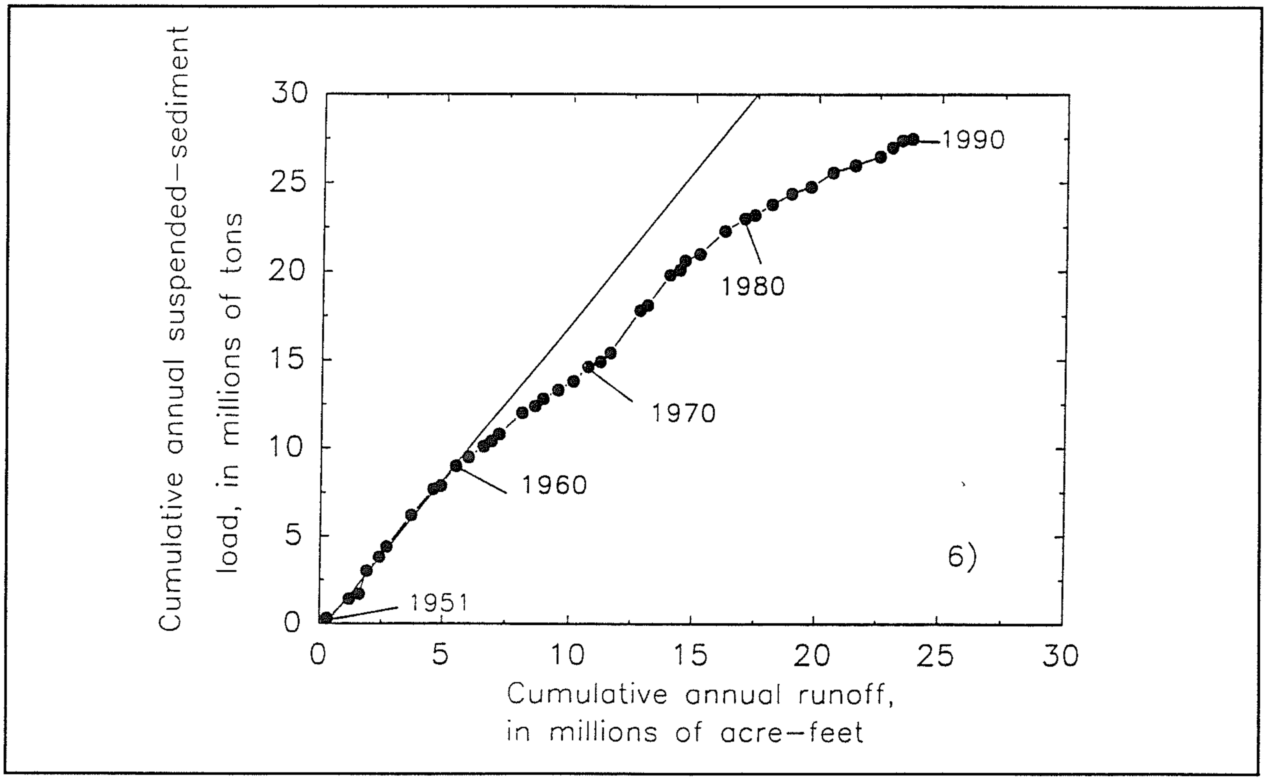

Figure 13. Double-mass curves showing relation between annual suspended sediment load and annual runoff for Animas River at Farmington station.

Green River at Green River. Changes in the slope of the double-mass curve in 1963 reflected the closures of several dams upstream from these stations.

Three major reservoirs were constructed upstream from the station Rio Grande at Otowi Bridge (Table 1). El Vado and Abiquiu reservoirs, completed in 1935 and 1963, respectively, apparently had no significant effect on the relation between suspended sediment load and runoff (Fig. 8). A break in slope of the double-mass curve at the station Rio Grande at Otowi Bridge occurred in 1973. It is unclear if this break in slope is due to the influence of Heron Reservoir, constructed in 1971. Heron Reservoir is located upstream from both El Vado and Abiquiu reservoirs and, therefore, its effect on suspended sediment loads is obscured by El Vado and Abiquiu reservoirs. At the station Rio Grande at San Marcial, downward breaks in the suspended sediment load/runoff relation occurred in 1904, 1937, and 1972 (Fig. 10). The 1937 and 1972 dates follow closely the closure of El Vado and Heron reservoirs, respectively. However, if this change in slope was due to closure of these reservoirs, it is unclear why the suspended sediment loads at the station Rio Grande at Otowi Bridge, which is located much closer to these reservoirs, was unaffected. At the station Pecos River near Artesia a change in the suspended sediment load/runoff relation occurred in 1973, and is not coincident with the closure of any upstream reservoirs (Table 1). A break in slope does not appear at the station Rio Grande at San Marcial in 1948 when the USGS changed sediment-sampling equipment; therefore, the change in sediment sampler does not seem to have affected suspended sediment concentrations at this station.

The double-mass curves in Figures 8-13 do not indicate that reservoir closures were a factor altering the suspended sediment load/runoff relation. However, these stations show the change in slope of the double-mass curve to be negative, indicating a decrease in annual suspended sediment loads relative to annual runoff.

RESERVOIR ANALYSIS

To determine if sediment concentrations are decreasing in New Mexico's rivers, reservoir sedimentation surveys were analyzed through time. At Elephant Butte Reservoir, Lake Sumner and McMillan Reservoir, sedimentation surveys were used to determine the average annual rate of sedimentation for the period of time between surveys (Dendy and Champion 1978). The loss in storage capacity between surveys, in acre-feet, was assumed to be equal to the volume of sediment deposited in the reservoir. To eliminate the effects of variable runoff, mean annual sedimentation rates were divided by mean annual runoff, in acre-feet, for the period between surveys (Figs. 14-16). The resulting normalized annual sedimentation rate is unit-less (acre-foot of sediment per acre-foot of runoff). At Elephant Butte Reservoir, a general decrease in the sedimentation rate is observed from the 1920s to the 1950s. Lake Sumner shows a decrease in the annual sedimentation rate from 1940 to 1973. McMillan Reservoir shows a high annual sedimentation rate in the first survey of 1915 (Fig. 16). Subsequent surveys indicate a much lower rate of sedimentation. Therefore, a decrease in the amount of sediment deposited versus runoff per year has been occurring since the closure of each reservoir (Figs. 14-16). This reservoir analysis confirms the downward trends of suspended sediment shown in Figures 2-7.

ARROYO EVOLUTION

During the period 1880 to 1920, many washes and channels in New Mexico incised and formed large arroyos (Bryan 1925; Antevs 1952; Cooke and Reeves 1976). Generally, two theories have prevailed for arroyo incision: incision caused by a climatic change (Leopold 1951; Bull 1964; Webb 1990) or incision caused by a change in land use (Rich 1911; Thornthwaite and others 1942; Antevs 1952). This paper does not address the cause(s) of arroyo incision but rather how arroyo channels may be affecting sediment production in several areas of New Mexico.

Field evidence of arroyos in New Mexico and elsewhere in the Southwest may provide a geomorphic explanation for the decrease in sediment measured at streamflow-gaging stations and reservoirs in New Mexico (Emmett 1974; Elliott 1979; Graf 1987; Gellis and others 1991). Following a period of channel incision, channel geometry in arroyos develops in a systematic fashion, known as arroyo evolution. When incision begins in an alluvial valley, downstream locations are affected first. The

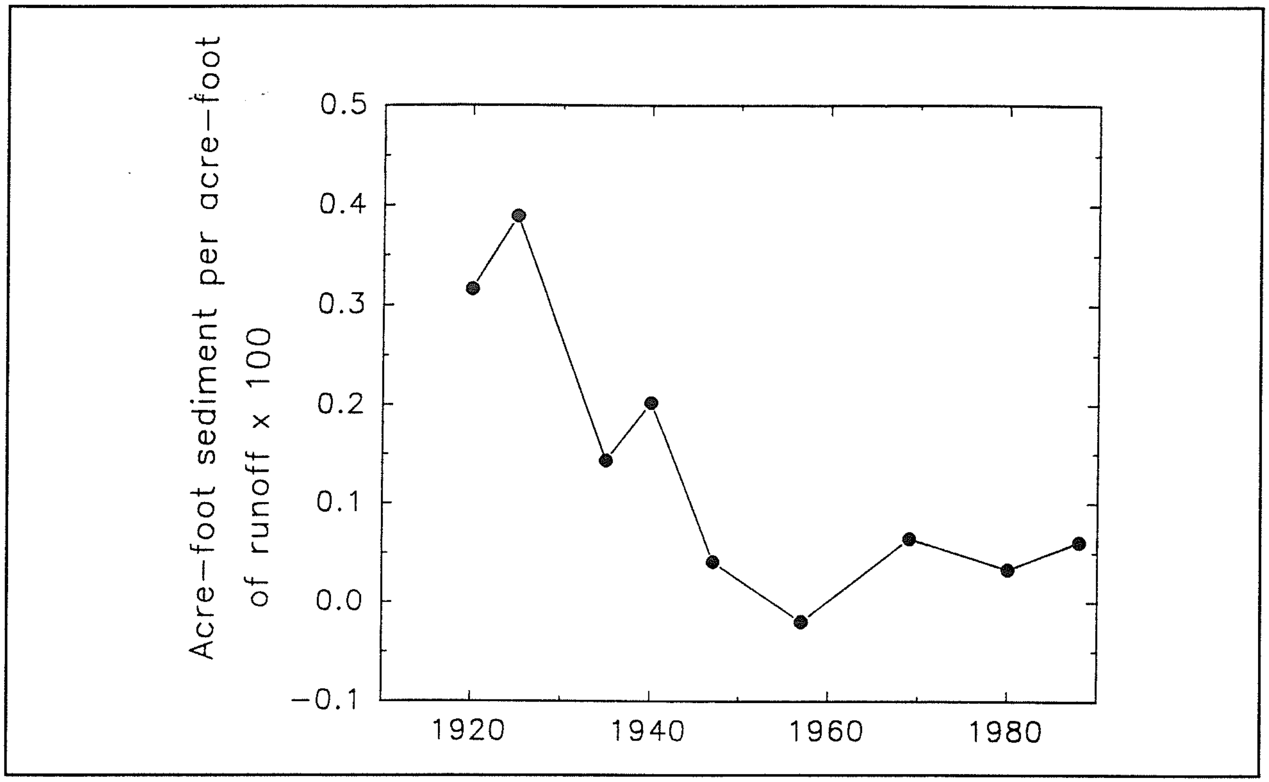

Figure 14. Sedimentation survey for Elephant Butte Reservoir. The values plotted represent average values for time periods between reservoir surveys.

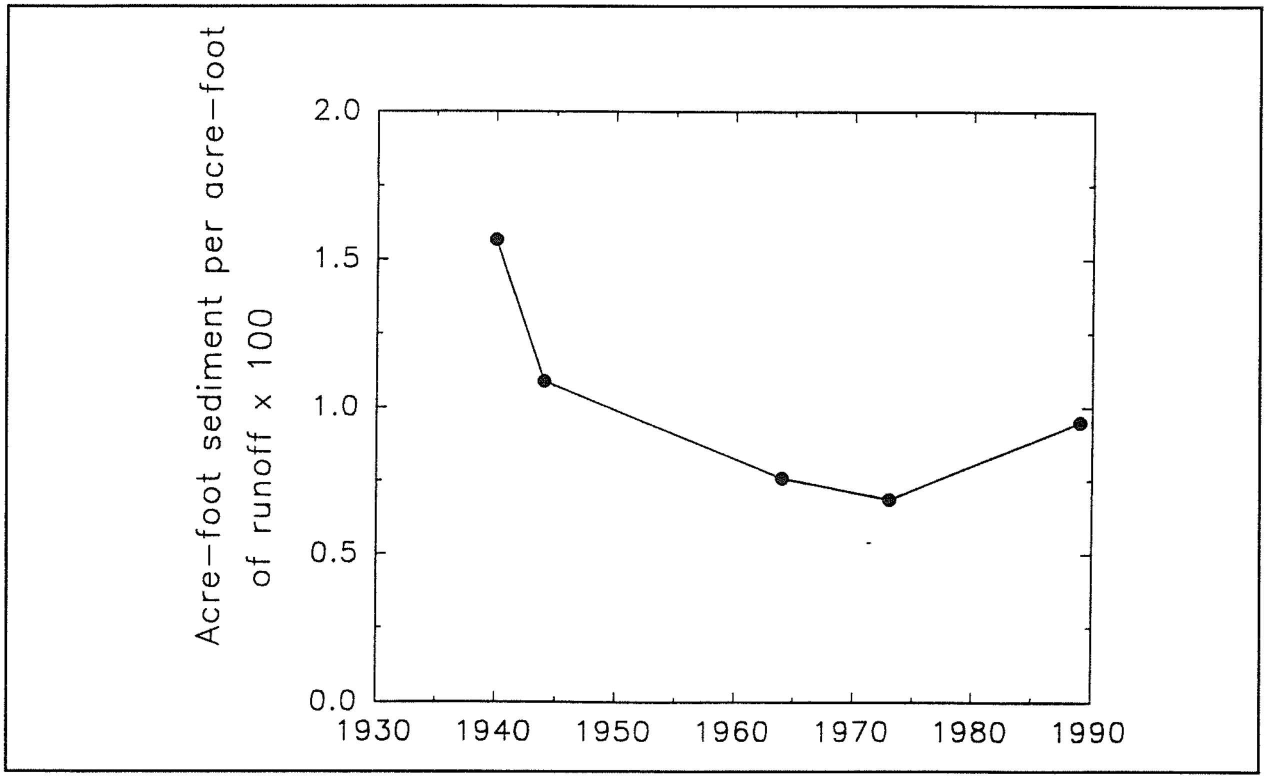

Figure 15. Sedimentation survey for Lake Sumner. The values plotted represent average values for time periods between reservoir surveys.

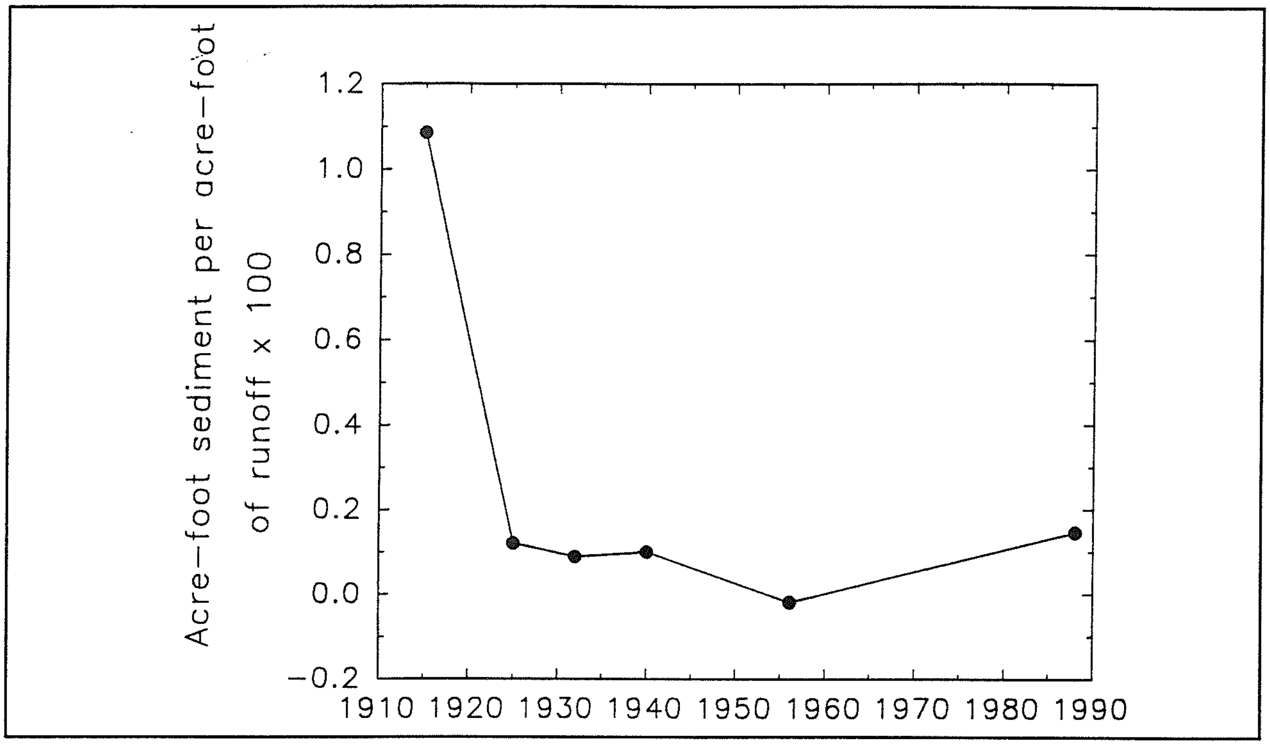

Figure 16. Sedimentation survey for McMillan Reservoir. The values plotted represent average values for time periods between reservoir surveys.

incision usually occurs as a series of headcuts that move upstream through time.

Changes that occur through time in the watershed, from downstream to upstream reaches, can be substituted by comparing changes that occur at one location through time as depicted in Figure 17 (Schumm and others 1984; Paine 1985). The first stage shown in Figure 17 is the channel before incision occurs (Stage A). As one or a series of headcuts moves up the watershed, the channel incises (Stage B). In Stage C the channel widens due to bank instability and braiding of the channel. As the channel continues to widen, a stage is reached where peak flows no longer impinge on the arroyo walls and the channel begins to aggrade (Stage D). Vegetation colonizes the incipient floodplain, increases the hydraulic roughness, and further enhances sediment deposition (Stage E). At this stage in arroyo evolution, the channel may completely fill (Stage F1) and become similar in form to Stage A, or it may incise again due to the oversteepening of the deposited sediment (Stage F2-G3). These sequential channel changes lead to an initial period of high erosion and sediment yields that decrease through time.

Studies of incised-channel evolution in western Tennessee support the arroyo evolution model (Simon 1989). Incision of channels in western Tennessee as a result of channelization and channel straightening increased sediment loads dramatically. As the channels adjusted to incision, decreases in sediment loads were measured through time. Simon (1989) used the changes in slope of the discharge suspended sediment relation to assess sediment changes through stages of channel evolution.

RIO PUERCO

Suspended sediment records are available for a large arroyo in New Mexico, the Rio Puerco near Bernardo (Fig. 1). Incision in the Rio Puerco began in the 1880s (Bryan and Post 1927). Bryan and Post estimated that during the period 1885-1927, 395,000 acre-feet of sediment was eroded or an average of 13.6 million tons of sediment was eroded annually. In the 42 years between 1948 and 1990, an average of 4.3 million tons of sediment was transported annually out of the Rio Puerco, which is 32 percent of the annual amount eroded between 1885 and 1927. Suspended sediment sam-

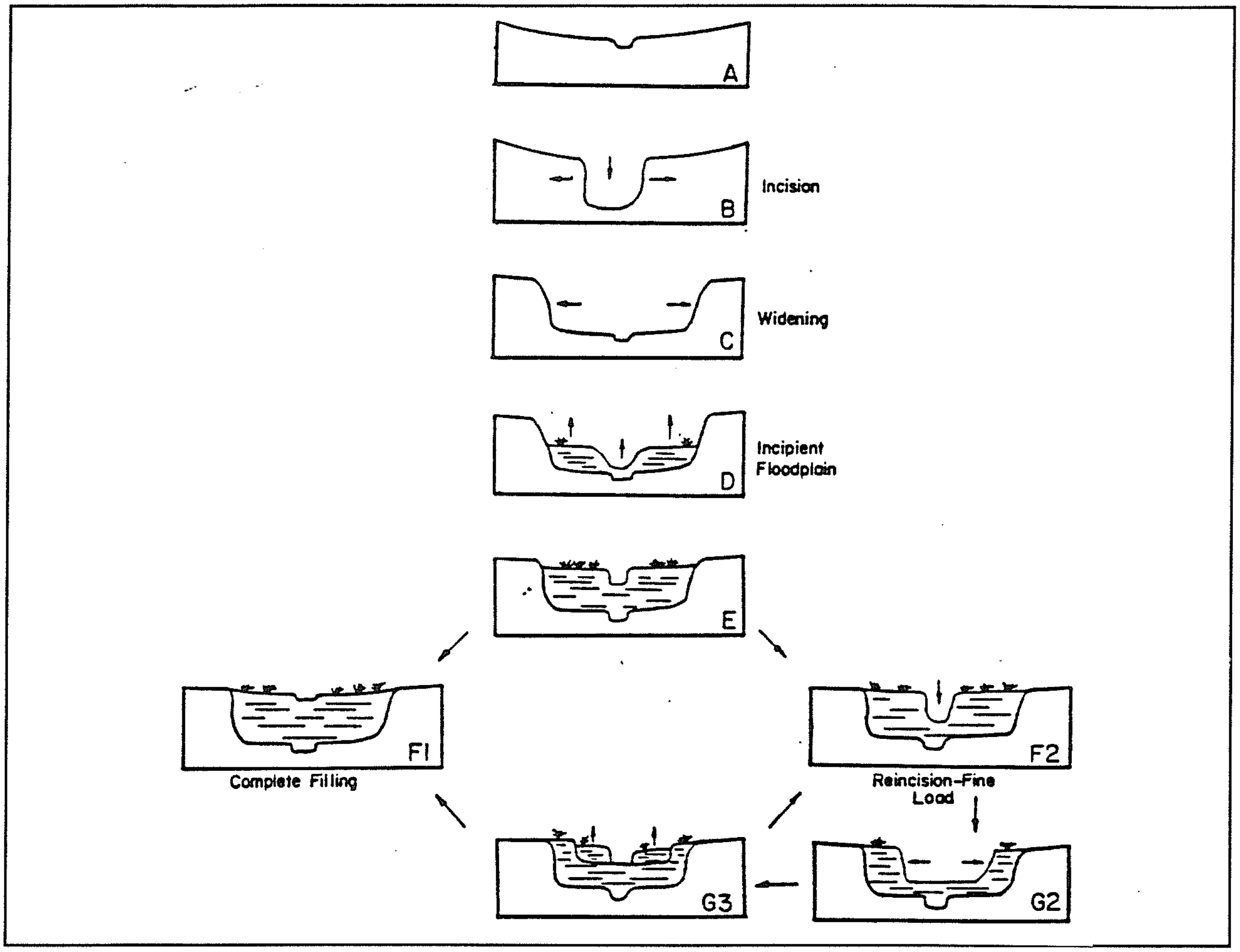

Figure 17. Arroyo evolution: stages A through G can represent changes at a cross-section through time or changes from the lower reaches to the upper reaches of the watershed at any point in time (Gellis 1988).

pling began at the Rio Puerco near Bernardo in 1948. Since 1948 suspended sediment loads have been decreasing relative to runoff (Figs. 2-13). Other suspended sediment records on the Rio Puerco are available at various times for the Arroyo Chico near Guadalupe and Rio Puerco above Arroyo Chico (Figs. 18,19). Although the suspended sediment records for these two stations are interrupted, there is a decrease in the mean of the annual suspended sediment concentrations for the two periods (Figs. 18,19).

Elliott (1979) documented arroyo changes in the Rio Puerco through time and through the watershed. The decreased suspended sediment loads measured at stations in the Rio Puerco watershed are probably a result of these channel changes. Similar channel changes and decreased suspended sediment loads were observed in arroyos draining northern Arizona in the Colorado River basin (Gellis and others 1991). If other arroyos in New Mexico are evolving like the Rio Puerco and northern Arizona washes, then a regional decrease in suspended sediment loads can be assumed.

CONCLUSION

Six streamflow-gaging stations in New Mexico:

- Rio Grande at Otowi Bridge
- Rio Puerco near Bernardo
- Rio Grande at San Marcial
- Pecos River near Artesia
- Rio Penasco at Dayton
- Animas River at Farmington

were tested for decreasing trends in suspended sediment loads relative to annual runoff. At all stations a negative slope for the best-fit regression line of annual suspended sediment concentration was observed. At four of the stations tested, the

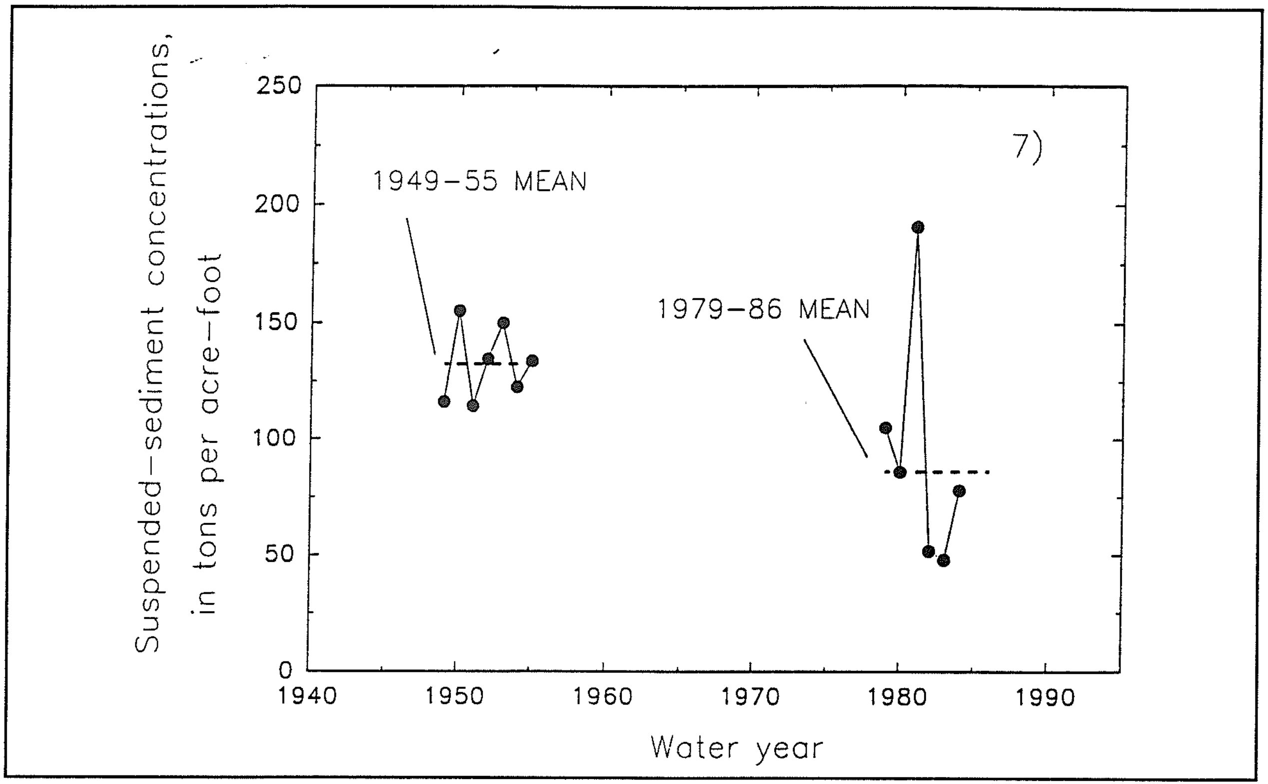

Figure 18. Annual suspended sediment concentrations and means through time for Arroyo Chico near Guadalupe station.

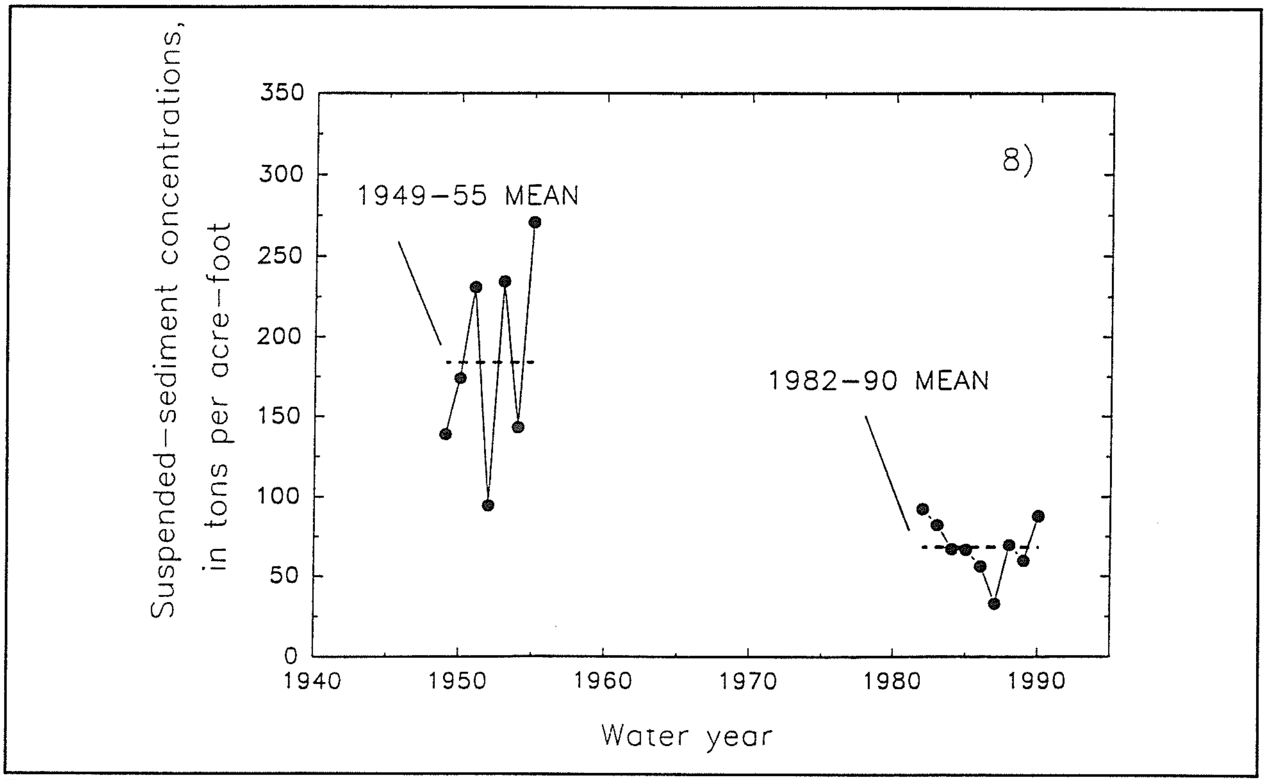

Figure 19. Annual suspended sediment concentrations and means through time for Rio Puerco above Arroyo Chico station.

hypotheses that fluctuations in the data are not random and that the data indicate a significant decreasing trend were supported by statistical analysis. Sediment surveys of Elephant Butte Reservoir, Lake Sumner, and McMillan Reservoir support the hypothesis of decreasing trends by showing an overall decrease in the annual amount of sediment deposited by runoff through time.

The hypothesis that reservoir closures and changes in sediment samplers affected the suspended sediment concentrations at these stations is probably not valid solely on the basis of the analysis of double-mass curves. The observed decrease in sediment loads may be due to the reduction in sediment delivery from tributary arroyos.

Arroyos that delivered vast quantities of sediment in the beginning of this century, as a result of incision and gullying, have been aggrading and delivering less sediment to the main channels. Field studies in selected arroyos of the Southwest indicate that channel aggradation follows a generalized channel geometry development through time called arroyo evolution. Coinciding with arroyo evolution is a decrease in sediment delivery through time. Annual suspended sediment loads in the Rio Puerco, a major sediment-producing arroyo, support this decrease through time and can be considered to reflect similar conditions for other arroyos in New Mexico and the Southwest. Therefore, the decreased suspended sediment loads measured at streamflow-gaging stations and the decreased sedimentation rates in selected reservoirs of New Mexico are at least in part due to the decrease in sediment from tributary arroyos.

Studies have shown that arroyos are aggrading and that sediment production is decreasing. This condition might be of interest to agencies involved in erosion control. By examining changes in channel behavior throughout the watershed, land managers and conservationists might be able to evaluate times and locations in the arroyo evolutionary cycle so that erosion controls could be used effectively.

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