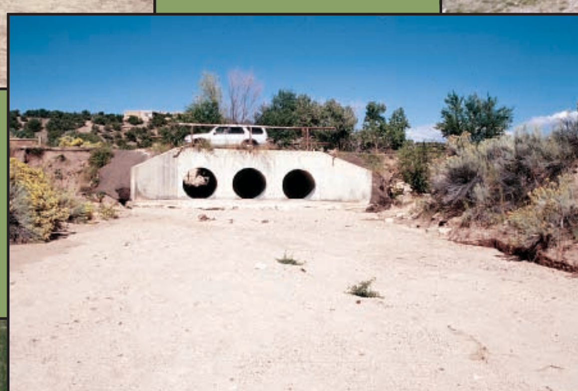
Channel and Hillslope Processes Revisited in the Arroyo de los Frijoles Watershed near Santa Fe, New Mexico



Professional Paper 1704

U.S. Department of the Interior
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Cover. Upper left photo: Stagger Reach, Arroyo de los Frijoles, May 11, 1993, view looking downstream; Upper right photo: Big Sweat Dam, June 17, 1993; Lower right photo: Main Project Reach, Arroyo de los Frijoles, March 10, 1998, view looking downstream to abandoned streamflow-gaging station on right bank; Lower left photo: Mouth of Green Rock Gulch in Slopewash Tributary of Arroyo de los Frijoles, May 11, 1993, view looking downstream; Center photo: Arroyo de los Frijoles at Buckman Road, September 27, 1997, view looking upstream. (Photographs by Allen C. Gellis, U.S. Geological Survey)

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By Allen C. Gellis, William W. Emmett, and Luna B. Leopold

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Conversion Factors and Datums

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square kilometer (km^2)	35.31	cubic foot (ft^3)
square meter (m^2)	10.76	square foot (ft^2)
	Flow rate	
cubic meter per second (m^3/s)	35.31	cubic feet per second (ft^3/s)
	Mass	
pounds (lb)	3.7324×10^{-4}	metric tons
metric tons	$2.205 \times 10^{+3}$	pounds
kilogram (kg)	2.2046	pound avoirdupois (lb)
	Density	
kilogram per cubic meter (kg/m^3)	0.06243	pound per cubic foot (lb/ft^3)

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27).

Channel and Hillslope Processes Revisited in the Arroyo de los Frijoles Watershed near Santa Fe, New Mexico

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Abstract

Detailed documentation of geomorphic changes in the landscape of more than a few years is rarely possible. Channel cross sections, channel profiles, sediment deposition behind dams, and hillslope-erosion plots, originally benchmarked within several watersheds outside Santa Fe, New Mexico, in the 1950's and 1960's, for a 1966 report that documented processes and rates of arid-region sediment production and deposition, were resurveyed in the mid-1990's. Many of the original study sites were relocated and surveyed in the mid-1990's to determine subsequent channel and hillslope changes and to determine whether trends of channel and hillslope aggradation and degradation that were evident in the 1950's and 1960's have continued. In general, the net change in channel geometry has been small over the last 30–40 years. The average change in cross-sectional area of 32 resurveyed cross sections was erosion of 0.27 square meter, which equates to a 4-percent increase in cross-sectional area. The average net change in thalweg elevation for 51 resurveyed cross sections was degradation of 0.04 meter. Unpublished data (1964–68) from the scour chains showed that 371 chains had an average scour of 0.14 ± 0.14 meter and that 372 chains showed an average fill of 0.13 + 0.11 meter. Scour, found in the original study (1958–64) to be proportional to the square root of discharge, was confirmed with the addition of unpublished data (1964–68). The observed channel changes have no consistent trend, compared either to results observed in the original 1966 study or to distance from the watershed divide. The conclusion drawn in the original study was that most channels were aggrading; the resurvey showed that aggradation did not continue.

An increase in housing and population in the Arroyo de los Frijoles watershed since the 1950's has led to more roads. Channel degradation is most noticeable at road crossings. The greatest degradation of the main channel Arroyo de los Frijoles, 1.53 meters, and the greatest aggradation, 0.38 meter, occur downstream and upstream, respectively, from a culvert in a dirt road.

Periods of high average annual rainfall intensity reported for Santa Fe for 1853–80 immediately preceded late 19th century arroyo incision, and another period of high-intensity rainfall began in 1967. This may indicate that climatic factors are again favorable for arroyo incision in this part of New Mexico; data from this resurvey, however, do not provide evidence of a renewed cycle of erosion.

At a 1930's Civilian Conservation Corps-constructed dam on Coyote C. Arroyo, the measured sediment yield from 1966 to 1993 was 139 metric tonnes per square kilometer per year. Sediment yields have decreased through time because of either a decrease in the trap efficiency of the reservoir over time or a decrease in sediment delivery to the reservoir because of upstream channel storage. The effects of base-level rise on the channel profile were documented in 1993 through resurveys of sediment deposits behind two small dams, Big Sweat Dam and Little Sweat Dam. Both dams, built in 1960, showed sediment deposition that extends 20 and 9.3 meters upstream, respectively, and the 1993 sediment gradient was nearly the same as the unaffected channel upstream. Big Sweat Dam showed fluctuations in channel gradient within 5.3 meters of the dam, which may be a result of local scour following complete filling of the dam, scour from increased sinuosity, or differences in the location of surveying stations over time. The sinuosity of the channel has increased over time, presumably from a reduction in slope. Channel gradients 0 to 11.0 meters upstream from Little Sweat Dam have remained constant at about 0.028 from 1964 to 1993.

Measurement of erosion or hillslope-erosion plots show that average values of surface erosion range from 0.019 to 0.096 centimeters per year and are within values reported for regional erosion and denudation studies. Sediment yield from the Slopewash Tributary erosion plot was 307 metric tonnes per square kilometer per year.

The reproducibility and accuracy of the resurveys from the 1950's to the 1990's attest to the concepts used to quantify geomorphic features established in the Vigil Network. With relatively simple techniques, more than 30 years of geomorphic change were observed in this study.

Introduction

Observing, quantifying, and understanding geologic processes in the modern record is a major occupation of process geomorphologists. The opportunity to describe geomorphic changes in detail is often not possible, however, because of a lack of reliable and precise historical data. Recognition of that lack of detailed data for hydrologic and geomorphic studies led to the establishment of a network of reference sites known as the Vigil Network (Leopold, 1962; Emmett and Hadley, 1968; Osterkamp and others, 1991). A principal objective of the Vigil Network is to preserve data on geomorphic processes for future generations. Geomorphic data collected at Vigil Network sites include observations of deposition behind dams, hillslope processes (mass movements, soil creep, and sheetwash erosion), vegetation, and fluvial processes (bank retreat, channel scour, and aggradation). Simple techniques are used to measure geomorphic processes: surveys, erosion pins, painted rocks, vegetation transects, and scour chains. A requisite of the Vigil Network is permanent survey benchmarks and monuments (Emmett, 1965).

Leopold and others (1966) described hillslope and channel processes and rates for four small watersheds near Santa Fe. Their interpretations of geomorphic processes were based on observations derived from surveyed channel cross sections, scour-chain measurements, erosion pins, and reservoir surveys. Their work is an example of a study at a Vigil Network site.

This report presents the results of a study that compares channel and hillslope measurements with the original study of Leopold and others (1966). The Leopold and others (1966) report was in inch-pound units and for this report was converted to metric units. Long-term rates of erosion, sediment yield, and the effects of base-level changes on channel profiles in a semiarid environment also are discussed. The causes for any observed changes are investigated, and conclusions on geomorphic change are compared with those in the original study. Data were collected in portions of four watersheds through 1968 but were never published and are presented in this report. These include longitudinal measurements of the channel behind Big Sweat and Little Sweat Dams, scour-chain measurements, and erosion-pin measurements. In addition, rainfall between 1958 and 1993 is described and implications of the trends are discussed in relation to channel changes.

Background

Arroyo changes in the American Southwest have been the focus of several investigations. These investigations have examined channel processes such as channel incision and aggradation and environmental variables that may affect channels (Bryan, 1928a; Cooke and Reeves, 1976; Gellis and others, 1991; Bull, 1997; Elliott and others, 1999). The word “arroyo” generally refers to a steep-sided channel entrenched into alluvium. Many alluvial valleys that contained either discontinuous or unincised channels became incised throughout the Southwest, generally between 1880 and 1920, creating arroyos. The causes of arroyo incision have been a topic of considerable debate. Arroyo incision has been attributed to climate change (Leopold, 1951; Balling and Wells, 1990), land use (Thornwaite and others, 1942; Cooke and Reeves, 1976), dam failures (Love, 1997), or a natural cyclicity of arroyo incision that may be related to intrinsic thresholds of valley slope (Schumm and Hadley, 1957; Patton and Schumm, 1975). Many arroyos that incised between 1880 and 1920 were reported as aggrading in the mid- and late-20th century (Leopold, 1976; Gellis, 1998; Elliott and others, 1999).

Although there was considerable discussion on the causes of arroyo formation during the first half of the 20th century, few actual measurements of channel and hillslope erosion were made. The study by Leopold and others (1966) in four watersheds near Santa Fe—Arroyo de los Frijoles (9.71 km^2), Coyote C. Arroyo (0.16 km^2), Morning Walk Wash (0.03 km^2), and Gunshot Arroyo (0.09 km^2) (fig. 1A–C)—provided quantitative data for examining the rates of channel and hillslope erosion and deposition and sought to explain causes for any observed change. Leopold and others (1966) quantified erosion rates by analyzing processes and rates of channel changes and by constructing a sediment budget for part of the Arroyo de los Frijoles watershed. The rates determined were supplemented with concurrent measurements of streamflow, rainfall, channel scour, hillslope erosion, mass movement, rock movement, vegetation, channel cross-sectional geometry, bed-material grain size, and sediment deposition behind dams. Channel scour was measured using chains, and hillslope erosion was measured using erosion pins. Channel and reservoir sections, scour chains, erosion plots, and mass-movement lines were monumented with steel bars.

The 1966 study reported measurements made from 1958 to 1964. Analysis of the measurements indicated that channels in most reaches in the Arroyo de los Frijoles watershed were aggrading. The sediment budget for Arroyo de los Frijoles indicated sheetwash as the largest source of sediment accounting for aggradation. The average rate of aggradation for all channels was 0.015 m/yr (Leopold and others, 1966, p. 239). At this rate, the channel would completely fill to the level of the highest terrace in 100 to 200 years. At scour chains, most sections showed scour and subsequent fill. The average scour depth was observed to be proportional to the square root of discharge per unit width of channel. No downstream trends in channel change or bed scour were evident.

Hillslope and channel erosion rates were compared to the amount of sediment accumulation behind an earthen dam about 1-m high on Coyote C. Arroyo, constructed in 1937 by the Civilian Conservation Corps (Leopold and others, 1966). In 1962–64, the reservoir was topographically mapped with a planetable to determine the amount of fill since established surveys in 1961. The drainage area of the dam is 0.155 km^2. During 1961–64, 59.0 m^3/yr of sediment was deposited (Leopold and others, 1966, p. 235), which was less than 5 percent of basinwide eroded sediment.

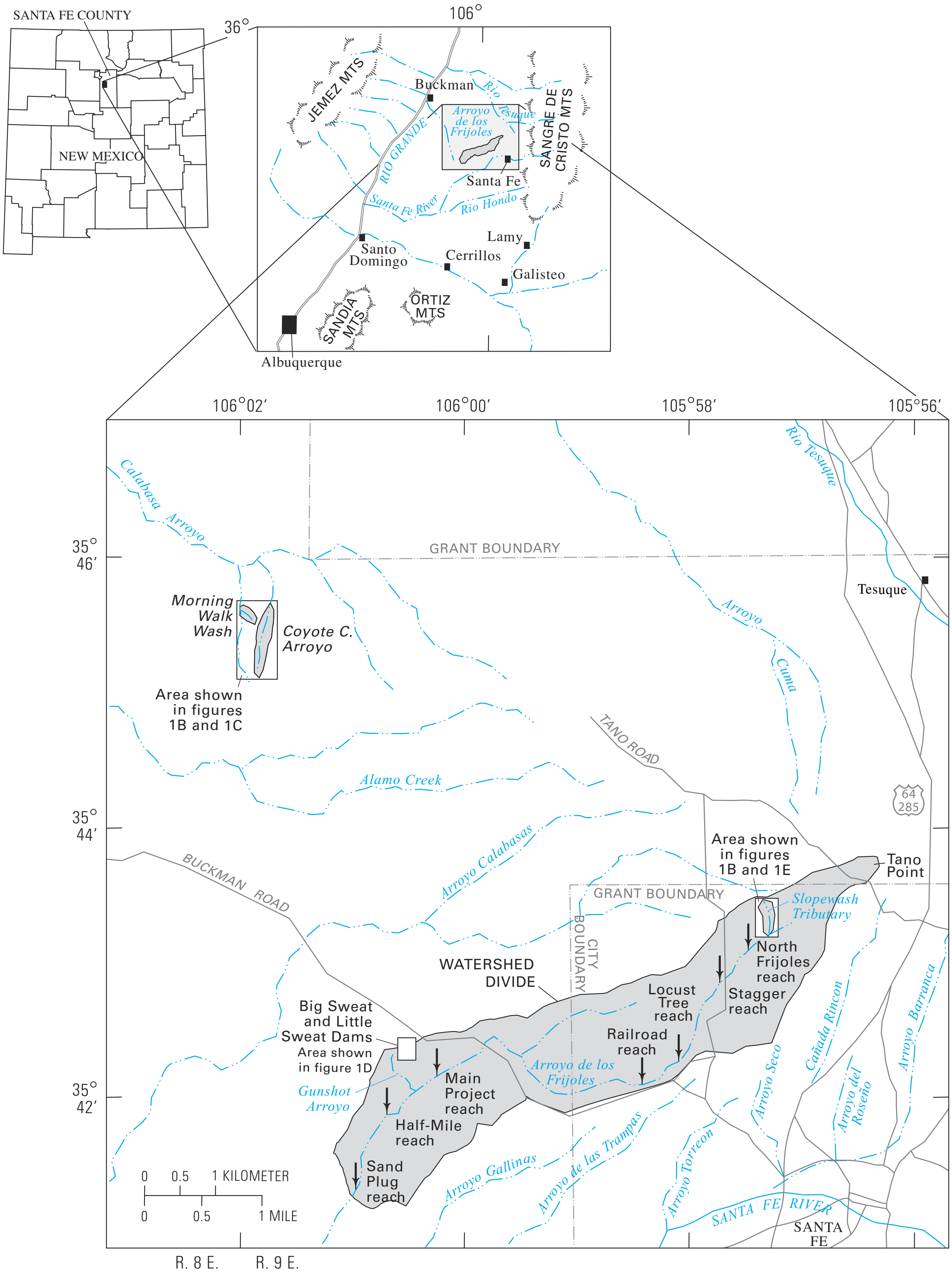
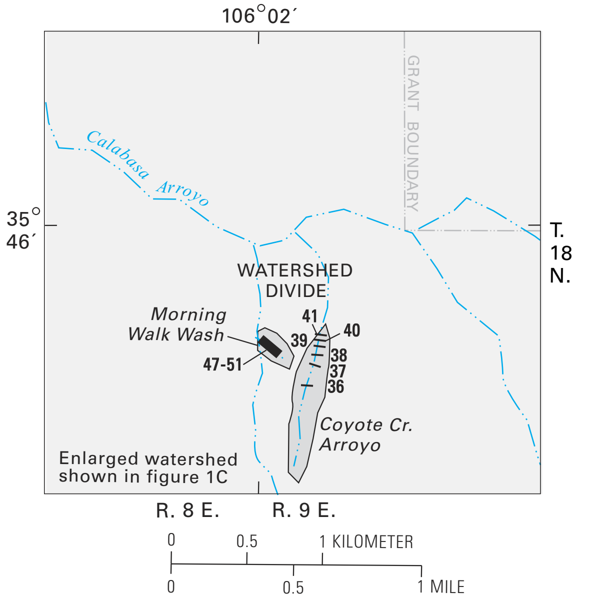


Figure 1A. Location of watersheds and location names used in this report. (Modified from Leopold and others, 1966.)



EXPLANATION

Full cross section surveyed (table 3)

• Resurvey at one station in the cross section

CROSS SECTION LABEL	CROSS SECTION NAME
1.	SWT-CS1
2.	SWT-CS2
3.	SWT-CS3
4.	LW-Chain 4
5.	NFA-Upper Chains
6.	NFA-Lower Chains
7.	Chain Section 15
8.	LW-16
9.	LW-17
10.	LW-18
11.	LW-19
12.	LTR 20-24
13.	LTR 30-33
14.	LW-35
15.	LW-37
16.	CS-40
17.	CS-45
18.	CH49
19.	Frijoles Range 1
20.	CH51
21.	MPR 52-59
22.	Frijoles Range 3
23.	CH61
24.	Frijoles Range 4
25.	Frijoles Range 5
26.	Frijoles Range 6
27.	LW 64
28.	Frijoles Range 7
29.	LW-75
30.	LW-76
31.	LW-77
32.	LW-79
33.	LW-82
34.	HMR-83
35.	SPR 84-88
36.	ACC-6
37.	ACC-5
38.	ACC-4
39.	ACC-3
40.	ACC-2
41.	ACC-1
42.	Gunshot Arroyo Station 468
43.	Gunshot Arroyo Station 417 top of headcut
44.	Gunshot Arroyo Station 417 bottom of headcut
45.	Gunshot Arroyo Station 230
46.	Gunshot Arroyo Station 25
47.	Morning Walk Wash-Upper Section South
48.	Morning Walk Wash-Upper Third Gully
49.	Morning Walk Wash-Upper Section North
50.	Morning Walk Wash-Lower South
51.	Morning Walk Wash-Lower North
52.	LW-16
53.	LTR 25-29
54.	LW-34
55.	LW-36
56.	LW-38
57.	LW-39
58.	LW-41
59.	LW-42
60.	LW-43
61.	LW-46
62.	LW-47
63.	LW-48
64.	LW-50
65.	LW-60
66.	LW-62
67.	LW-63
68.	LW-65
69.	LW-66
70.	MPR-67-72
71.	LW-73
72.	LW-74
73.	LW-78
74.	LW-80
75.	LW-81
76.	SPR-89
77.	SPR-90

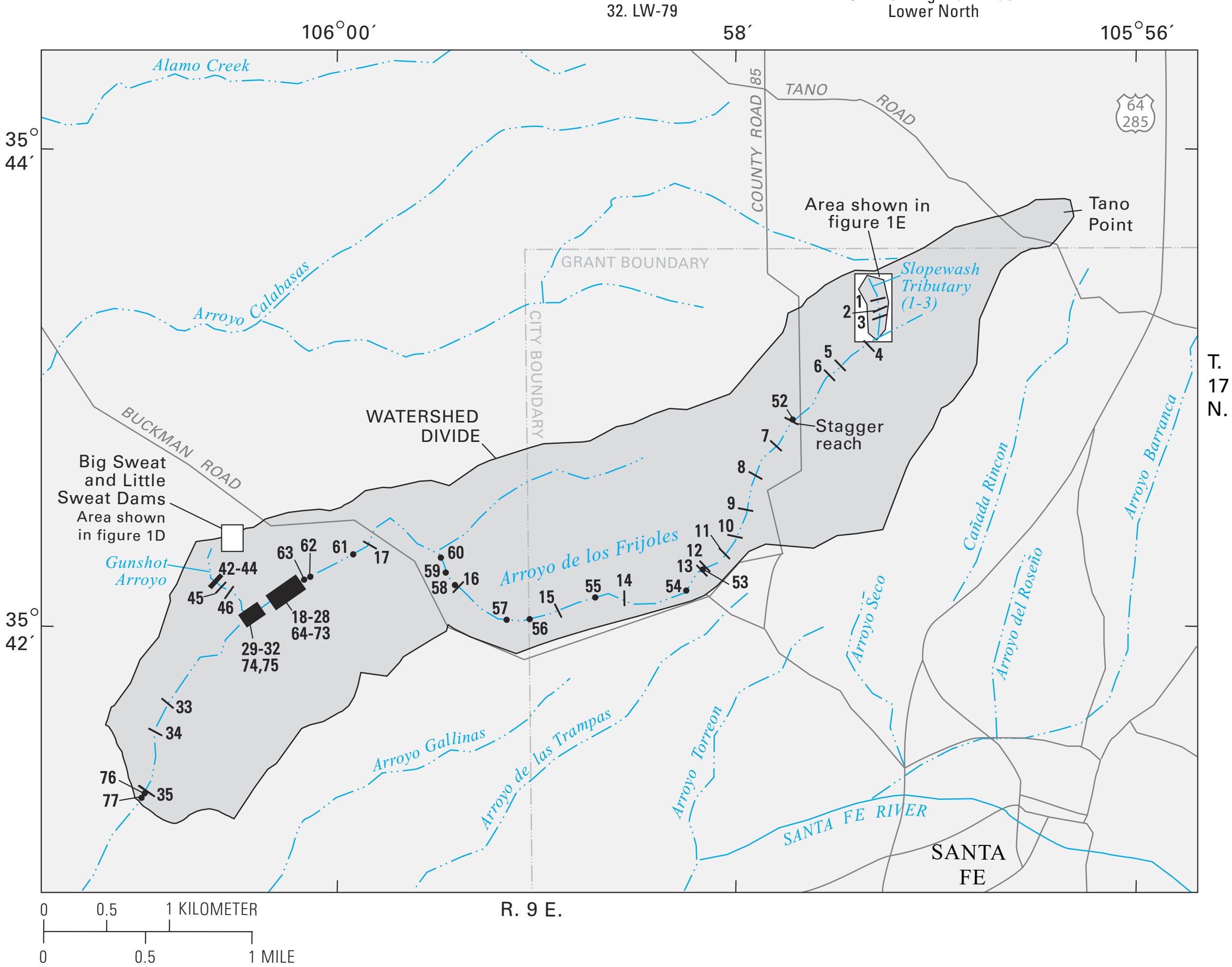


Figure 1B. Approximate location of watersheds and cross sections surveyed in watersheds in 1993 to 1997. (Modified from Leopold and others, 1966—Continued.)

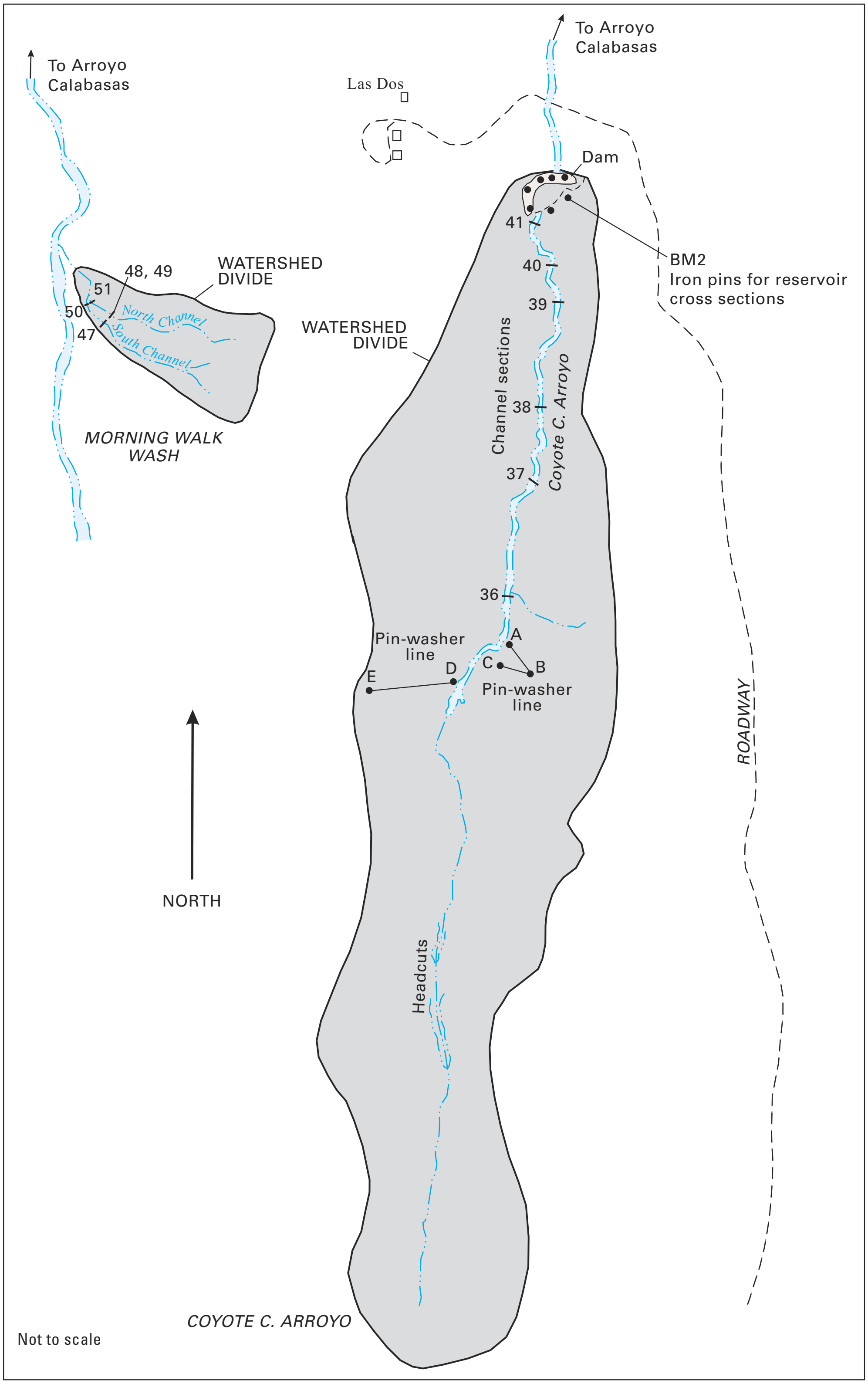


Figure 1C. Coyote C. Arroyo and Morning Walk Wash watersheds showing cross sections and erosion pins. See figure 1A for location within study area. (Modified from Leopold and others, 1966—Continued.)

To determine how base-level rise affects the channel longitudinal profile, two small concrete dams, Big Sweat Dam and Little Sweat Dam (fig. 1D), were constructed in 1960, each on an ephemeral channel draining into Arroyo de los Frijoles (Leopold and Bull, 1979). By 1962, the sediment wedge in Big Sweat Dam had reached 15.2 m upstream and by 1964 had reached 24.4 m. In 4 years the gradient decreased 27 percent, from 0.045 m in 1960, before the dam was built, to 0.033 m in 1964 (Leopold and Bull, 1979, p. 189). After 1964, the gradient remained constant, and the maximum distance upstream from the dam that sediment was deposited was 33.5 m or 15 percent of the distance along the channel from the dam to the watershed divide.

To measure the rate of hillslope erosion, a grid system of erosion pins was installed in 1959 on the slopes of Slopewash Tributary (Leopold and others, 1966, p. 220–222) (fig. 1E). The erosion pins were measured from 1959 to 1964 and showed deposition of 0.12 cm/yr and erosion of 0.36 cm/yr or a net surface lowering of 0.24 cm/yr (Leopold and others, 1966, p. 222).

Another important conclusion of the 1966 study, based on earlier work by Leopold (1951), involved rainfall intensity in Santa Fe from 1853 to 1961 (fig. 2). From 1856 to 1870, annual rainfall was similar to long-term averages but fell on fewer days per year, thus rainfall intensity was higher (fig. 2A,B). Rainfall intensity was higher during a period when rains of low intensity (0.25 to 12.4 mm) were low (fig. 2C,D). Leopold and others (1966) hypothesized that vegetation would be depleted during this period because of the low amounts of low-intensity rainfall. Intense rainfall in combination with depleted vegetation led to arroyo incision. Periods of arroyo incision or channel erosion for the Rio Puerco in New Mexico were reported from about 1885 to 1890 (Bryan, 1928b) and for arroyos on the Zuni Reservation in about 1905 (Balling and Wells, 1990). Therefore, if rainfall recorded in Santa Fe is valid for a wider area, arroyo incision reported in these areas of New Mexico occurred shortly after the climate change identified by Leopold (1951).

Streamflow was recorded from 1958 to 1968 at three streamflow-gaging stations in the main channel Arroyo de los Frijoles: North Frijoles reach, Locust Tree reach, and Main Project reach (figs. 1 and 3) (Leopold and others, 1966). For the Main Project reach (fig. 1A,B), flows were recorded 38 times between 1958 and 1968. The highest peak flow recorded was 86.6 m^3/s on September 13, 1958 (Leopold and others, 1966, p. 203), and 86.6 m^3/s on August 1–2, 1966 (U.S. Geological Survey, unpublished data). All flows were recorded between May and October, and 63 percent occurred in July and August. Rainfall during the summer months near Santa Fe can be intense and is localized. Discharge increased in the downstream direction only 5 of the 38 times. Concentrations in eight samples of suspended sediment collected from 1958 to 1962 ranged from 28,300 to 126,000 ppm (parts per million). Median grain size of the suspended sediment was silt and clay and ranged from 0.004 to 0.016 mm (U.S. Geological Survey, unpublished data).

In this report the following terms will be used to describe changes in the channel bed, hillslope, and behind impoundments. Deposition is the addition of sediment at one particular location on the channel bed, hillslope, or behind an impoundment. Aggradation is an increase in the channel thalweg elevation over time by sediment deposition and degradation is a lowering of the channel thalweg elevation over time by sediment removal. Aggradation and degradation are terms used to describe channel changes for the entire cross section. Scour is the lowering of the channel bed elevation at one specific location in the cross section and fill is an increase in the channel bed at one specific location. For the entire channel cross section, erosion is the removal of sediment which increases cross-sectional area and deposition is the addition of sediment which decreases cross-sectional area. Incision is used to describe channel degradation over a broader length of the channel. On hillslopes, erosion refers to removal of sediment and a lowering of ground elevation and deposition is the addition of sediment.

Study Area

The study area is located northwest of the city of Santa Fe (fig. 1A). Bedrock in the study area is composed of the Tesuque and Ancha Formations of the upper part of the Santa Fe Group of Tertiary age and unconsolidated gravel, sand, and silt also of Tertiary age (Miller and others, 1963). Ephemeral channels in the area reflect the underlying geology and have sand-sized bed material (median size ranging from 0.50 mm for Coyote C. Arroyo to 0.78 mm for Arroyo de los Frijoles in its upper reaches) (Leopold and others, 1966, p. 204). The climate is semiarid with an average annual rainfall of 361 mm from 1853 to 1993. Vegetation in the area is open piñon-juniper woodland with sparse grass and exposed soil in many areas.

Methods

Rainfall Data

Annual and monthly rainfall data for 1868–1993 were obtained from National Weather Service records and for 1853–67 were obtained from the New Mexico Office of the State Engineer (State of New Mexico, 1956). Daily rainfall was obtained only for 1868 to 1995. If records for 1 year had more than 15 days of missing rainfall, that year was not used. The average intensity and frequency of rainfall, in varying size classes for 1853–67, were obtained from Leopold and others (1966, figs. 171–173, p. 241–242).

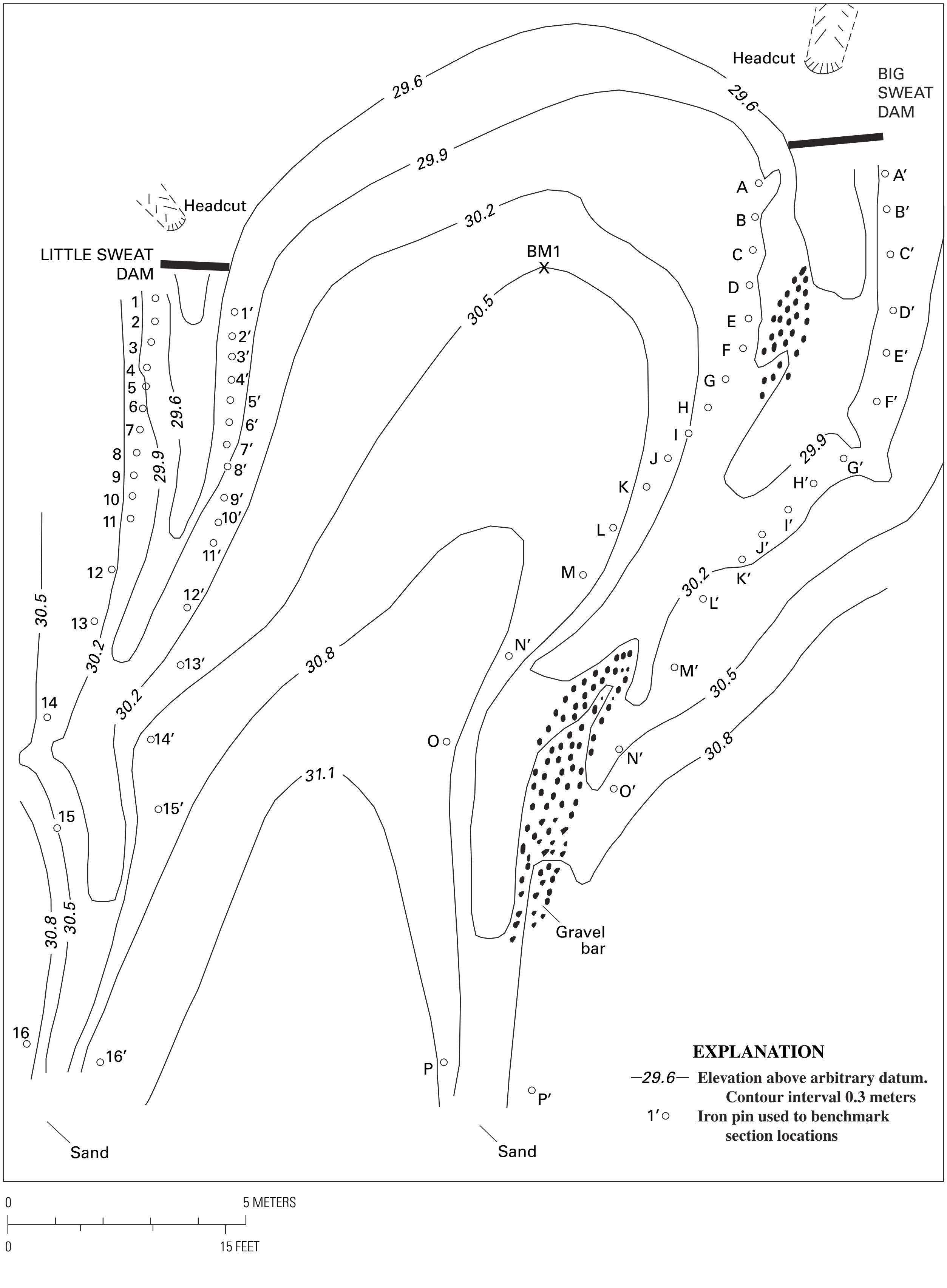


Figure 1D. Big Sweat Dam and Little Sweat Dam near Gunshot Arroyo showing topography. (Modified from Miller and Leopold, 1961—Continued.)

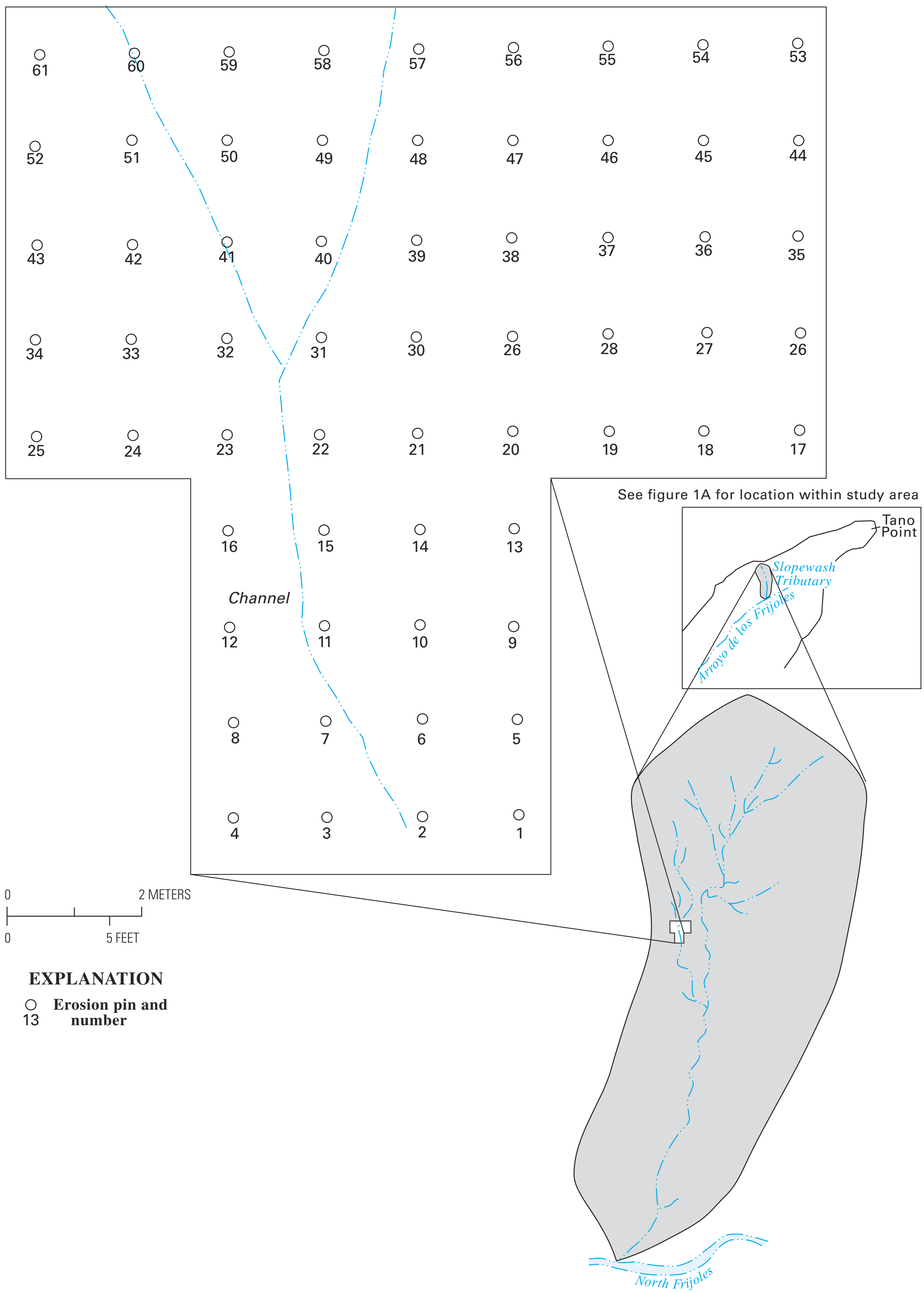


Figure 1E. Schematic showing erosion pin plot on hillslope adjacent to Slopewash Tributary. (Modified from Leopold and others, 1961—Continued.)

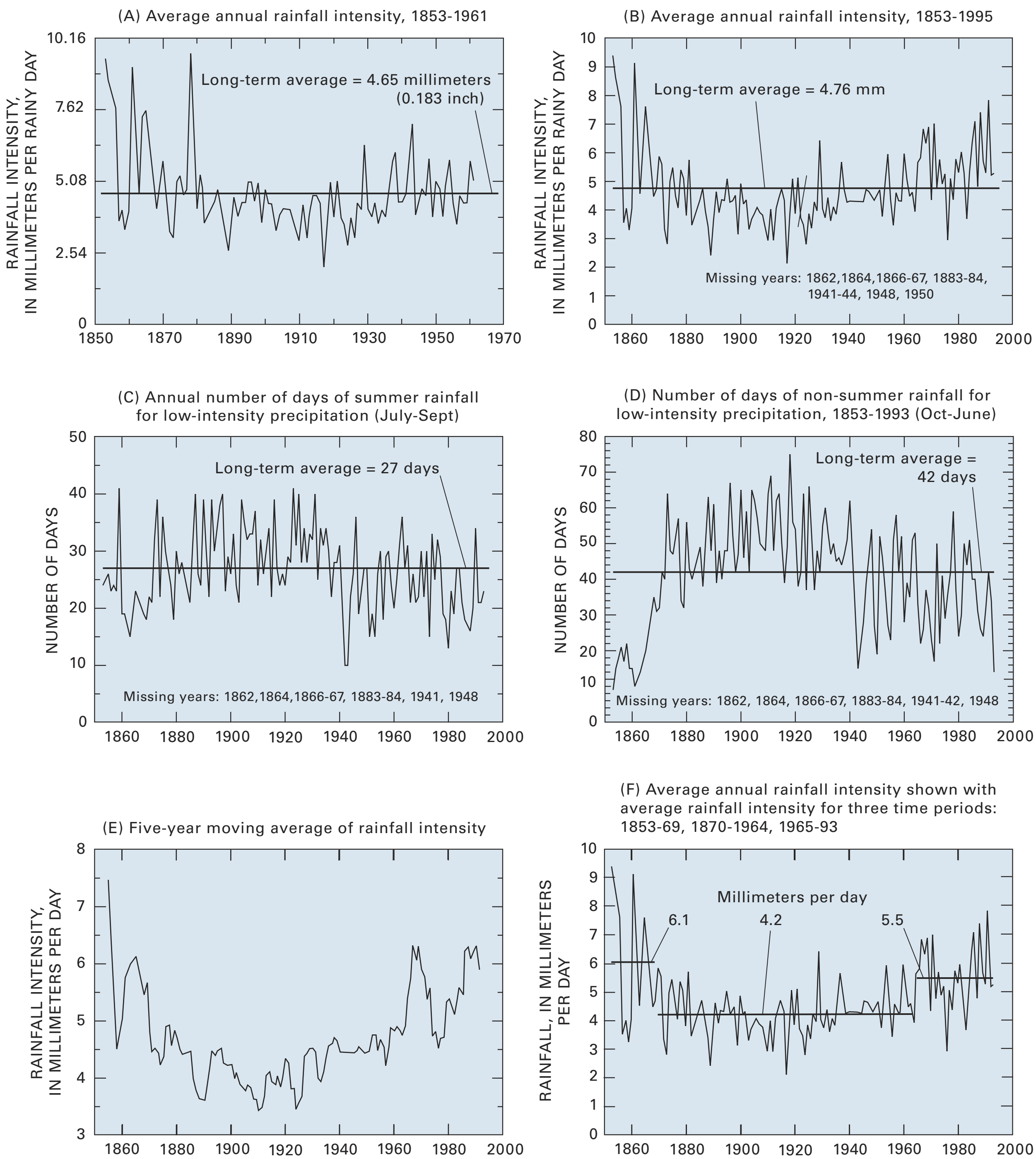


Figure 2. Rainfall recorded at the Santa Fe rain gage: (A) average annual rainfall intensity, 1853–1961 (Leopold and others, 1966); (B) average annual rainfall intensity, 1853–1993; (C) annual number of days of summer rainfall for low-intensity rainfall (0.25–12.4 mm), 1883–1993; (D) number of days of non-summer rainfall for low-intensity rainfall of 0.25–12.4 mm, 1883–1993; (E) Five-year moving average of rainfall intensity; and (F) average annual rainfall intensity shown with average rainfall intensity for three time periods: 1853–1869, 1870–1964, and 1965–93.

(A)

(B)

Figure 3. Main Project reach, Arroyo de los Frijoles. (A) Looking downstream to streamflow-gaging station, August 10, 1960; (B) Looking downstream to streamflow-gaging station, March 1988.

Channel Cross-Sectional Surveys

In the original study (Leopold and others, 1966), 63 channel cross sections were monumented from 1958 to 1960 in the main channel Arroyo de los Frijoles watershed. Six additional cross sections were monumented in Coyote C. Arroyo in 1961, 5 in Morning Walk Wash in 1961, and 5 in Gunshot Arroyo in 1962, for a total of 79 cross sections.

All cross sections were originally monumented with steel bars on the left and right banks. All cross sections in Coyote C. Arroyo, Morning Walk Wash, and Gunshot Arroyo were surveyed to measure changes in channel geometry of the entire cross section. Eighteen of the 63 cross sections in the main channel Arroyo de los Frijoles were surveyed to measure changes in channel geometry of the entire cross section and to measure scour and fill in the channel. Scour chains were installed at the remaining 45 cross sections in Arroyo de los Frijoles that were not monumented for cross-sectional surveys, and elevations of the channel bed were measured only at the scour-chain locations. To provide useful information for future surveys, all 1993 and 1997 surveys were full cross-sectional surveys.

For the 1993 and 1997 resurveys, a survey level was used, and the distance the tape was stretched from steel bar to steel bar was the same as in the original survey. If the original left- and right-bank steel bars were found, the accuracy of the elevations in the resurvey was determined by comparing the difference in elevations of the left- and right-bank steel bars in the original survey to the difference in elevations of the left- and right-bank steel bars in the resurvey. In the original survey, all cross-sectional elevations were tied into the same datum. If one of the original steel bars could not be found in 1993 and 1997, the remaining steel bar was tied into the closest upstream or downstream cross-sectional steel bar. If elevation control could not be determined, the accuracy of the resurvey was assessed on the basis of comparisons of surfaces in the cross section that might not change over time, such as the highest surface on which the steel bars are located. Techniques used to survey the channel cross sections are similar to those in Gellis (1998).

Channel width is the horizontal distance between the tops of the vertical banks that define the left and right sides of the channel. Channel depth was measured by averaging the heights of the two channel banks to the lowest elevation in the channel or thalweg.

In the 1993 and 1997 resurveys, changes in thalweg elevation and cross-sectional area were compared with those from the original surveys. Data from the original study were obtained from plots of cross sections of the channel and from original data sheets listing the thalweg elevations. A channel was categorized as aggrading if the elevation in the thalweg increased over time. In the original study at least one of the scour chains was installed in the thalweg of the channel cross section. Because the thalweg may have migrated since the original study, scour chains located in 1993 were not always located at the thalweg. Therefore, aggradation or degradation at these cross sections could be quantified only as the difference between the thalweg elevation in 1993 and the scour-chain elevation in the original survey.

The Arroyo de los Frijoles channel was originally surveyed during 1958–59. At cross section CS-45 (cross section 17 in fig. 1A), the original elevation of the thalweg could not be located, so an elevation from a survey conducted in 1960 was used as the original elevation instead. The longitudinal profile of Gunshot Arroyo (fig. 1) was resurveyed in 1998 and compared with the original 1962 survey.

A positive change in cross-sectional area indicates erosion (degradation). Channel cross-sectional area can increase by a deepening of the thalweg and(or) widening of the channel cross section. Because channel cross sections are not evenly spaced, an alternative to averaging cross-sectional area changes for each channel was weighting each measurement to channel length. Changes in cross-sectional area are expressed as a percentage by dividing the original cross-sectional area by the resurveyed cross-sectional area and multiplying by 100. A weighted change in cross-sectional area was computed for the entire length of each channel by multiplying the change in cross-sectional area by the channel length-weighted distance, then summing the values. The channel length-weighted distance is the length of a reach, representative of the measurement, divided by the entire channel length. A channel reach is defined as the sum of one-half the distance to the nearest upstream cross section plus one-half the distance to the nearest downstream cross section. Using a channel-weighted distance to represent cross-sectional area changes of the channel length assumes that each cross section is representative of a longer segment. Because of the small drainage areas of Morning Walk Wash and Gunshot Arroyo, a weighted change in cross-sectional area was not computed and an average was used.

The location of each cross section was obtained from Leopold and others' (1966) project file notes that indicated the taped distance of each cross section from the divide at Slopewash Tributary. Because the location of the cross sections was measured with a tape, there may be some error in the exact location of cross sections displayed in figures and tables in this report.

Channel-Bed Scour and Fill

In the original study, channel-bed scour and fill associated with several individual flow events were measured by repeat surveys of scour chains. Scour chains were placed in 63 cross sections in the main channel Arroyo de los Frijoles. Scour and fill measurements were not made in Coyote C. Arroyo, Morning Walk Wash, or Gunshot Arroyo. For the scour and fill measurements, at least one of the locations was the thalweg or lowest part of the channel cross section. At some reaches more than one scour chain was placed in the channel cross section, resulting in a total of 90 chains. Although the results of the 1958–64 scour-chain measurements were published in Leopold and others (1966), measurements continued through 1968 (USGS unpublished data) and are interpreted in this report. Seventy-nine chains were surveyed from 1964 to 1968 and some chains were surveyed as many as nine times, resulting in 372 measurements of scour and fill. The procedures used by Leopold and others (1966) were used in this study.

Depth of scour and fill in many of the cross sections was measured by vertically installing one or more 1.22-m chains, 12.7 mm thick, in a hole dug in the channel bed with the top link at or slightly above the bed surface. After a flow, the chain would lie horizontally at some depth below the bed surface if scour and fill occurred. Maximum depth of scour was measured from the elevation of the channel bed of the preceding survey to the elevation of the bend in the current scour chain. Fill was measured by the bend in the chain relative to the channel bed. The chains were reset after each measurement. Changes in bed elevation at the chain location were quantified from 1958 to 1968. At selected times from 1958 to 1962, changes in the entire cross section were examined.

For the 1993 resurvey, some of the original scour chains were found in many of the cross sections. The maximum scour since the last time the chains had been measured (from 1964 to 1968) was quantified by subtracting the elevation of the bend in the chain from the elevation of the channel bed in the original survey.

Deposition Behind Dams and Base-Level Experiments

The dam on Coyote C. Arroyo (fig. 1A), constructed by the Civilian Conservation Corps in 1937, was used in the original study to quantify sediment yield over time. Sediment yields measured in Coyote C. Arroyo were thought to represent conditions for a wider area (Leopold and others, 1966). Cross sections across the sediment pool were monumented with steel bars in 1961. Seven steel pins were monumented to resurvey sediment deposition (Leopold and others, 1966, fig. 170). The steel bars in 1993 were resurveyed using the same procedures used in the channel cross sections. Connecting all steel bars defined the outside boundary of the sediment pool. The steel bars were placed to quantify most of the sediment deposition, but some sediment was deposited outside the polygon and is not included in the volume calculations. Cores of sediment were collected to define the density of sediment. Volumes of sediment deposited between 1961 and 1993 were calculated using a computer software package. Easting, northing, and elevation data for the 1961 and 1993 cross sections are gridded in the software package. The grids for both years are the same size, and volume calculations are made for each grid cell. The total volume of deposited sediment is a solid defined by the upper and lower surfaces.

To investigate the effect of base-level rise on the channel profile, Big Sweat Dam and Little Sweat Dam were constructed in 1960 on ephemeral tributaries to Arroyo de los Frijoles (fig. 1A,B,D) (Miller and Leopold, 1961; Leopold and Bull, 1979). The dams were constructed of cement blocks to a height of 0.61 m. Big Sweat Dam and Little Sweat Dam drain 0.015 and 0.0034 km^2, respectively (Leopold and Bull, 1979). Sixteen cross sections were originally surveyed in 1960 for Big Sweat and Little Sweat Dams. The longitudinal profile for these dams and all 16 cross sections were resurveyed in 1993 and compared with previous surveys of all 16 cross sections in 1964, 1968, and 1974 for Big Sweat Dam and in 1962 and 1964 for Little Sweat Dam. Weighted slopes along the profile were computed for each survey by multiplying the slope by the reach length-weighted distance, then summing.

Hillslope-Erosion Plots

In 1959, a 232-m^2 erosion plot was established on a hillslope adjacent to Slopewash Tributary (fig. 1A,D). The plot consisted of a grid of 61 pins spaced 1.524 m apart, resulting in an area of 2.322 m^2 for each square in the grid. Hillslope sediment erosion and deposition were measured in the original study at two sites: one site in the Coyote C. Arroyo watershed, the other on Slopewash Tributary (fig. 1). In Coyote C. Arroyo, three lines with a total of 65 erosion pins were installed in 1961 and measured at selected times through 1968 (fig. 1C). The erosion pins in lines AB and BC were spaced 1.52 m apart and in line ED were spaced 3.05 m apart. In Slopewash Tributary, a 232-m^2 erosion plot of 61 erosion pins spaced on 1.52-m centers and arranged in a 9 by 9 grid was installed in 1959 and measured at selected times through 1967 (fig. 1E). Each row in the grid contained either four or nine erosion pins spaced 1.52 m apart.

Each erosion pin was a 25.4-cm-long nail with a washer driven flush to the ground. The amount of sediment overlying the washer is deposition. The distance from the bottom of the nail to the top of the washer is erosion. The net change in ground surface is the difference between the two. If a large amount of sediment was deposited on top of the washer, the washer would be reset to ground surface.

The measurements in 1993 were made in accordance with Leopold and others (1966). For washers that were not reset, the total change in ground surface since installation corresponds to the differences quantified by the 1993 measurements. For washers that were reset, the amount of deposition and erosion that had been measured earlier was added to the 1993 measurements to quantify the total change in ground surface. A benchmark or steel bar was driven into the ground near the erosion-pin sites and used to determine if the pins moved over time by soil action or wetting and drying. During the 1993 measurements at Slopewash Tributary, the top of the pin heads was surveyed to the benchmark to determine whether they had moved over time. At Coyote C. Arroyo, the benchmark appeared disturbed; therefore, the tops of the pins were not surveyed to the benchmark. In the original study at Coyote C. Arroyo, the tops of the pins were surveyed to the benchmark only in 1962. If a pin moved, it could be moved back to its original position, and the amount of deposition and erosion could be computed.

Land Use

Changes in roads in the Arroyo de los Frijoles watershed from 1952–53 to 1987 were determined from 1952–53 1:19,800-scale and 1987 1:24,000-scale aerial photographs. Housing development in the watershed since 1952 was determined from USGS 1:24,000-scale topographic maps.

Rainfall Trends

This section describes rainfall trends for the National Weather Service rain gage at Santa Fe. Average annual rainfall data for the study area using this rain gage are listed in table 1. Because channel cross sections were originally surveyed at different times, average rainfall totals are listed for the resurvey periods, 1951–93, 1958–93, and 1960–93. Rainfall during various time periods in the 1990's are within 5 percent of the long-term record.

Leopold (1951), Cooke (1974), and Balling and Wells (1990) suggested that periods of generally low annual rainfall punctuated by intense summer storm activity may trigger arroyo incision. Following the presentation of rainfall analysis by Leopold (1951), the data were subdivided into six time periods consisting of 20- to 30-year intervals (table 2). The average number of days per year of daily rainfall totals was divided into three classes: low intensity (0.25 to 12.4 mm), medium intensity (greater than 12.4 to 25.4 mm), and high intensity (greater than 25.4 mm). Rainfall was analyzed by calendar year.

To determine whether average annual rainfall from 1853 to 1993 changed significantly, the slope of the regression line was tested to determine if it was significantly less than or greater than zero (Kachigan, 1986; Helsel and Hirsch, 1992). The null hypothesis (Ho) is that the regression line has no slope. The alternative hypothesis is that the regression line has a significant slope. The test statistic, *T*, is defined as

$$t = \frac{b - \beta}{Sb} = -0.89 \quad (1)$$

where

b = slope of the regression line = -0.183
ß = slope being tested = 0

$$Sb = \frac{Sy.x}{\sqrt{\sum_{i=1}^{n} (x_i - \bar{x})^2}} \quad (2)$$

and

$$Sy.x = \sqrt{\sum_{i=1}^{n} \frac{(y_i - y_i')^2}{n-2}} \quad (3)$$

$Sy.x$ = standard error of estimate,
x_i = year,
x = mean of all years,
y_i = rainfall,
y_i = estimated value of rainfall from the regression equation,
y_i = $713.47 - 0.183x_i$,
n = number of observations.

Ho is rejected if

$$|t| > t_{critical}$$

With n–2 degrees of freedom and a significance probability level of 2.5 percent, t_{critical} – 1.98. Because t does not exceed t_{critical}, the null hypothesis is accepted that the slope of the regression is not significantly different from zero. Thus, average annual rainfall at Santa Fe has no significant trend from 1853 to 1993.

No trend was observed in average annual rainfall; the intensity of rainfall in the six time periods did change, however (table 2). As previously concluded by Leopold and others (1966), the 1853–80 time period, which immediately preceded arroyo formation in many watersheds, was characterized by less frequent low-intensity storms and more frequent high-intensity storms. The data also show a continuous increase in the number of low-intensity storms from 1881 through 1930 and a decrease in the number of high-intensity storms after 1880. Since about 1930, the frequency of low-intensity storms has again decreased, and since 1950, the frequency of high-intensity storms has increased (table 2).

Leopold and others (1966) suggested another way to estimate rainfall intensity: calculating average annual rainfall intensity by dividing annual rainfall by the total number of days having rainfall in that year (fig. 2A). For a constant annual precipitation, higher values of average annual rainfall intensity would indicate that annual rainfall occurred on fewer days, presumably with a greater intensity that could have resulted in accelerated erosion. A continuation of their analysis of average annual rainfall intensity through 1993, when most of the channels were resurveyed, is shown in figure 2B. Differences in rainfall-intensity values shown in figures 2A,B may be attributed to minor differences in analytical procedures or minor changes in historical precipitation records.

Five-year moving averages of rainfall intensity indicate that the data can be partitioned into three time periods: 1853 to 1869 (average rainfall = 6.1 mm/day), 1870 to 1964 (4.2 mm/day), and 1965 to 1993 (5.5 mm/day) (fig. 2E,F). A *T*-test was used to determine whether rainfall intensity changed significantly from one time period to the next (Swan and Sandilands, 1995). The null hypothesis (Ho) indicates that mean rainfall intensity between the groups has no difference. The alternative hypothesis is that average rainfall intensity changed from one time period to the next. The test statistic, *T*, is defined as

Table 1. Rainfall summaries for selected time periods in Arroyo de los Frijoles, Coyote C. Arroyo, Gunshot Arroyo, and Morning Walk Wash.

[Rainfall in millimeters; data from National Weather Service rain gage at Santa Fe, New Mexico]

Description	Time period	Average annual rainfall, mm (missing years: 1862, 1864, 1866–67, 1883–84, 1941–44, 1948, 1950)	Average summer rainfall, mm (July to September) (missing years: 1862, 1864, 1866–67, 1883–84, 1941, 1948)	Average non-summer rainfall, mm (October to June) (missing years: 1862, 1864, 1866–67, 1883–84, 1941–42, 1944)
Period of record	1853–1995	361	161	200
Initial surveys to resurvey in 1993	1951–93	353	157	195
Initial surveys to resurvey in 1993	1958–93	363	159	206
Initial surveys to resurvey in 1993	1960–93	364	160	205
Scour chains	1964–68	388	201	185
Scour chains	1964–93	363	160	203
Scour chains	1966–93	358	158	202
Scour chains	1968–93	359	155	204
Early sediment surveys at dam at Coyote C. Arroyo	1961–64	340	176	187
Resurvey period at dam at Coyote C. Arroyo	1961–93	361	161	202

Table 2. Average rainfall frequency of low-, moderate-, and high-intensity rainfall, Santa Fe, New Mexico.

[mm, millimeters]

Time period	Average low-intensity rainfall (days with rainfall 0.25 to 12.4 mm)	Average moderate-intensity rainfall (days with rainfall ranging from greater than 12.7 to 25.4 mm)	Average high-intensity rainfall (days with rainfall greater than 25.4 mm)	Average annual rainfall (mm)
1853–80	68.1	4.6	2.1	345
1881–1910	82.2	5.5	1.1	360
1911–30	83.0	5.4	1.2	364
1931–50	76.6	4.8	1.1	357
1951–70	63.5	5.3	1.4	350
1971–93	58.6	5.2	1.6	355

$$T = \frac{\bar{X}A - \bar{X}B}{\sqrt{S^2(1/nA + nB)}}, \quad (4)$$

where

X = mean of the time period,

S = variance,

and

n = number of observations.

At a significance level of 5 percent, the *T*-test result for the difference in means from 1853 to 1869 and from 1870 to 1964 is 5.60, which is greater than the *p*-value of 1.660; therefore, the decrease in rainfall intensity between 1853 and 1869 and between 1870 and 1964 is significant. At a significance level of 5 percent, the *T*-test result for the difference in means between 1870 and 1964 and 1965–93 is 6.80, which is greater than the *p*-value of 1.661; therefore, the increase in rainfall intensity from 1870 to 1964 and from 1965 to 1993 is significant. Rainfall intensities in the 1853–69 period, which immediately preceded arroyo incision, are significantly higher than from 1870 to 1964. Another period of rainfall intensity beginning in 1965 is also significantly higher than the preceding rainfall.

Low-intensity rainfall, which supports vegetation growth, decreased significantly after 1940 in the number of days for both summer and non-summer rainfall (fig. 2C,D). *T*-tests performed on low-intensity rainfall data show a significant decrease after 1940. If rainfall intensity is a triggering mechanism for arroyo cutting, then rainfall since 1967 may indicate that climatic factors are again favorable for arroyo incision in this part of New Mexico.

Channel and Hillslope Processes

Channel Cross-Sectional Resurveys

In 1993 and 1997, 51 of the original 79 cross sections were located and resurveyed in the four watersheds (fig. 1B). Thirty-five of the 51 cross sections are located in the main channel Arroyo de los Frijoles watershed; 16 of these 35 cross sections are where Leopold and others (1966) made full cross-sectional surveys (table 3, fig. 4), and 19 are cross sections where only one original channel elevation was investigated—the elevation at the scour chain. Sixteen cross sections in Coyote C. Arroyo, Gunshot Arroyo, and Morning Walk Wash (table 3, fig. 4) are where original full cross-sectional surveys were made, and these cross sections were resurveyed in 1993.

In the upper section of Morning Walk Wash, three channels were surveyed in 1993 between the left-bank and right-bank steel bars and in the lower section, two channels were surveyed between the left-bank and right-bank steel bars (fig. 4BB,CC). For the purpose of discussion, each channel is considered a separate cross section. The total number of full cross sections surveyed in the four watersheds was 32.

Elevation accuracy was determined for 41 of the 51 resurveyed cross sections (appendix 1). The three cross sections in the Morning Walk Wash upper section were tied into the same datum as the two cross sections in the Morning Walk Wash lower section (fig. 4BB,CC). Information was insufficient to assess elevation control (appendix 1) in seven cross sections. Cross sections 1, 5, 22, and 25 (figs. 1 and 4A,D,J,L) indicate that using one intact steel bar was sufficient. For cross sections 8 (LW-16), 9 (LW-17), and 16 (CS-40) (fig. 1), interpretations on channel change were based on one steel bar; however, there may be some error in these interpretations.

Of the 41 cross sections assessed for elevation control, 8 cross sections (20 percent) had no measurable differences in elevation, 23 (56 percent) had differences ranging from greater than 0 to 1 cm, 6 (15 percent) had differences in elevation ranging from greater than 1 to 2 cm, and 4 (10 percent) had differences in elevation ranging from greater than 2 to 3 cm (appendix 1). The average difference in elevation for all 41 cross sections was 0.8 + 0.8 cm, which is within the normal surveying error of 1.5 cm (Kissam, 1978).

The channels in the four watersheds are not deep, narrow trenches typical of many arroyos in the Southwest presumably because the bed material is composed of sand with little silt and clay. The resurveyed cross sections represent a variety of channel sizes, ranging in width from less than 2 to about 60 m and ranging in depth from about 0.2 to 3.0 m (fig. 4; table 4). The original surveyed widths and depths are not much different from those in the resurveys (tables 3 and 4).

Changes in Cross-Sectional Area

Of the 32 full cross sections resurveyed in the four watersheds, 20 cross sections (62 percent) increased in cross-sectional area and 12 (38 percent) decreased in area (table 3). The average change in cross-sectional area was erosion of 0.27 m^2 (table 4) or 4 percent of the original channel area, a relatively small value. For the 20 cross sections that eroded, the average increase in cross-sectional area was 2.20 m^2 or 22 percent of the original cross-sectional area, with a standard deviation of 3.63 m^2. For cross sections that deposited sediment, the average decrease in cross-sectional area was 2.93 m^2 or 26 percent of the original area, with a standard deviation of 2.49 m^2. The average erosion of 2.20 m^2 and deposition of 2.93 m^2 are so small that the changes in cross-sectional areas are considered insignificant.

The average change in cross-sectional area of all cross sections in Arroyo de los Frijoles was erosion of 1.81 m^2 (10 percent of its channel area), in Morning Walk Wash was 0.57 m^2 (19 percent of its channel area), and in Gunshot Arroyo was 0.73 m^2 (17 percent of its channel area) (table 4). Coyote C. Arroyo had an average decrease in cross-sectional area resulting from sediment deposition of 4.45 m^2 or 34 percent of its channel area (fig. 5A). The weighted change in cross-sectional area for Arroyo de los Frijoles was erosion of 4.87 m^2 (table 4) over a distance of 9,191 m of channel length, which corresponds to a volume of 44,760 m^3. For Coyote C.

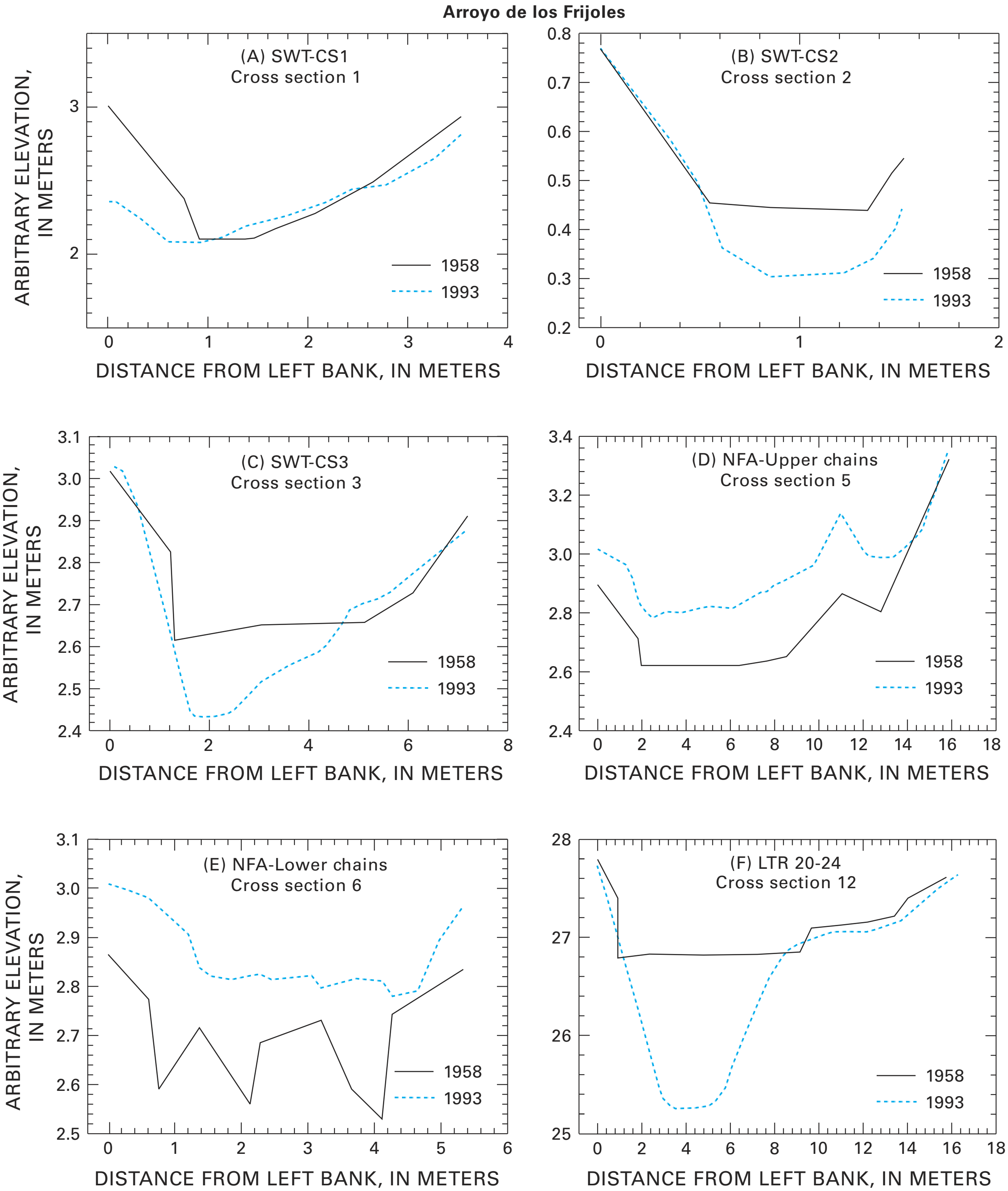


Figure 4. Survey cross sections in Arroyo de los Frijoles watershed (A to P), Coyote C. Arroyo (Q to V), Gunshot Arroyo (W to AA), and Morning Walk Wash (BB to CC). Location of cross sections in figure 1B.

Arroyo de los Frijoles

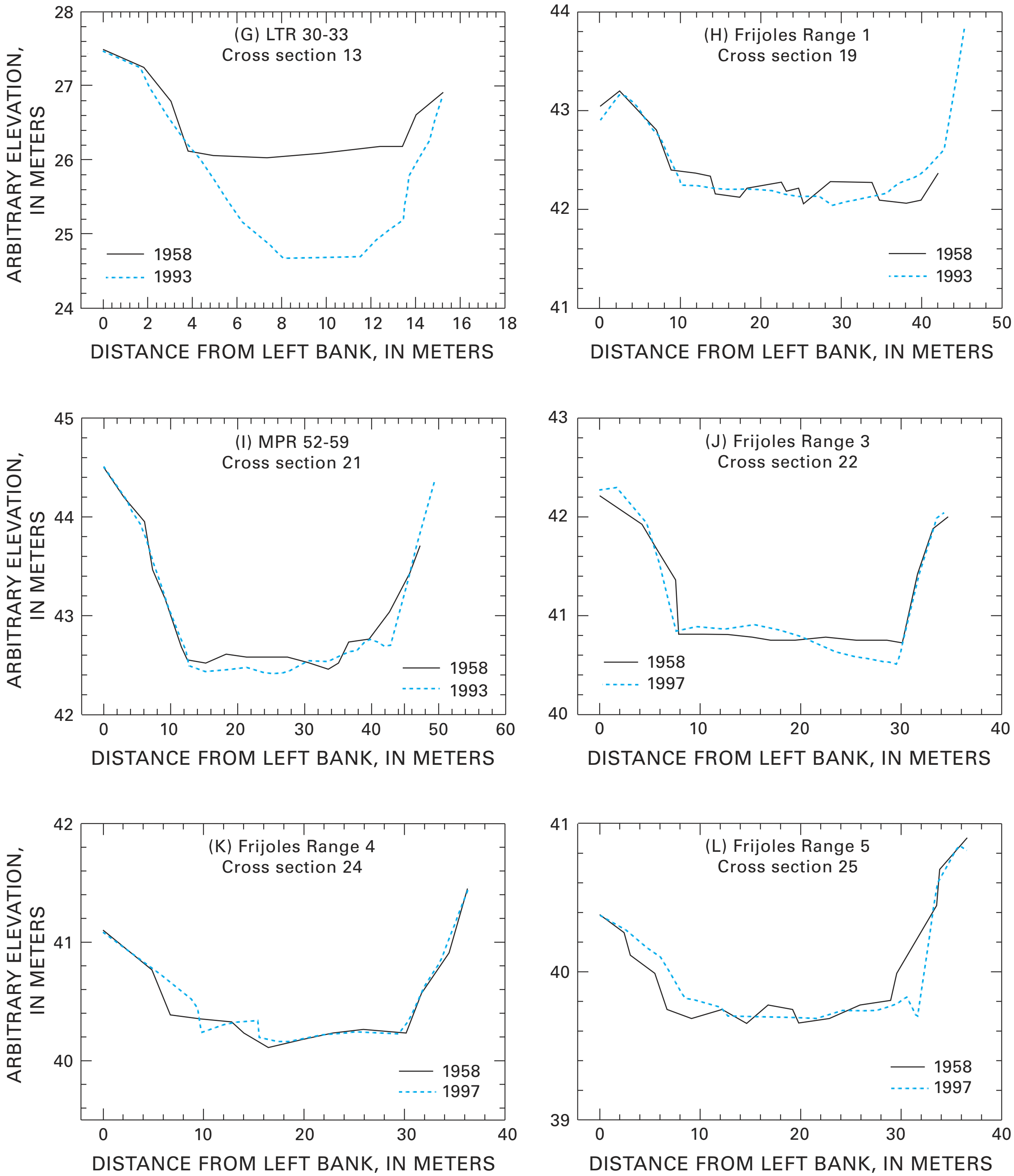


Figure 4. Survey cross sections in Arroyo de los Frijoles watershed (A to P), Coyote C. Arroyo (Q to V), Gunshot Arroyo (W to AA), and Morning Walk Wash (BB to CC)—Continued.

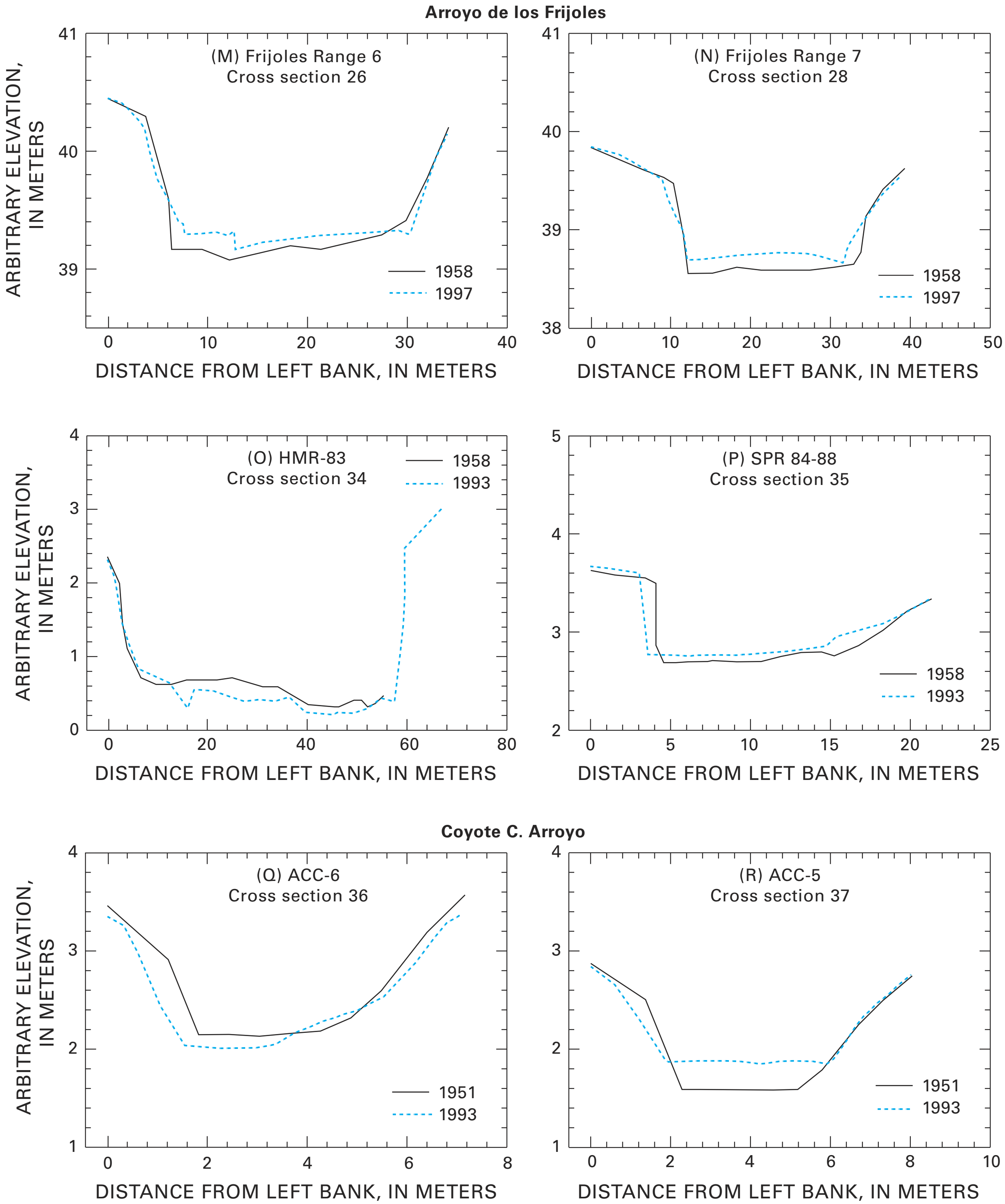


Figure 4. Survey cross sections in Arroyo de los Frijoles watershed (A to P), Coyote C. Arroyo (Q to V), Gunshot Arroyo (W to AA), and Morning Walk Wash (BB to CC)—Continued.

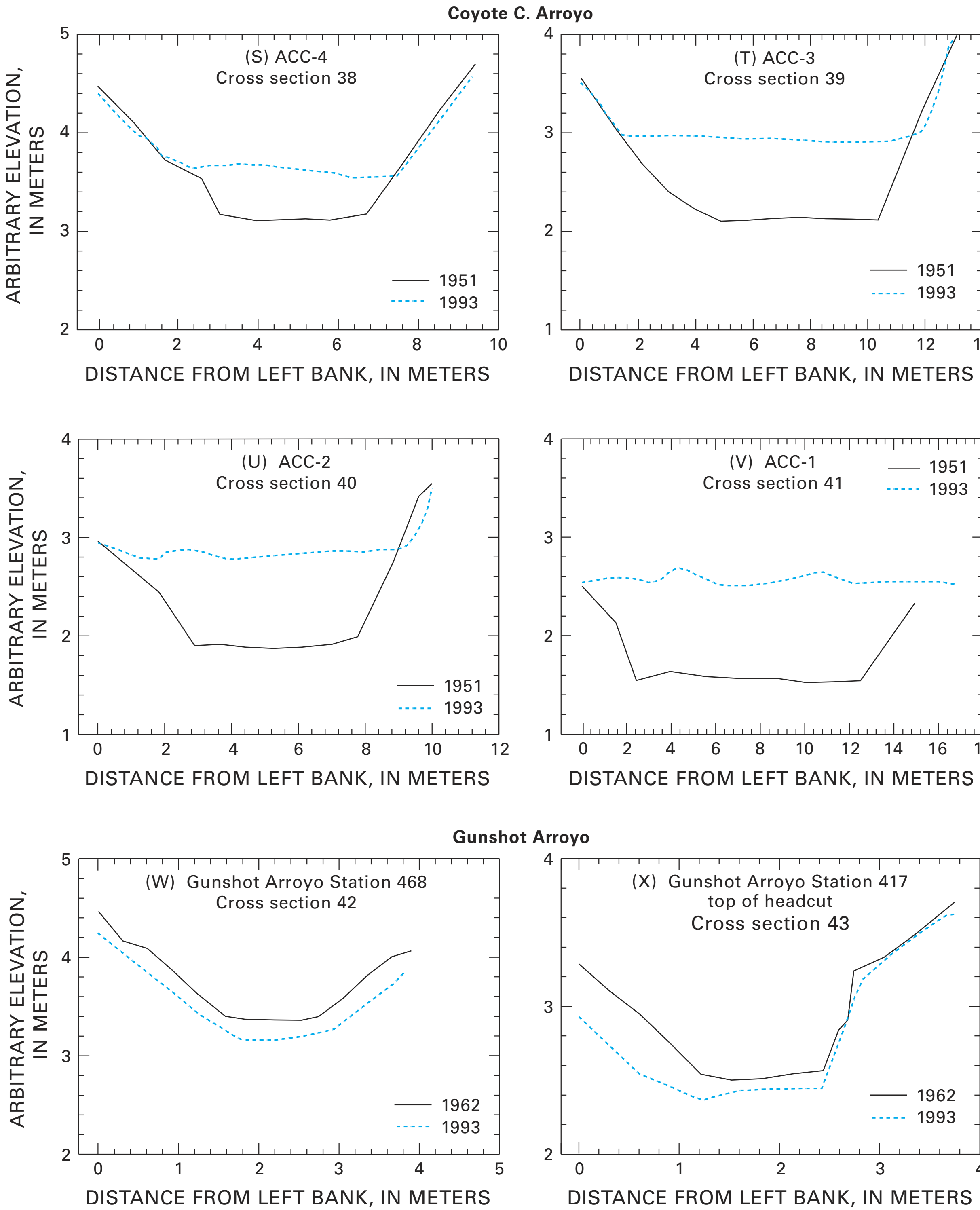


Figure 4. Survey cross sections in Arroyo de los Frijoles watershed (A to P), Coyote C. Arroyo (Q to V), Gunshot Arroyo (W to AA), and Morning Walk Wash (BB to CC)—Continued.

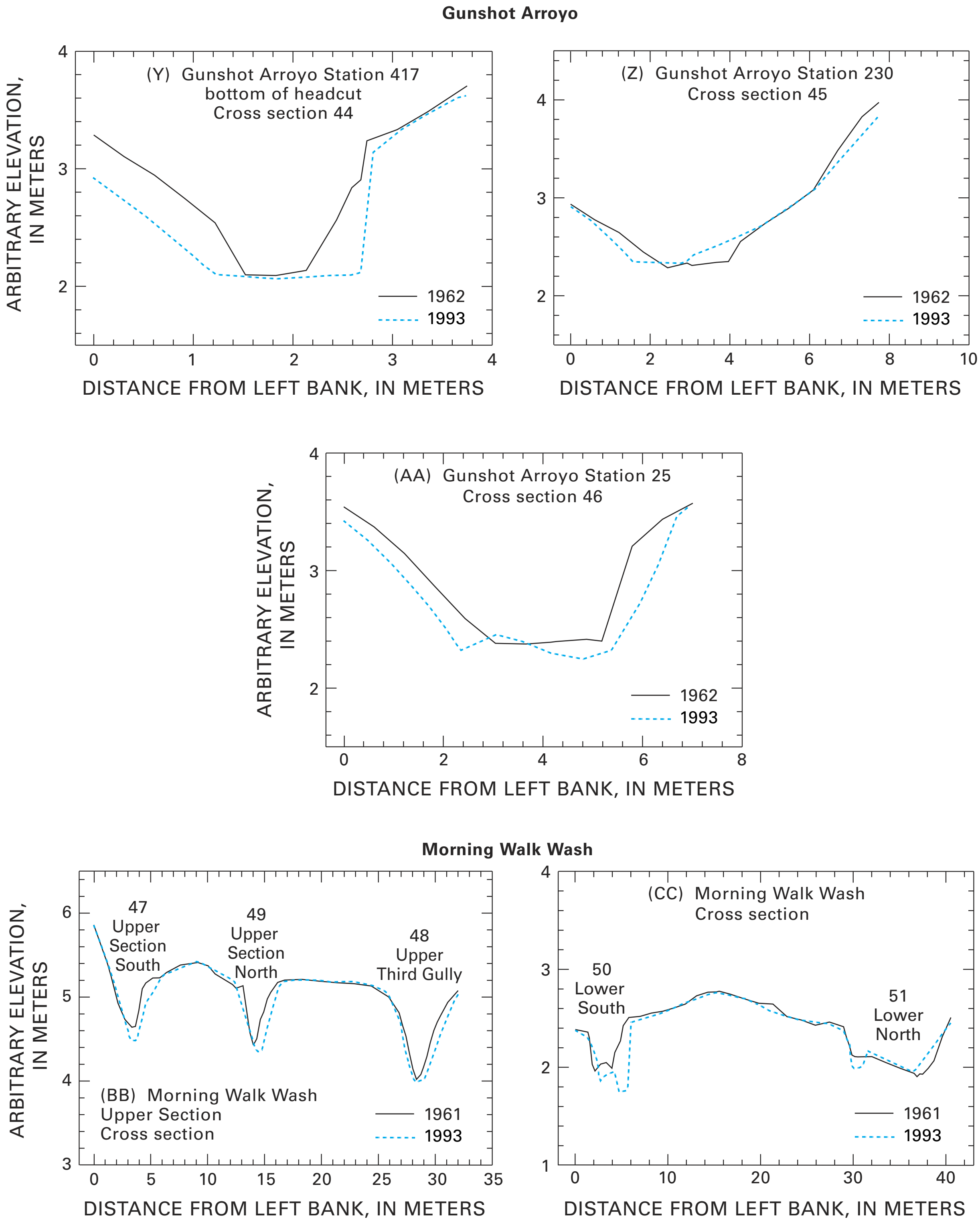


Figure 4. Survey cross sections in Arroyo de los Frijoles watershed (A to P), Coyote C. Arroyo (Q to V), Gunshot Arroyo (W to AA), and Morning Walk Wash (BB to CC)—Continued.

Table 3. Characteristics of resurveyed cross sections between original survey and resurvey in 1993–97.

[m, meter; m/m, meters per meter; m^2, square meter. A positive value in thalweg elevation indicates aggradation; a negative value means the cross section has eroded and increased in area. Only cross sections with original full cross-sectional surveys have a width and depth listed, --, no data]

Cross-section number and name (figure 1)	Date of surveys	Taped distance from divide (m)	Original width (m)	Original depth (m)	Width-to-depth ratio (m/m)	Change in thalweg elevation (m)	Change in cross-sectional area (m^2)	Percent change in cross-sectional area
Arroyo de los Frijoles								
SWT-CS1	8/1958–6/1993	203	3.5	0.87	4.1	-0.03	0.42	21
SWT-CS2	8/1958–6/1993	284	1.8	0.28	6.2	-0.14	0.11	41
SWT-CS3	8/1958–6/1993	305	7.2	0.35	20.6	-0.18	0.41	22
LW-Chain 4	8/1959–5/1993	563	--	--	--	0.22	--	--
NFA-Upper	8/1958–6/1993	819	11.0	0.26	42.6	0.16	-0.63	-9
NFA-Lower	8/1958–6/1993	912	3.7	0.23	16.0	0.25	-1.09	-58
Chain section 15	8/1959–5/1993	1,642	--	--	--	-0.16	--	--
LW-16	8/1959–5/1993	1,970	--	--	--	0.09	--	--
LW-17	8/1959–5/1993	2,278	--	--	--	0.38	--	--
LW-18	8/1959–5/1993	2,552	--	--	--	0.19	--	--
LW-19	8/1959–5/1993	2,721	--	--	--	-0.36	--	--
LTR 20-24	8/1958–6/1993	2,906	13.1	0.61	21.5	-1.53	8.14	59
LTR 30-33	8/1958–6/1993	2,955	13.4	1.05	12.8	-1.34	11.39	85
LW-35	8/1959–5/1993	3,557	--	--	--	-0.35	--	--
LW-37	8/1959–5/1993	4,115	--	--	--	-0.25	--	--
CS-40	8/1959–5/1993	5,006	--	--	--	-0.09	--	--
CS-45	8/1960–6/1993	6,732	--	--	--	0.08	--	--
CH49	8/1960–6/1993	7,376	--	--	--	-0.19	--	--
Frijoles range 1	8/1958–9/1997	7,417	42.4	1.43	29.7	-0.02	0.85	2
CH51	8/1960–5/1993	7,437	--	--	--	-0.19	--	--
MPR 52-59	7/1958–5/1993	7,452	49.4	1.99	24.8	-0.04	2.39	3
Frijoles range 3	8/1958–9/1997	7,482	30.5	1.18	25.9	-0.22	0.23	1
CH61	11/1958–5/1993	7,504	--	--	--	-0.60	--	--
Frijoles range 4	8/1958–9/1997	7,515	25.0	0.37	68.3	0.05	-1.07	-3
Frijoles range 5	8/1958–9/1997	7,547	31.1	0.70	44.2	0.03	0.03	0
Frijoles range 6	8/1958–9/1997	7,580	30.3	1.17	25.8	0.08	-1.56	-5
LW-64	11/1958–6/1993	7,596	--	--	--	0.10	--	--
Frijoles range 7	8/1958–9/1997	7,612	27.7	0.73	37.8	0.11	-0.37	-1
LW-75	8/1959–5/1993	7,751	--	--	--	-0.52	--	--
LW-76	11/1958–5/1993	7,782	--	--	--	-0.02	--	--
LW-77	11/1958–5/1993	7,812	--	--	--	-0.08	--	--
LW-79	8/1959–5/1993	7,873	--	--	--	0.15	--	--
LW-82	1958–6/1993	8,687	--	--	--	-0.02	--	--
HMR-83	8/1958–6/1993	8,902	57.0	2.06	27.7	-0.11	12.24	10
SPR 84-88	11/1958–6/1993	9,394	17.1	0.93	18.4	0.27	-2.49	-14

Table 3. Characteristics of resurveyed cross sections between original survey and resurvey in 1993–97.—Continued

[m, meter; m/m, meters per meter; m^2, square meter. A positive value in thalweg elevation indicates aggradation; a negative value means the cross section has eroded and increased in area. Only cross sections with original full cross-sectional surveys have a width and depth listed, --, no data]

Cross-section number and name (figure 1)	Date of surveys	Taped distance from divide (m)	Original width (m)	Original depth (m)	Width-to-depth ratio (m/m)	Change in thalweg elevation (m)	Change in cross-sectional area (m^2)	Percent change in cross-sectional area
Coyote C. Arroyo, Gunshot Arroyo, and Morning Walk Wash								
ACC-6	7/1961–5/1993	674	7.2	1.38	5.2	-0.12	0.95	13
ACC-5	7/1961–5/1993	803	8.0	1.23	6.6	0.27	-0.76	-11
ACC-4	7/1961–5/1993	892	9.4	1.48	6.4	0.44	-1.97	-20
ACC-3	7/1961–5/1993	1,009	13.1	1.67	7.9	0.80	-6.65	-37
ACC-2	7/1961–5/1993	1,045	8.8	0.98	9.0	0.91	-5.83	-52
ACC-1	7/1961–5/1993	1,100	14.9	0.89	16.8	0.98	-12.46	-96
Gunshot Arroyo Station 468	7/1962–6/1993	208	3.9	0.90	4.3	-0.20	0.73	21
Gunshot Arroyo Station 417 top of headcut	7/1962–6/1993	223	2.7	0.76	3.6	-0.13	0.59	16
Gunshot Arroyo Station 417 bottom of headcut	7/1962–6/1993	223	2.7	1.17	2.3	-0.03	0.90	22
Gunshot Arroyo Station 230	7/1962–6/1993	280	7.7	1.17	6.6	0.05	0.17	3
Gunshot Arroyo Station 25	7/1962–6/1993	343	5.2	0.91	5.7	-0.13	1.24	21
Morning Walk Wash-Upper Section North	7/1961–6/1993	165	7.6	1.09	7.0	-0.08	0.60	28
Morning Walk Wash-Upper Third Gully	7/1961–6/1993	183	6.1	1.02	6.0	-0.03	0.79	20
Morning Walk Wash-Upper Section South	7/1961–6/1993	210	5.2	0.70	7.4	-0.16	0.51	10
Morning Walk Wash-Lower North	7/1961–6/1993	213	13.1	0.58	22.6	0.04	-0.30	-5
Morning Walk Wash-Lower South	7/1961–6/1993	265	5.8	0.48	12.0	-0.22	1.23	33

Table 4. Summary of resurveyed channel characteristics in 1993 and 1997 in relation to Leopold and others' (1966) original channel surveys in Arroyo de los Frijoles, Coyote C. Arroyo, Gunshot Arroyo, and Morning Walk Wash.

[m^2, square meter; --, no data]

Watershed (figure 1)	Drainage area (square kilometers)	Number of cross sections resurveyed for cross-sectional area	Range of width (meters)	Range of depth (meters)	Number of cross sections in cross-sectional area		Average change in cross-sectional area (m^2) (positive numbers indicate erosion)	Number of cross sections resurveyed in 1993 and 1997 for changes in thalweg elevation	Number of cross sections that aggraded	Number of cross sections that degraded	Average change in channel elevation (meters) (positive numbers indicate aggradation)	Weighted change in cross-sectional area (m^2) (positive numbers indicate degradation)	Percent change in cross-sectional area (positive numbers indicate degradation)
					Decreasing	Increasing							
Main Channel Arroyo de los Frijoles	9.71	16	1.2 to 60	0.19 to 3.0	6	10	1.81	35	13	22	-0.13	4.87	10
Arroyo Coyote C.	0.16	6	7.2 to 14.9	0.85 to 1.5	5	1	-4.45	6	5	1	0.55	-3.15	-34
Morning Walk Wash	0.03	5	5.2 to 13.4	0.48 to 1.1	1	4	0.57	5	2	3	-0.09	--	17
Gunshot Arroyo	0.09	5	2.7 to 7.7	0.68 to 1.2	0	5	0.73	5	1	4	-0.09	--	17
Total		32	1.2 to 60	0.19 to 3.0	12	20	0.27	51	20	31	-0.04	--	4

Arroyo, the weighted change in cross-sectional area was deposition of 3.15 m^2 (table 4) over a distance of 427 m of channel length, which corresponds to a volume of 1,345 m^3 or 420 m^3 per year. Using a dry density of sediment of 1,180 kg/m^3 for Coyote C. Arroyo yields a net deposition of 49.6 metric tonnes/yr.

Changes in Thalweg Elevation

Of the 32 full cross sections resurveyed in the four watersheds, 18 (56 percent) degraded or showed a decrease in thalweg elevation and 14 (44 percent) aggraded (table 3). The average change in thalweg elevation was about -0.01 m. In general, as channels aggrade, cross-sectional areas decrease. However, at two locations (Gunshot Arroyo Station 230, and Frijoles Range 5) the cross sections both aggraded and increased in cross-sectional area. Therefore, as these channels aggraded they also widened and showed a net increase in cross-sectional area.

Resurveys of the 51 cross sections in channels that had a survey at only one station in the channel, combined with the surveys for full cross-sectional surveys, indicate that 31 (61 percent), had degraded (table 4). The average change in all 51 cross sections was degradation of 0.04 m or 1.14 mm/yr. The average decrease in elevation of the 31 degrading cross sections was 0.25 m with a standard deviation of 0.34 m. The average increase in elevation of the 20 aggrading cross sections was 0.28 m with a standard deviation of 0.28 m. The largest degradation recorded was 1.53 m in Arroyo de los Frijoles at cross section LTR 20-24 (table 3). The largest measured aggradation was 0.98 m in Coyote C. Arroyo at cross section ACC-1 (table 3).

Comparison of the 1993 resurveys with the original surveys for Gunshot Arroyo and Morning Walk Wash showed that each had an average channel degradation of 0.09 m (table 4). Coyote C. Arroyo showed an average aggradation of 0.55 m (table 4).

The main channel Arroyo de los Frijoles was the focus of many resurveys in the original study. Thalweg elevations were obtained from previous surveys conducted in 1958–60, 1962, 1964, 1966, and 1968 (U.S. Geological Survey, unpublished data). Thalweg elevations were resurveyed in 1993 and 1997 (table 5). Average changes in thalweg elevation and channel length-weighted change for Arroyo de los Frijoles from surveys in 1962, 1964, 1966, and 1993 and 1997, compared with the original thalweg survey in 1958–60, are listed in table 6. Arroyo de los Frijoles showed an average degradation of 0.13 m (table 4; fig. 5B). The channel length-weighted change in thalweg elevation from the original survey to 1993 and 1997 was -0.12 m for the main channel Arroyo de los Frijoles (table 6). Comparison of the resurveys showed aggradation from the original survey (performed from 1958

Table 5. Elevation of thalweg at 63 cross sections from 1958 to 1997 in the main channel Arroyo de los Frijoles.

[-- indicates the channel elevation was not surveyed. Elevations are in meters (m) above sea level unless noted with ‘ * ‘, which indicates arbitrary elevation]

Cross-section-number or letter and name	Scour-chain number	Taped distance from divide at Slopewash Tributary (m)	Date of original thalweg elevation	Thalweg elevation from					
				1958–60 surveys (m)	1962 resurveys (m)	1964 resurveys (m)	1966 resurveys (m)	1968 resurveys (m)	1993 and 1997 resurveys (m)
SWT-CS1	1	203	11/1958	2,201.24	2,201.34	2,201.28	2,201.24	--	2,201.21
SWT-CS2	2	284	11/1958	2,197.74	2,197.76	2,197.80	2,197.72	--	2,197.61
SWT-CS3	3	305	11/1958	2,197.12	2,197.16	2,197.15	2,197.10	--	2,196.94
LW-Chain 4	4	563	8/1959	2,189.97	2,190.05	2,190.00	2,190.08	--	2,190.18
NFA-Upper	6–9	819	11/1958	2,183.75	2,183.65	2,183.75	2,183.76	2,183.75	2,183.91
NFA-Lower	10–13	912	11/1958	2,181.79	2,181.88	2,181.91	2,181.83	2,181.85	2,182.04
LW-14	14	1,321	8/1959	2,170.65	2,170.69	2,170.54	2,170.48	--	--
Chain section 15	15	1,642	8/1959	2,167.21	2,167.21	2,167.19	2,167.07	--	2,167.05
LW-16	16	1,970	8/1959	2,161.36	2,161.44	2,161.57	2,161.31	--	2,161.45
LW-17	17	2,278	8/1959	2,155.28	2,155.35	2,155.37	2,155.18	--	2,155.66
LW-18	18	2,552	8/1959	2,151.29	2,150.70	2,150.91	2,150.12	--	2,151.48
LW-19	19	2,721	8/1959	2,148.00	2,148.13	2,148.14	--	--	2,147.64
LTR 20-24	20–24	2,906	11/1958	2,144.73	2,144.82	2,144.87	2,144.51	2,144.65	2,143.20
LTR 25-29	25–29	2,926	8/1958	2,144.38	2,144.56	2,144.62	2,144.15	2,144.35	--
LTR 30-33	30–33	2,955	11/1959	2,143.97	2,144.21	2,144.18	2,143.87	2,143.98	2,142.62
LW-34	34	3,103	8/1959	2,141.95	2,141.96	2,141.92	2,141.81	--	--
LW-35	35	3,557	8/1959	2,134.05	2,133.94	2,133.87	2,134.02	--	2,133.69
LW-36	36	3,840	8/1959	2,129.30	2,129.35	2,129.22	2,129.26	--	--
LW-37	37	4,115	8/1959	2,124.26	2,124.48	2,124.48	--	--	2,124.01
LW-38	38	4,402	8/1959	2,119.30	2,119.41	2,119.34	2,119.34	--	--
LW-39	39	4,605	8/1959	2,114.25	2,114.42	2,114.33	2,114.32	--	--
CS-40	40	5,006	8/1959	2,109.75	2,109.79	2,109.73	2,109.87	--	2,109.66
LW-41	41	5,038	8/1959	2,105.16	2,104.85	2,104.81	2,104.50	--	--
LW-42	42	5,955	8/1959	2,099.86	2,099.97	2,099.74	2,099.90	--	--
LW-43	43	6,046	8/1959	2,095.70	2,095.50	2,095.60	2,095.70	--	--
CS-45	45	6,732	8/1960	2,085.27	2,085.30	2,085.30	2,085.24	--	2,085.15
LW-46	46	7,046	8/1959	2,079.80	2,079.89	2,080.03	2,079.89	--	--
LW-47	47	7,315	11/1958	2,075.42	2,075.54	2,075.59	2,075.45	--	--
LW-48	48	7,346	11/1958	2,074.96	2,074.99	2,075.00	2,075.05	--	--
CH-49	49	7,376	11/1958	2,074.40	2,074.33	2,074.42	2,074.46	--	2,074.22
LW-50	50	7,407	11/1958	2,073.81	2,073.81	2,073.80	2,073.68	--	--
Frijoles range 1		7,417	8/1958	42.06 *	--	--	--	--	42.04
CH-51	51	7,437	0.01	2,073.39	2,073.41	2,073.37	2,073.31	--	2,073.20
MPR 52-59	52–59	7,452	7/1958	2,073.21	2,073.20	2,073.12	2,073.13	2,073.20	2,073.17
LW-60	60	7,474	11/1958	2,072.88	2,072.98	2,073.02	2,073.01	--	--

Table 5. Elevation of thalweg at 63 cross sections from 1958 to 1997 in the main channel Arroyo de los Frijoles.—Continued

[-- indicates the channel elevation was not surveyed. Elevations are in meters (m) above sea level unless noted with ‘ * ‘, which indicates arbitrary elevation]

Cross-section-number or letter and name	Scour-chain number	Taped distance from divide at Slopewash Tributary (m)	Date of original thalweg elevation	Thalweg elevation from					
				1958–60 surveys (m)	1962 resurveys (m)	1964 resurveys (m)	1966 resurveys (m)	1968 resurveys (m)	1993 and 1997 resurveys (m)
CH-61	61	7,504	11/1958	2,072.92	2,072.45	2,072.47	2,072.57	--	2,072.31
Frijoles range 4		7,515	8/1958	40.11 *	--	--	--	--	40.16
LW-62	62	7,535	11/1958	2,071.82	2,071.80	2,071.86	2,071.93	--	--
Frijoles range 5		7,547	8/1958	39.65 *	--	--	--	--	39.69
LW-63	63	7,565	11/1958	2,071.20	2,071.29	2,071.33	2,071.28	--	--
Frijoles range 6		7,580	8/1958	39.08 *	--	--	--	--	39.16
LW-64	64	7,596	11/1958	2,070.62	2,070.69	2,070.83	2,070.78	--	2,070.72
Frijoles range 7		7,612	8/1958	38.55 *	--	--	--	--	38.66
LW-65	65	7,626	11/1958	2,070.29	2,070.33	2,070.35	2,070.39	--	--
LW-66	66	7,657	11/1958	2,069.98	2,069.84	2,069.92	2,069.93	--	--
MPR 67-72	67–72	7,678	7/1958	2,069.18	2,069.38	2,069.41	2,069.42	2,069.42	--
LW-73	73	7,690	1958	2,069.60	2,069.29	2,069.33	2,069.35	--	--
LW-74	74	7,721	1958	2,069.17	2,068.78	2,068.92	2,068.92	--	--
LW-75	75	7,751	1958	2,068.72	2,068.22	2,068.42	2,068.49	--	2,068.21
LW-76	76	7,782	11/1958	2,067.81	2,067.65	2,067.82	2,067.90	--	2,067.79
LW-77	77	7,812	11/1958	2,067.08	2,067.20	2,067.20	2,067.18	--	2,067.00
LW-78	78	7,843	11/1958	2,066.50	2,066.67	2,066.59	2,066.53	--	--
LW-79	79	7,873	1958	2,066.14	2,066.22	2,066.23	2,066.21	--	2,066.29
LW-80	80	8,086	1958	2,062.75	2,062.76	--	--	--	--
LW-81	81	8,377	1958	2,058.01	2,057.88	2,057.90	--	--	--
LW-82	82	8,687	1958	2,052.71	2,052.70	2,052.68	--	--	2,052.68
HMR-83	83	8,902	9/1958	2,049.32	2,049.42	2,049.29	--	--	2,049.21
SPR 84-88	84–88	9,394	11/1958	2,040.49	2,040.68	2,040.57	--	--	2,040.75
SPR 89	89	9,510	1958	2,038.90	2,039.13	2,038.96	--	--	--
SPR 90	90	9,754	1958	2,035.82	2,036.24	2,036.36	--	--	--

Table 6. Average changes and channel length-weighted changes in thalweg elevations for the main channel Arroyo de los Frijoles

[(Leopold and others, 1966)]

Time period	Average change in thalweg elevation (meters)[1]	Channel length-weighted change in thalweg elevation (meters)[1]	Length of channel used in weighting (meters)	Number of cross sections
1962 to original survey	0.01	0.02	9,551	55
1964 to original survey	0.02	0.00	9,551	54
1966 to original survey	-0.06	-0.11	7,670	46
1993 and 1997 to original survey	-0.13	-0.12	9,191	35

[1]Negative value indicates degradation; positive value indicates aggradation.

to 1960) to 1962 and 1964. Degradation occurred from the original survey to 1966 and from the original survey to 1993 and 1997 (table 6).

Full cross-sectional surveys made in 1993 and 1997 compared with the original surveys showed little change. In cross sections in which only 1 station in the channel was surveyed in the original study (n = 19), 13 showed slight degradation of about 0.01 m/yr. Because the entire data set essentially showed no change, the resurvey did not establish a clear progressive trend in aggradation or degradation.

General trends in channel changes reported for 1958–64 (Leopold and others, 1966) did not continue through the next 35–39 years (figs. 6 and 7). For the main channel Arroyo de los Frijoles, the newer surveys indicate slight degradation, whereas the 1958–64 study showed a consistent trend in aggradation (tables 4 and 6). The average aggradation from 1958 to 1964 was 0.012 m/yr (Leopold and others, 1966, p. 219). Twenty-nine of the 35 resurveyed cross sections in the main channel Arroyo de los Frijoles were used in a comparison of channel aggradation and degradation with the original surveys (1958–64) (fig. 7). Channel changes for 1958–64 were not published for six of the resurveyed cross sections (19, 22, 24, 25, 26, and 28). Thirteen (45 percent) cross sections showed the same trend as in the original study. Six cross sections that were aggrading in the original survey continued to aggrade by the 1993 and 1997 resurveys, and seven cross sections that were degrading in the original survey continued to degrade by the 1993 and 1997 resurveys (fig. 7).

Along the main channel Arroyo de los Frijoles, changes in channel elevation periodically alternate from aggradation to degradation (fig. 8). The changes in channel elevation during 1993–97 compared with those during the original survey show several adjacent cross sections with the same trend in channel-elevation change over time (fig. 8). The alternating trend in channel-elevation change over time may reflect the sandy nature of the channel, the localized nature of streamflow and scour in an ephemeral channel, and human disturbance.

All 35 surveyed full cross sections show no relation between aggradation and degradation either to distance from the watershed divide or to width-to-depth ratio (fig. 9). Miller and Leopold (1961), in an unpublished preliminary report on channel changes in Arroyo de los Frijoles from 1958 to 1960, reported similar observations that upstream areas are not characterized by degradation and downstream areas are not characterized by aggradation. In arroyos investigated on Zuni Reservation, New Mexico, an increase in channel erosion and an increase in cross-sectional area were observed with a decrease in width-to-depth ratios (Gellis, 1998).

Coyote C. Arroyo (fig. 1) showed both aggradation and degradation between the original survey and the 1993 resurvey, part of which may be related to the movement of a large headcut (fig. 10). In 1961, four headcuts were identified in the Coyote C. Arroyo channel. The largest headcut, 523 m from the watershed divide, was studied in detail between 1961 and 1964. In 1993 the headcut had moved approximately 22 m upstream or 0.69 m per year. In Coyote C. Arroyo, cross sections that are farther away from the headcut have aggraded the most (fig. 10). This trend in aggradation may be due to the base-level effect of the dam or to the movement of a headcut.

Arroyo channels deepen by the upstream migration of a headcut (Gellis, 1998). Channel-top width-to-depth ratios are typically lower in reaches immediately downstream from a headcut than upstream because of the increased depth. For example, in Oaklimeter Creek, an incised channel in Mississippi, top width-to-depth ratios generally were 4.7 in the channel reach upstream from the headcut and 3.8 in the channel reach immediately downstream (Schumm and others, 1984). Top width-to-depth ratios ranged from 2.29 to 3.63 downstream from headcuts in the three watersheds on the Zuni Reservation, New Mexico (Gellis, 1998). Immediately upstream from the headcut, the channel had not deepened and its top width-to-depth ratios were higher, ranging from 3.96 to 8.21. As the headcut advances upstream, the channel aggrades downstream. For gullies in Israel, Seginer (1966) found a positive correlation between the distance from the headcut and the downstream gully cross-sectional area. In Coyote C. Arroyo, a similar process was observed that aggradation occurred in reaches furthest from the headcut.

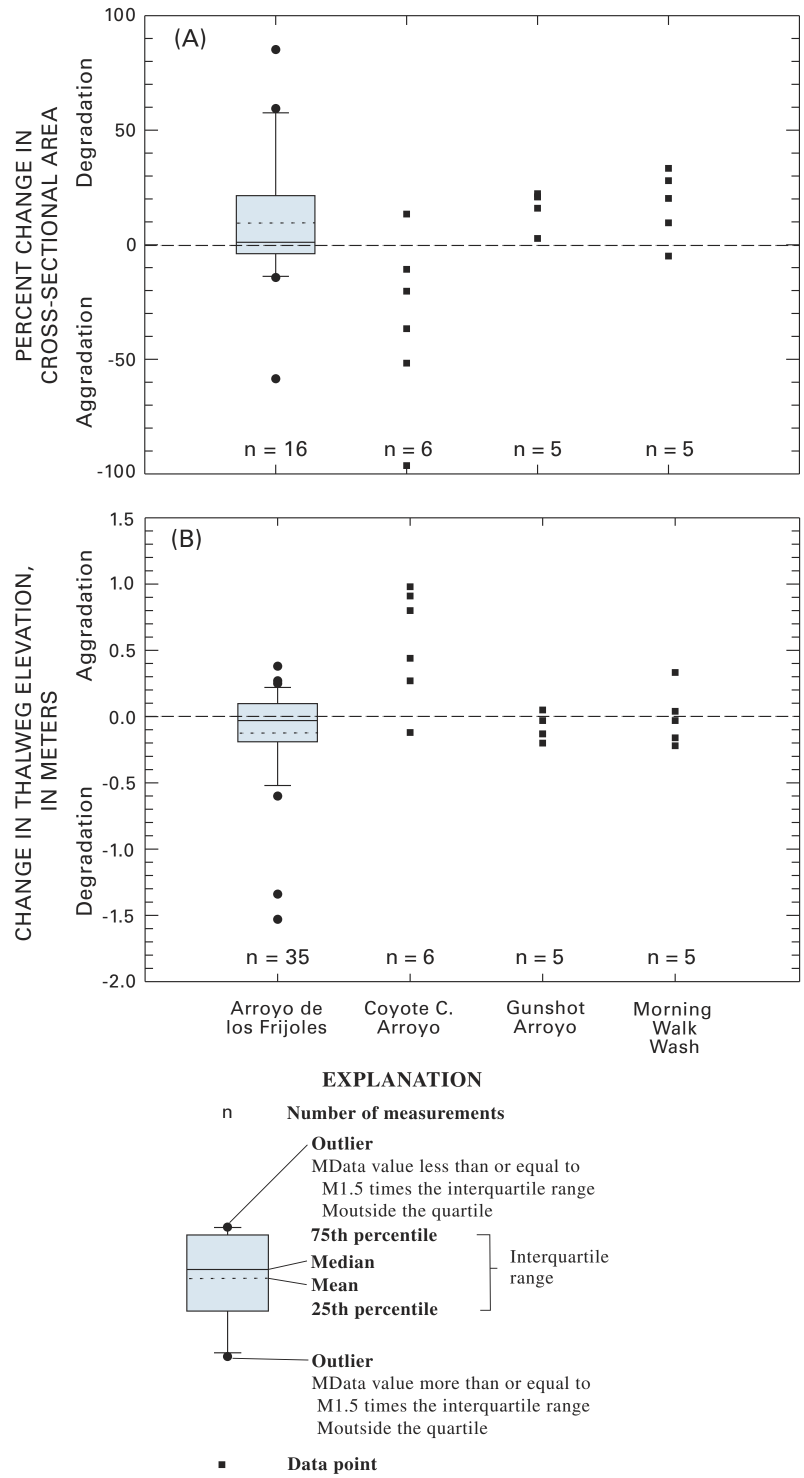


Figure 5. Change in (A) percent cross-sectional area and (B) thalweg elevation.

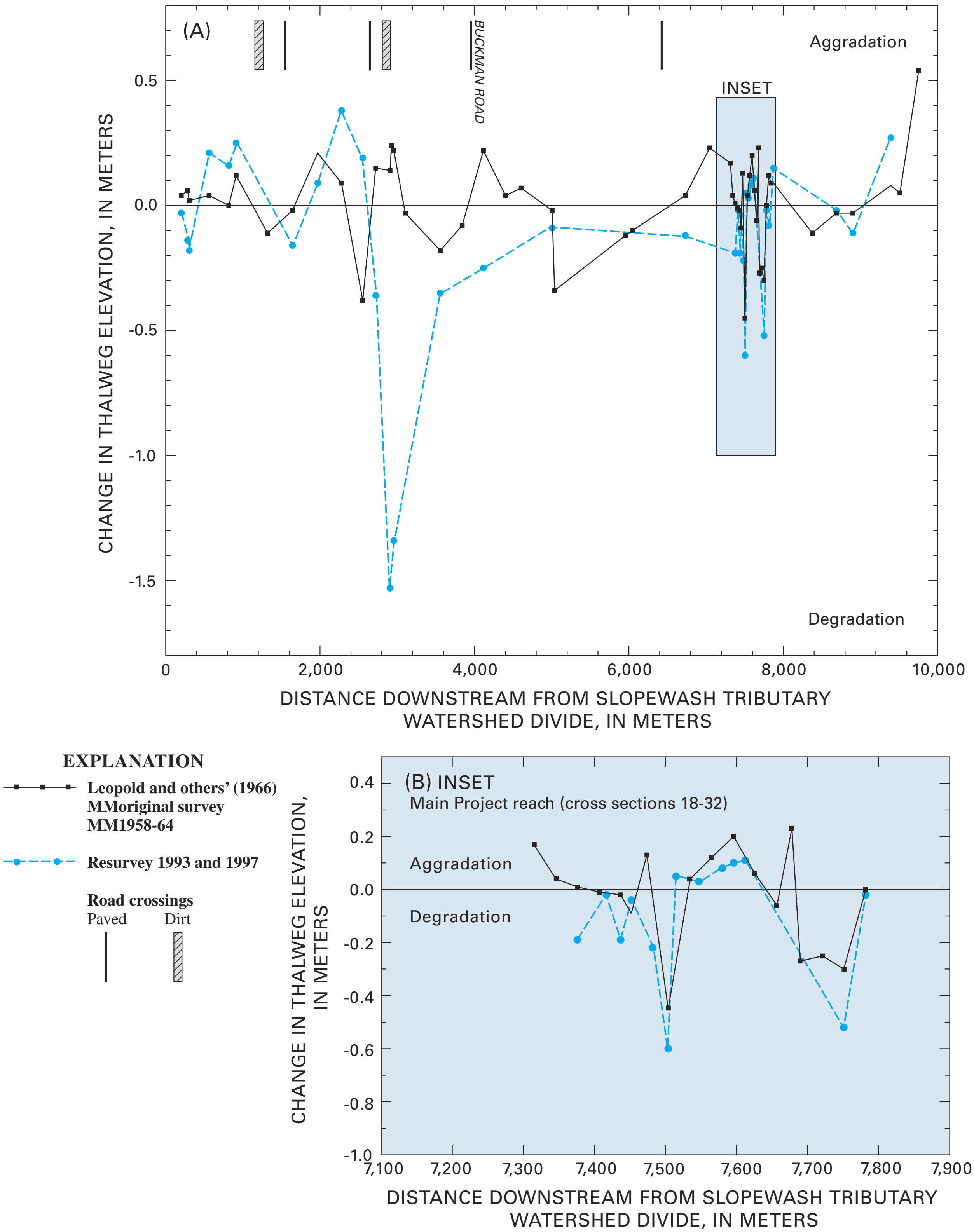


Figure 6. Aggradation and degradation of 35 cross sections resurveyed in 1997 compared with Leopold and others' (1966) original survey from 1958 to 1964 at (A) main channel Arroyo de los Frijoles, and (B) Main Project reach in Arroyo de los Frijoles. Location of reaches in figure 1.

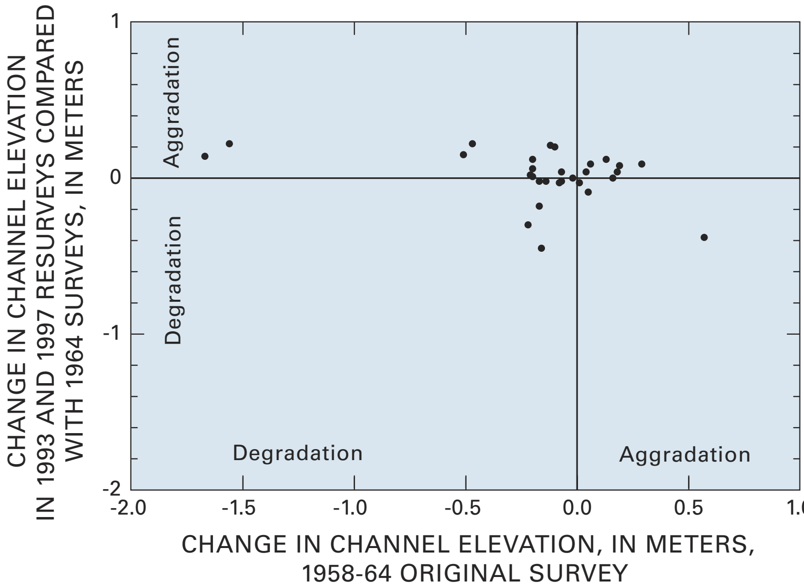


Figure 7. Channel elevation changes for the main channel Arroyo de los Frijoles at the cross sections resurveyed in 1993 and 1997 compared with Leopold and others' (1966) original 1958–64 surveys.

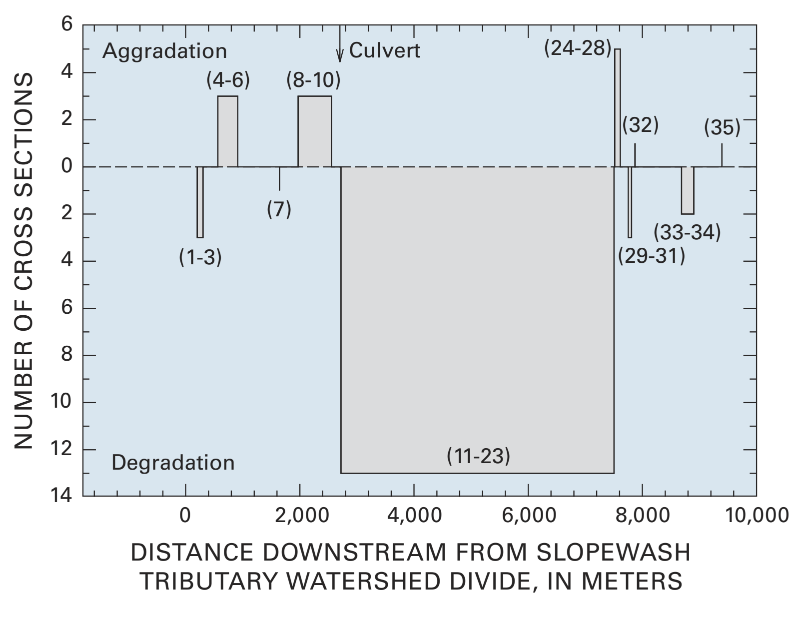


Figure 8. Adjacent cross sections in the main channel Arroyo de los Frijoles showing similar channel changes in aggradation or degradation of the thalweg elevation from Leopold and others' (1966) survey to resurvey conducted in 1993 and 1997. Cross section numbers in parentheses. Location of cross sections shown in figure 1.

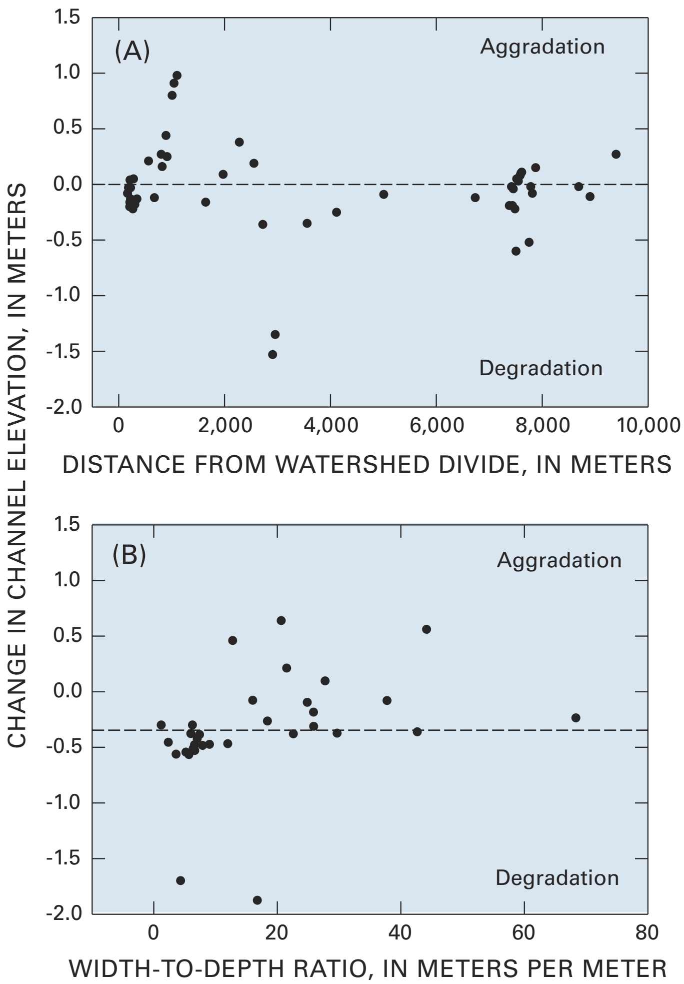


Figure 9. Change in thalweg elevation compared with (A) distance downstream from watershed divide for all 1993 and 1997 resurveyed cross sections, and (B) width-to-depth ratios for 32 cross sections with full cross-sectional surveys.

If arroyo incision is related to increases in precipitation intensity (Leopold, 1951; Leopold and others, 1966), then Santa Fe precipitation records indicate that climatic factors may be favorable for arroyo incision in this part of New Mexico. The 1993–98 channel resurveys showed little change in channel-bed elevation between 1993 and the 1950's, indicating that channels have not yet responded to a higher frequency of intense rainfall. Furthermore, recent data for other arroyo watersheds in New Mexico indicate that arroyos are aggrading. Results of resurveys between 1992 and 1994 for 85 channel cross sections in three subbasins of the Rio Nutria watershed on Zuni Reservation indicate that 72 percent of cross sections aggraded (Gellis, 1998). Replicate arroyo surveys of the Rio Puerco in two reaches indicate aggradation of 2.55 and 0.7 m, from 1936 to 1995 and from 1977 to 1994, respectively (Elliott and others, 1999).

Changes in Gunshot Arroyo

The longitudinal profile of Gunshot Arroyo (fig. 11A,B) was originally surveyed in 1962 and resurveyed in 1998. The profile shows little change between 1962 and 1998 (fig. 11A,B): for the entire profile (350 m), the average change in channel elevation was degradation of 0.08 m or 2.22 mm/yr. Maximum degradation of the channel was 0.58 m, 250 m upstream from the mouth (fig. 11C). Maximum aggradation was 0.35 m, 327 m upstream from the mouth. Two cross sections at station 417 were surveyed immediately downstream and upstream from a headcut about 127 m upstream from the mouth (fig. 11A). The headcut is in bedrock of the Santa Fe Group of Tertiary age. The 1998 resurvey indicated that the headcut had eroded very little. In 1962 the headcut depth was 0.41 m; in 1998 the depth was 0.33 m. Resurveys in 1993 indicated widening of the channel at station 417 and an increase in cross-sectional area of 0.90 m^2 (22 percent) and 0.59 m^2 (16 percent) at station 468 downstream and station 417 upstream from the headcut, respectively (fig. 4; fig. 11C; table 3).

Channel-Bed Scour and Fill

Measurement of channel scour and fill that continued after the Leopold and others (1966) study are presented here (fig. 12). Between 1964 and 1968, 371 measurements of scour and 32 measurements of fill were made. One measurement of scour was missed on June 10, 1965, but a measurement of fill was recorded. Scour is measured as the difference between the elevation of the bend in the scour chain and the previous surveyed channel-bed elevation.

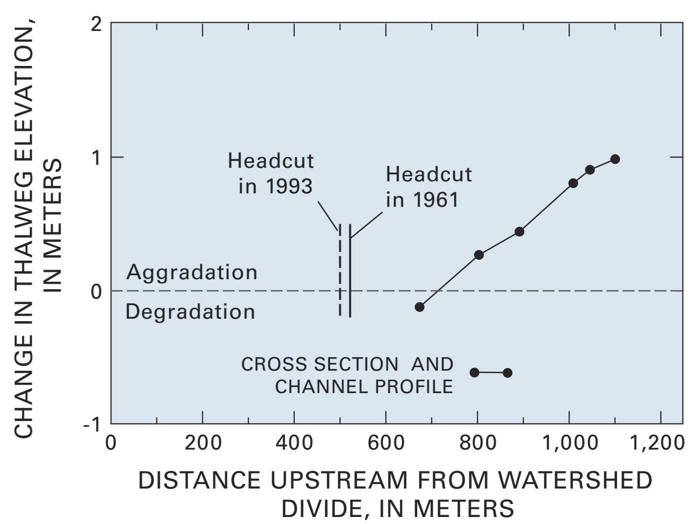


Figure 10. Change in thalweg elevation between the Leopold and others' (1966) original 1961 survey and the 1993 resurvey of channel cross sections in Coyote C. Arroyo.

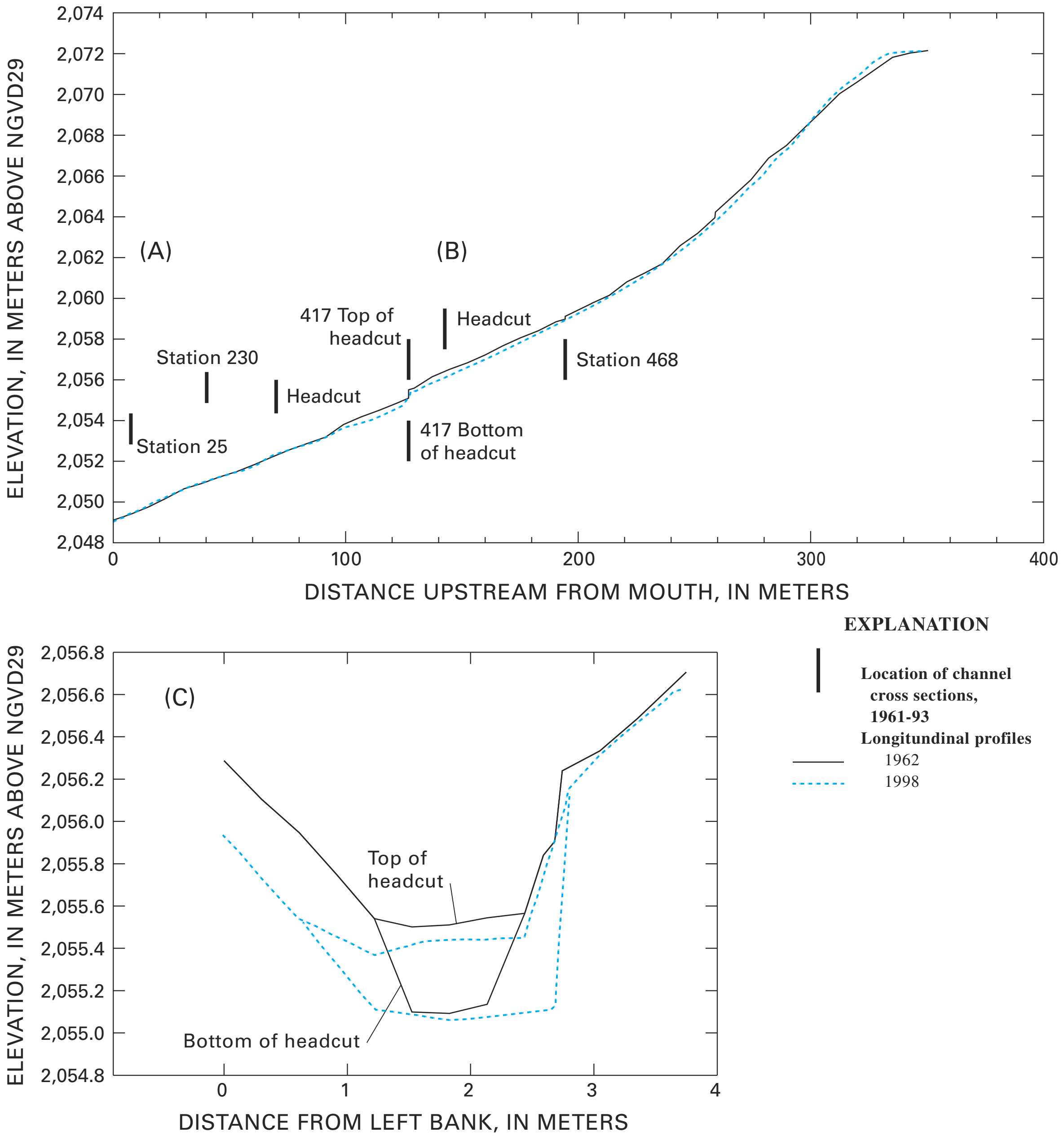


Figure 11. Gunshot Arroyo (A) resurvey of longitudinal profile, 1988, (B) from station 0 to 200 meters and from station 200 to 350 meters, and (C) channel changes at station 417 bottom of headcut and station 417 top of headcut. The longitudinal profile does not extend to the watershed divide.

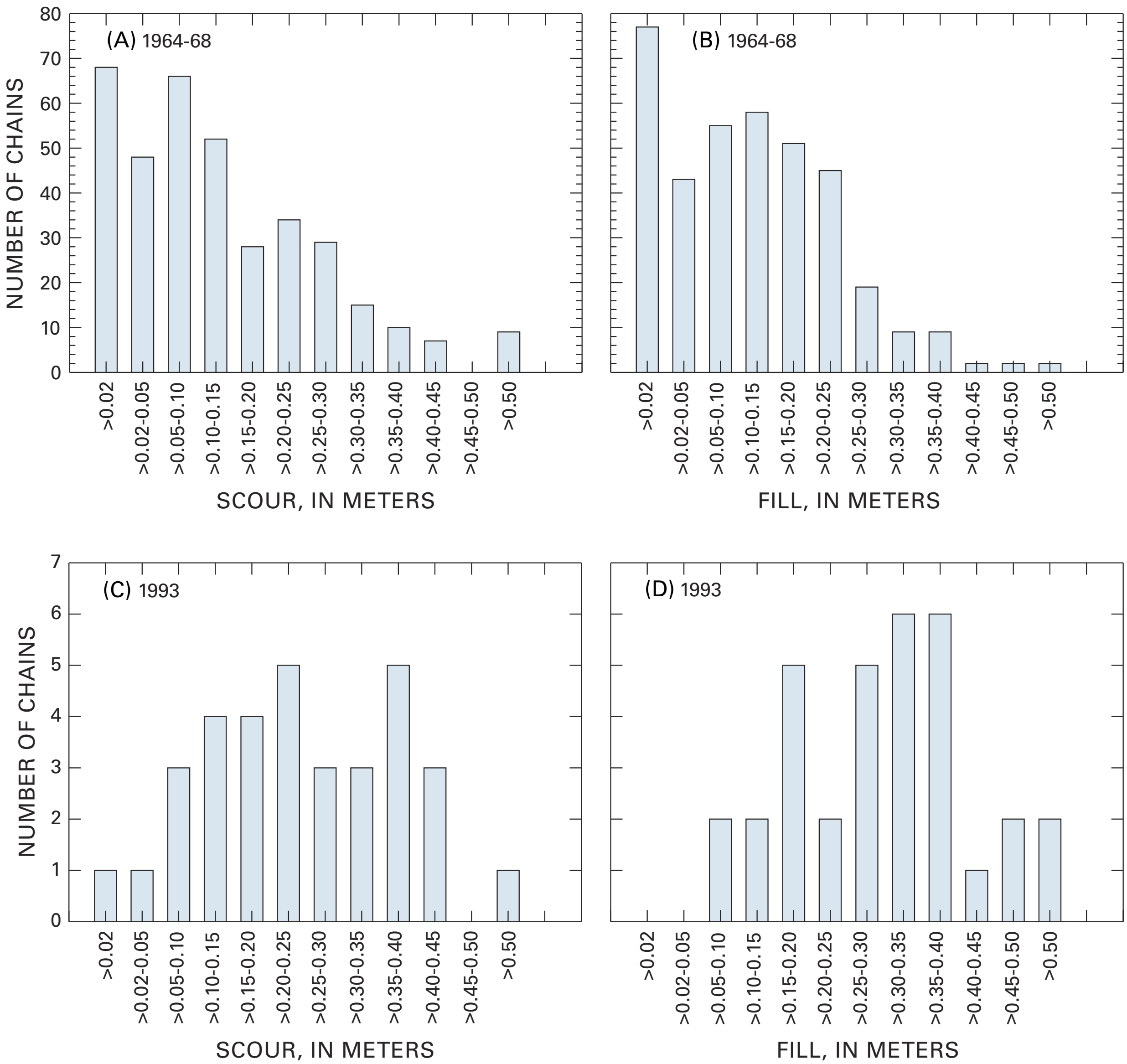


Figure 12. Scour-chain measurements of (A) scour, 1964–68, (B) fill, 1964–68, (C) scour, 1993, and (D) fill, 1993.

If scour occurred, the difference in elevation should be positive. Twenty-seven of the 371 measurements of scour had values between -0.003 and -0.09 m. Twenty-two scour chains measured from -0.003 to -0.091 m were considered within survey error and given a value of zero. The remaining five measurements (-0.03, -0.04, -0.04, -0.05, -0.09) were considered in error and were not used.

The average scour from the 366 measurements was 0.14 ± 0.14 m. About 50 percent of the scour measurements were 0.10 m or less; 11 percent were greater than 0.35 m (fig. 12A). The greatest scour (0.87 m) was measured June 7, 1965, at cross section LW-18 (fig. 1).

From 1964 to 1968, 372 fill measurements were recorded using scour chains. One fill measurement from 1964 to 1968 showed the top of the scour chain to be 0.08 m higher than the current bed elevation. This measurement was given a value of zero. The average fill at all 33 chains was 0.13 m ± 0.11 m. About 47 percent of the fill measured from 1964 to 1968 was less 0.10 m or less (fig. 12B), and about 11 percent of the fill was greater than 0.25 m. The greatest fill (0.72 m) was recorded June 10, 1965, at cross section MPR 67-72.

Fifty-four discharge measurements were made from 1964 to 1968 at three crest-stage stations in the main channel Arroyo de los Frijoles: North Frijoles reach, Locust Tree reach, and Main Project reach (figs. 1 and 3). Peak-discharge measurements were reported for each chain survey at cross sections near the streamflow-gaging stations NFA-Upper, NFA-Lower, LTR 20-24, LTR 30-33, MPR 52-59, and MPR 67-72. These cross sections all contain more than one scour chain, and a mean depth of scour was calculated for these three cross sections by averaging the values of scour from all chains in a cross section. A plot of mean values of scour compared to peak discharge for these unpublished data (54 measurements) combined with data from Leopold and others (1966, fig. 159, p. 222) (83 measurements) indicates results similar to the original study; the average depth of scour is directly proportional to the square root of discharge per unit width of channel (fig. 13).

In 1993, 33 of the original scour chains were located in 20 cross sections in the Arroyo de los Frijoles watershed. Prior to 1993, 3 of the 33 chains were measured in 1964, 14 were measured in 1966, and 16 were measured in 1968. With the exception of cross section 3 at Slopewash Tributary SWT-CS3, all cross sections showed scour. Scour ranged from 0 to 0.52 m; average scour of all 33 chains was 0.24 ± 0.13 m (fig. 12C). Fifty-four percent of the scour ranged from 0 to 0.25 m (fig. 12C), and 15 percent of the scour measured was 0.10 m or less, a smaller percentage than measured from 1964 to 1968 (fig. 12A–C). Twelve percent of the scour was greater than 0.4 m. The greatest scour (0.52 m) was measured at cross section LW-15.

Fill measured atop the chains in Arroyo de los Frijoles in 1993 ranged from 0.08 to 0.54 m (fig. 12D); average deposition was 0.29 ± 0.12 m. Thirty-three percent of the fill measured was less than 0.25 m, and 15 percent of the fill was greater than 0.4 m. The greatest fill (0.54 m) was measured at cross section LW-15. The apparent higher frequency of scour and fill in the intermediate ranges (0.10 to 0.40 m) from 1968 to 1993 (fig. 12C–D) may reflect the longer time period between measurements and a higher probability of more frequent and higher flow events to mobilize sediment in the bed. The higher percentage of lower values measured from 1964 to 1968 is expected because attempts were made to measure the chains immediately after each runoff event, regardless of the magnitude.

The 1993 scour measurements were recorded relative to the last surveyed elevation of the channel. Because the last measurements were made from 1964 to 1968, runoff events prior to 1993 may have raised or lowered the channel bed. The channel elevation immediately prior to the event that caused scour and fill and the chain measurement in 1993 may have been higher or lower than the 1964–68 channel elevation. Thus, the 1993 measurements may be in error. The elevation of the channel has not changed significantly since 1964. If the elevations are assumed to have remained relatively stable since 1964–68, then the scour and fill measurements may represent the largest runoff event since 1964.

Scour and fill for 1968–93 in relation to distance along the main channel Arroyo de los Frijoles are shown in figure 14. Also shown in figure 14 are overall thalweg net changes along the channel. Scour and fill were averaged for four cross sections containing more than one scour chain. No longitudinal trend in scour and fill or in net changes in the channel thalweg was apparent. The maximum scour (0.52 m) and maximum fill (0.54 m) (fig. 14A) occur at the same cross section (LW-15), 1,642 m downstream from the watershed divide at Slopewash Tributary. In 1993, the scour chain was not located in the cross section (LTR 20-24) that showed the greatest amount of thalweg degradation (1.53 m), located immediately downstream from a culvert 2,906 m from the watershed divide at Slopewash Tributary. Extreme scour may have removed the scour chain at this location.

Using data from flume experiments and field studies of steep, sand-bed ephemeral channels, which included data for Arroyo de los Frijoles, Foley (1978) concluded that scour occurs locally at all flows and that streambed elevation changes little over a longer reach. Scour and fill may alternate locally at several locations during a flood. The scour and fill were observed to be from bed-form migrations of antidunes, whereas the streams had flow in the upper flow regime (Foley, 1978). The average depth of maximum scour for a cross section was not considered a good indicator of maximum flow conditions, and data from this study on channel scour between the 1950’s and 1993 may support this idea. Changes in the overall elevation of the main channel Arroyo de los Frijoles are minor, whereas local changes in channel-bed elevation can be greater.

Leopold and others (1966) observed that rainfall events are so intense and localized that only a part of the watershed is affected by runoff. For example, the highest daily rainfall recorded at Santa Fe for 1858–1993 was 92 mm

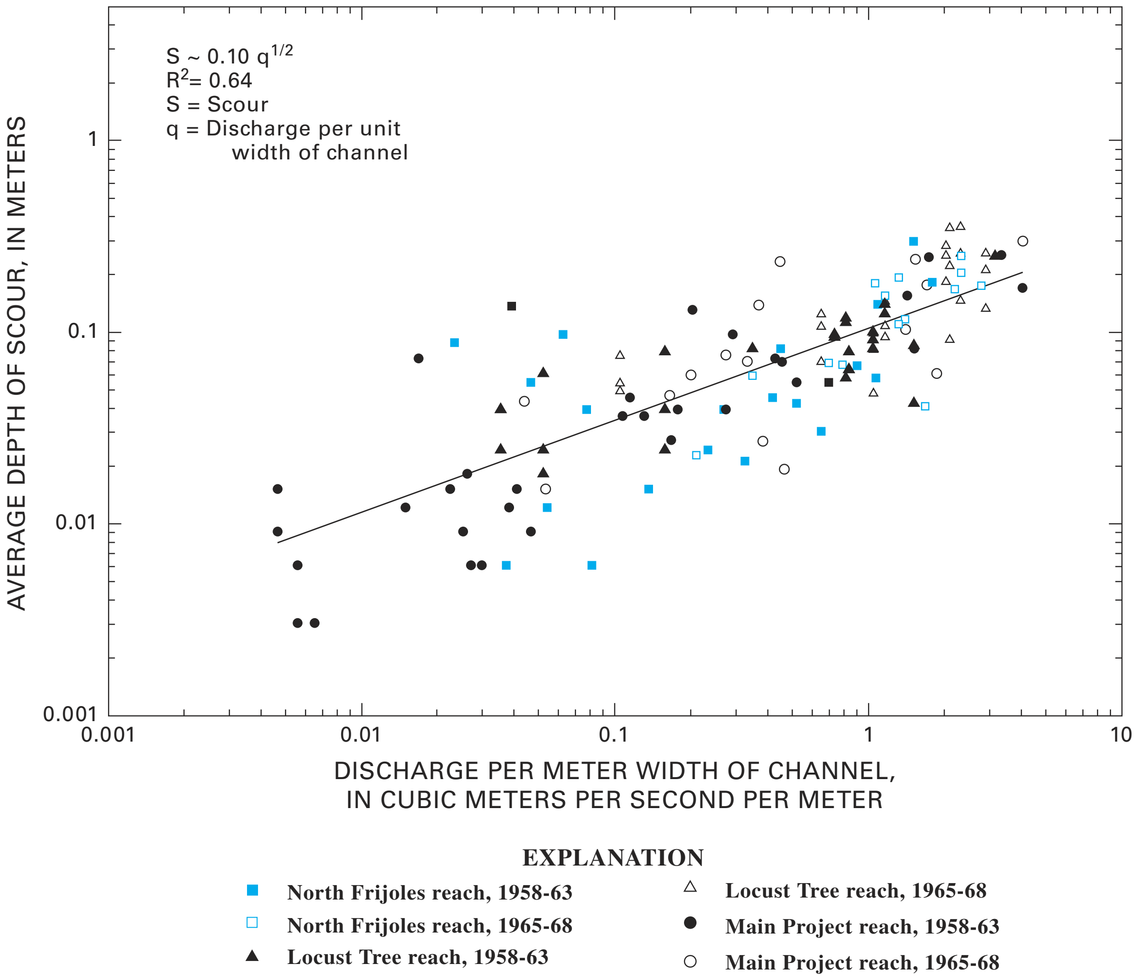


Figure 13. Depth of scour as a function of discharge at scour-chain sections. Each point represents an average scour across the channel bed based on 4–10 chains per cross section. Location of reaches shown in figure 1.

on August 1, 1968, when flow was still being measured in Arroyo de los Frijoles. No streamflow was recorded at the gages. Only twice in the original study period was an increase in discharge observed in the downstream direction. High streamflow in parts of the watershed may have scoured the channels, and sediment may have been deposited in areas of infiltration.

Deposition Behind Dams and Base-Level Experiments

Deposition Behind Dams

A resurvey of the sediment pool behind the earthen dam in Coyote C. Arroyo (fig. 1C and fig. 15) showed that 584 m^3 of sediment was deposited between 1961 and 1993 (table 7). The density of sediment behind the dam is 1,180 kg/m^3, resulting in 689 metric tonnes of sediment or 21.5 metric tonnes/yr. The average annual sediment yield for 1961–93 is 139 metric tonnes/km^2/yr. Earlier surveys of sediment deposition from 1961 to 1963 indicated that the deposition rate was higher in that period than in 1961–93 (table 7) (Leopold and others, 1966). In 32 years, deposition decreased nearly an order of magnitude, from 172 to 21.5 metric tonnes/yr (table 7). Average annual rainfall did not change from 1961 to 1993 (table 1); therefore, changes in depositional rates are not likely due to changes in rainfall and runoff. Instead, deposition may be due to changes in the trap efficiency of the structure, which would decrease over time (Vanoni, 1977), and(or) to a decrease in sediment delivery because of upstream channel storage.

Sediment yields reported for Coyote C. Arroyo and for the Slopewash Tributary erosion plot are in the range of average sediment yields reported for New Mexico (table 8). The sediment-yield values in table 8 were obtained from suspended-sediment data that did not include bedload. If bedload data were included, the sediment-yield values in table 8 would be higher.

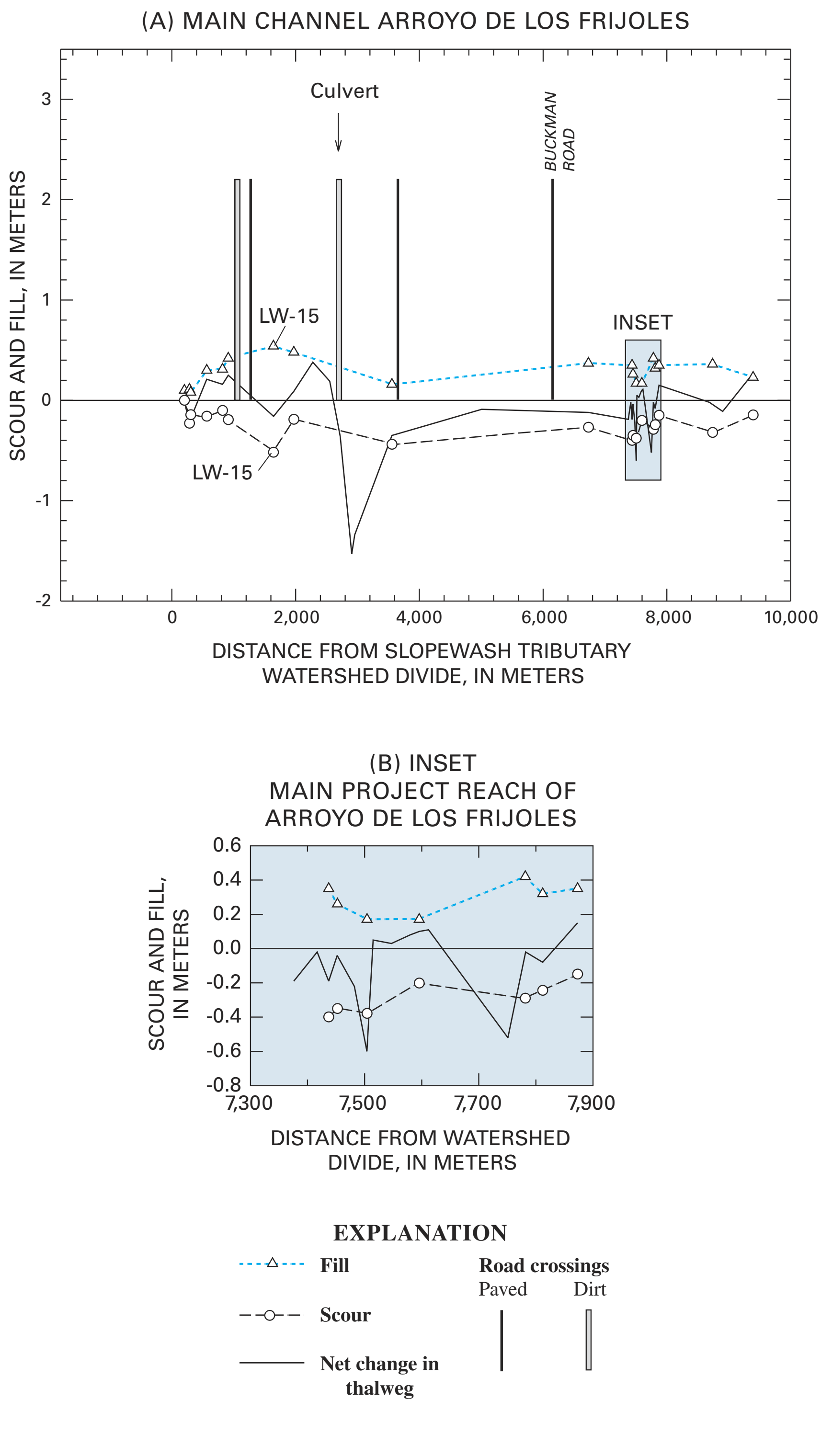


Figure 14. Scour and fill from 1993 resurveys of scour chains at (A) main channel Arroyo de los Frijoles, and (B) Main Project reach in Arroyo de los Frijoles plotted with net change in thalweg from 1993 and 1997 resurveys. Location of reaches in figure 1.

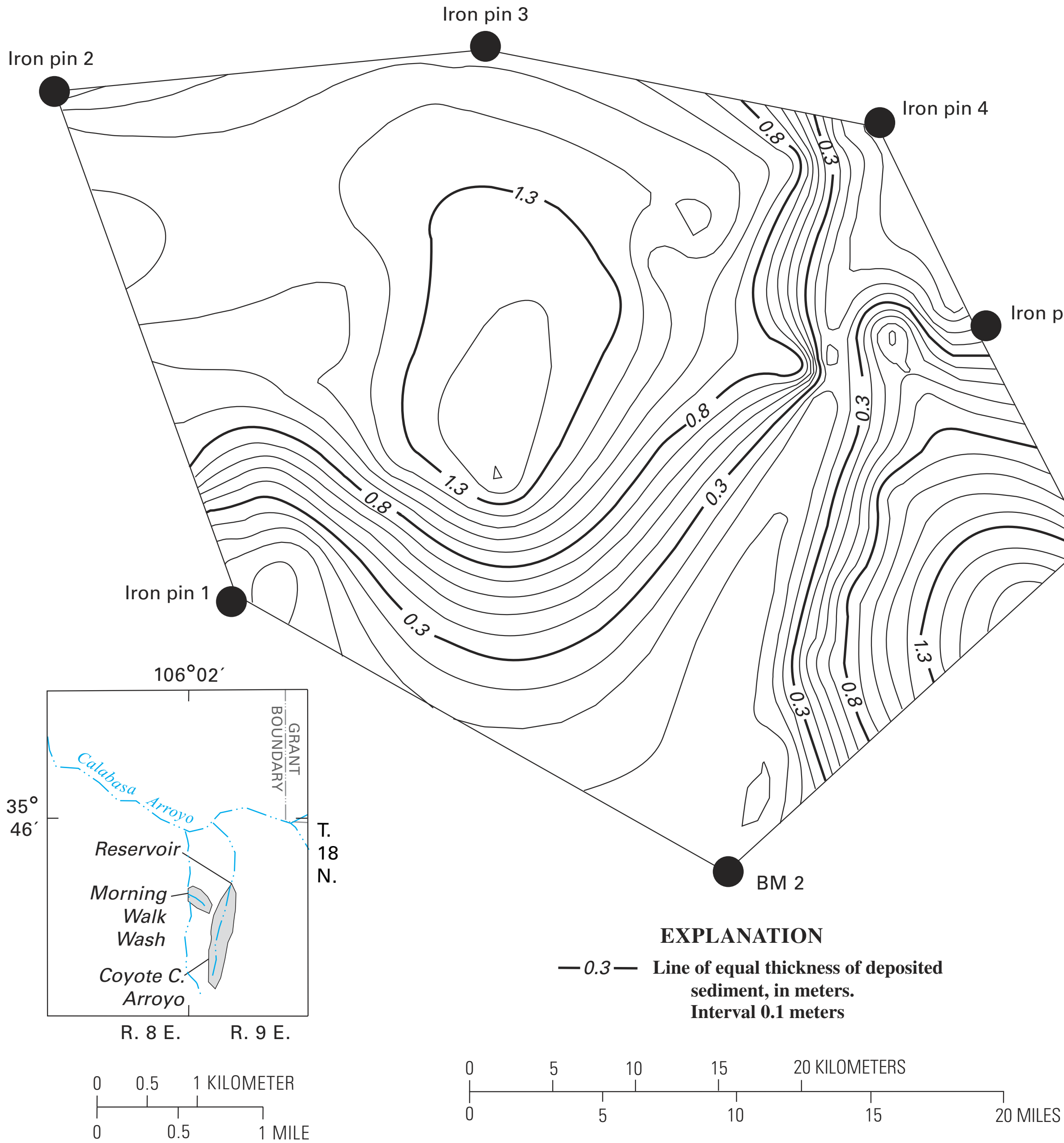


Figure 15. Thickness map of sediment deposited at reservoir on Coyote C. Arroyo. Location of reservoir shown in figure 1C.

Table 7. (A) Deposition rates in the sediment pool behind the earthen dam at Coyote C. Arroyo, 1961–93. (B) Sedimentation rates for selected time periods at Coyote C. Arroyo.

[km^2, square kilometer; m^3, cubic meter]

(A)

Drainage area (km^2)	Total sediment deposition (m^3)	Sediment yield (tonnes/ km^2/year)
0.155	584	139

(B)

	Selected time period			
	1961–62	1961–63	1961–64	1961–93
Metric tonnes per year	172	98.1	69.5	21.5

Base-Level Experiments

By analyzing deposition behind Big Sweat Dam, Leopold and Bull (1979) determined that the longitudinal profile of the channel had changed 15.2 m upstream 2 years after construction and 24.4 m upstream after 4 years. Photographs showing Big Sweat Dam in 1960 shortly after construction and in 1998 illustrating deposition behind the dam are shown in figure 16. From 1960 to 1964, channel slope decreased from 0.045 to 0.033 (27 percent) (Leopold and Bull, 1979, p. 189). From 1964 to 1974, the effect of increased base level did not extend beyond 30.5 m upstream, and channel slope remained at 0.033 (Leopold and Bull, 1979, p. 189).

In 1993, Big Sweat and Little Sweat Dams were still intact (figs. 16, 17). Changes in the profile of deposition behind the dam are reported for the same cross sections as in the original survey. Deposition behind Big Sweat Dam extended about 20 m upstream to cross section O (fig. 17A,B). Weighted slopes of the channel from 0 to 9.1 m above the dam remained constant (within 0.04 m/m) from 1968 to 1993 (table 9A). Reaches less than 5.3 m above the dam, however, had varying slopes from 1960 to 1993 (table 9A). The overall elevation of the sediment surface behind Big Sweat Dam was lower in 1993 than in 1968 and 1974 (fig. 17A,B). The lower elevation may be due to the sediment pool behind the dam filling in, which has led subsequently to local scour.

Table 8. Selected summary of sediment yields in New Mexico streams.

[km^2/yr, square kilometers per year; USGS, U.S. Geological Survey]

Location	Period of observation	Drainage area (km^2)	Average annual sediment yield (metric tonnes/km^2/yr)	Reference
Rio Puerco above Arroyo Chico	1949–55; 1958–95	1,088	732	USGS New Mexico Water-Data Reports
Arroyo Chico near Guadalupe	1949–55; 1979–86	3,600	487	USGS New Mexico Water-Data Reports
Rio San Jose at Correo	1949–55	6.760	71.6	USGS New Mexico Water-Data Reports
Rio Puerco at Bernardo	1948–96	19,036	212	USGS New Mexico Water-Data Reports
Rio Santa Cruz at Santa Cruz Reservoir	1929–41	238	354	Brown, 1945
Gallinas River at Storrie Reservoir near Las Vegas	1918–40	386	144	Brown, 1945
Jemez Creek at San Ysidro	1936–41	2,212	254	Brown, 1945
Rio (Arroyo) Salado at San Ysidro	1937–40	324	257	Brown, 1945
Rio Grande at San Marcial[1]	1948–73	64,128	104	USGS New Mexico Water-Data Reports
Coyote C. Arroyo	1961–93	0.155	110	Current study
Big Sweat Dam	1960–93	0.015	21.4	Current study
Little Sweat Dam	1960–93	0.0034	31.6	Current study

[1]Measurements before closure of Cochiti Reservoir.

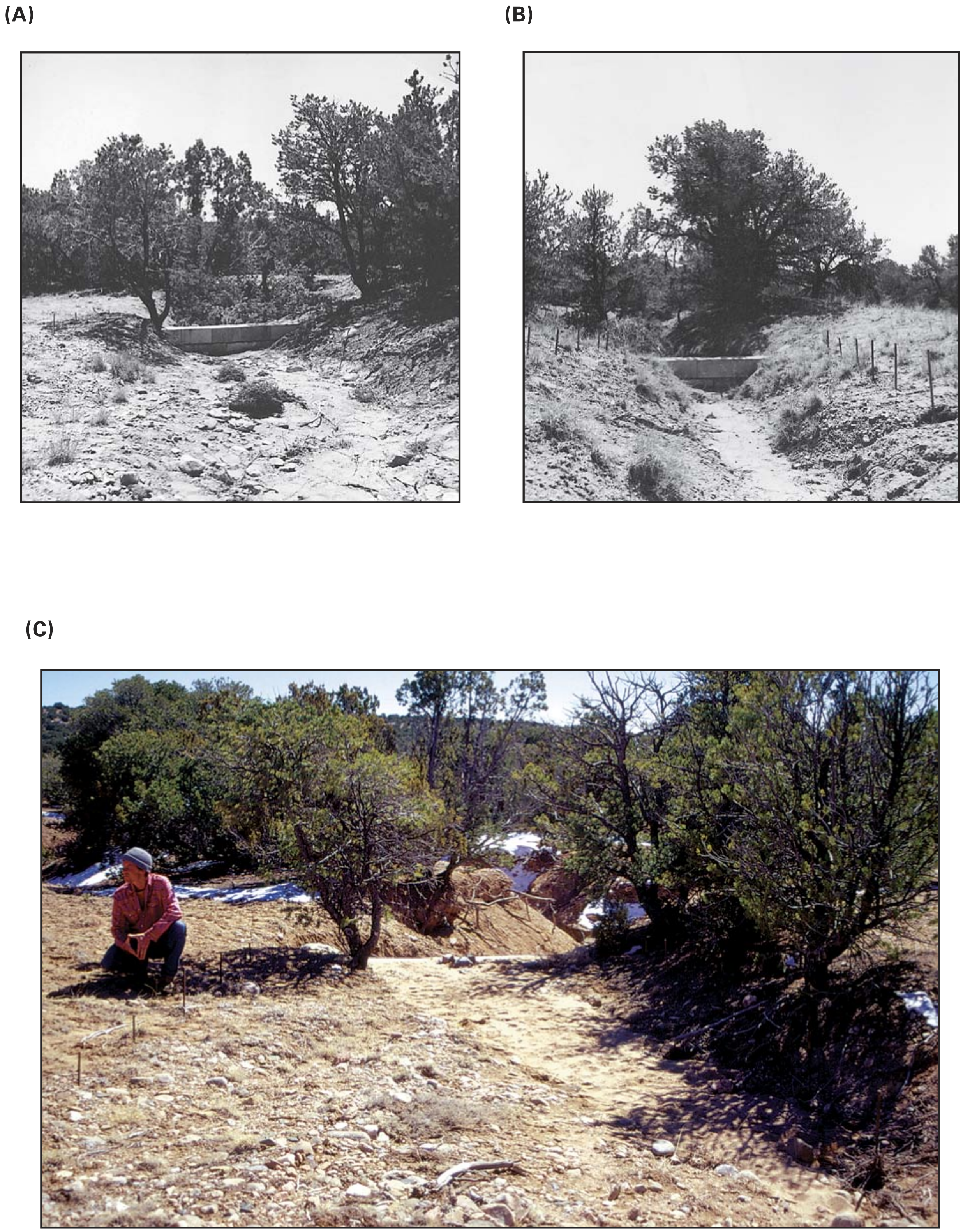


Figure 16. (A) View looking downstream toward Big Sweat Dam shortly after its construction in 1960. (B) Little Sweat Dam, 1960. (C) View looking downstream toward Big Sweat Dam, 1998. Location of dams shown in figure 1B.

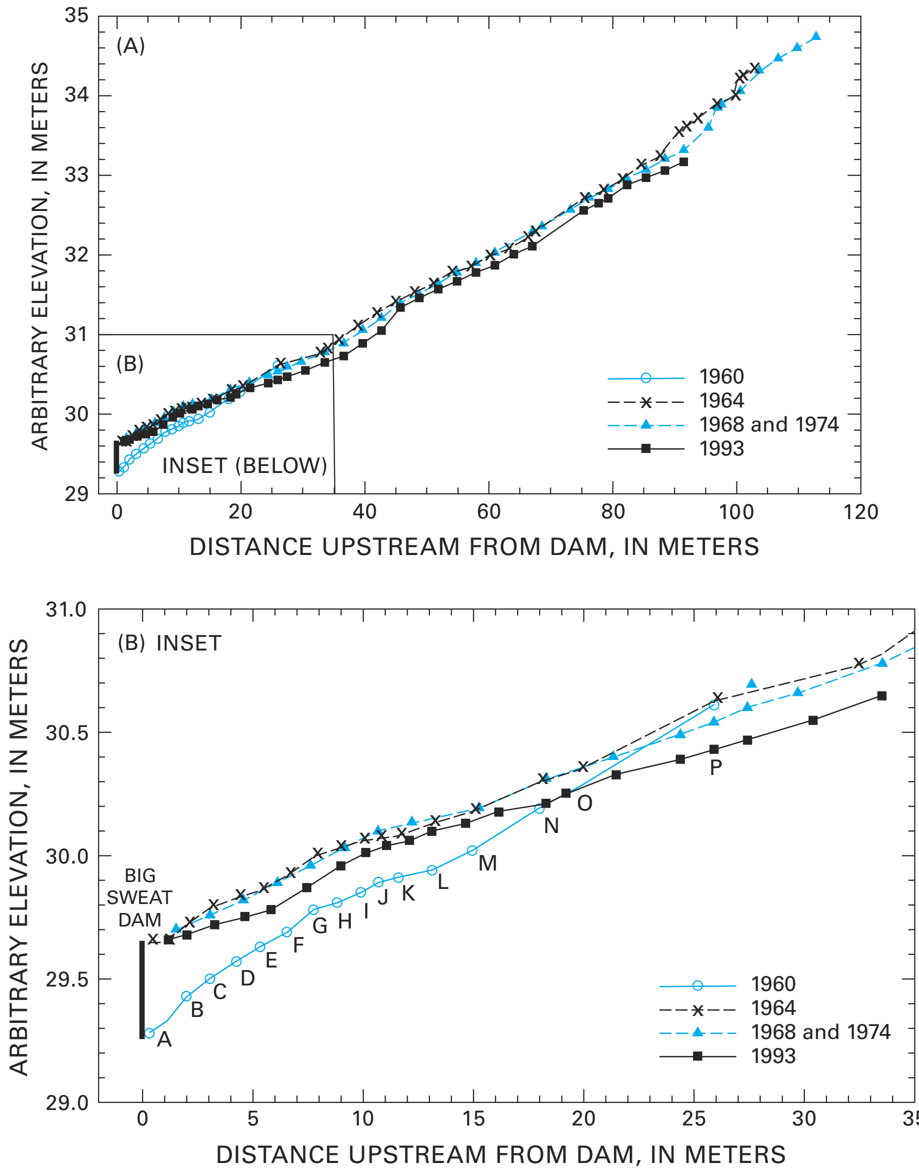
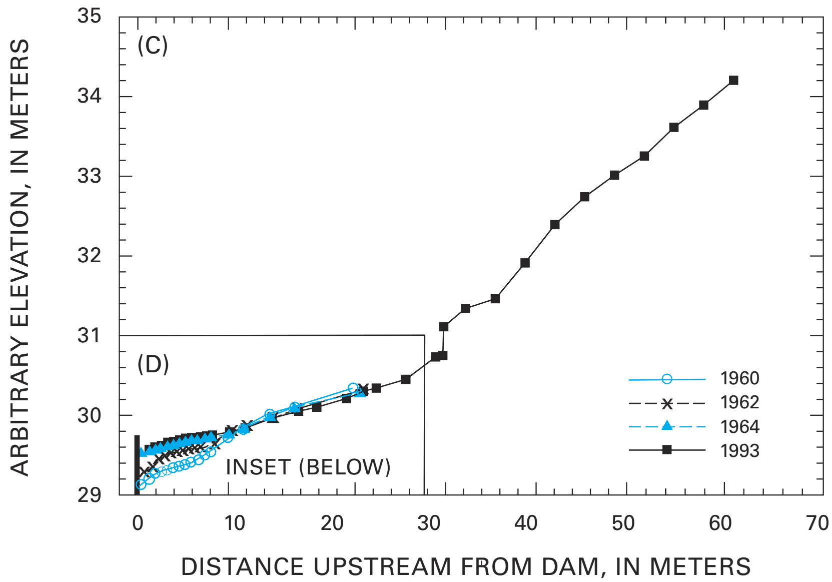


Figure 17. Successive channel-bed profiles of: (A) Entire length of channel upstream from Big Sweat Dam. (B) Profiles of the channel within 35 meters of the dam showing locations of resurveyed channel cross sections.

Data collected for Little Sweat Dam have not been previously published. Surveys conducted in 1962, 1964, and 1993 are shown in figure 17. Two years after construction, the channel-bed profile had been affected by deposition about 9.3 m upstream from the dam (fig. 17). From 1964 to 1993, little deposition extended to 9.3 m upstream from the dam (fig. 17C,D). Channel gradients 0 to 11 m upstream have remained constant at about 0.028 from 1964 to 1993. By 1962, the channel gradient had decreased 0.011 m/m (17 percent) 11.0 m upstream from the dam. From 1962 to 1964, the weighted slope decreased 0.026 m/m (53 percent) (table 9B). Channel-weighted slope from 0 to 11.0 m upstream from the dam ranged from 0.029 in 1964 to 0.027 in 1993. The interpretation of changes in Little Sweat Dam is similar to Leopold and Bull’s (1979) interpreted changes in Big Sweat Dam; the channel-weighted slope remained about constant from 1960 to 1964 from about 9 to 23 m above the dam. The elevation of the sediment surface has changed little since 1964.

The 1993 resurveys and earlier surveys of Big Sweat Dam differ in the interpretation of channel gradients. The



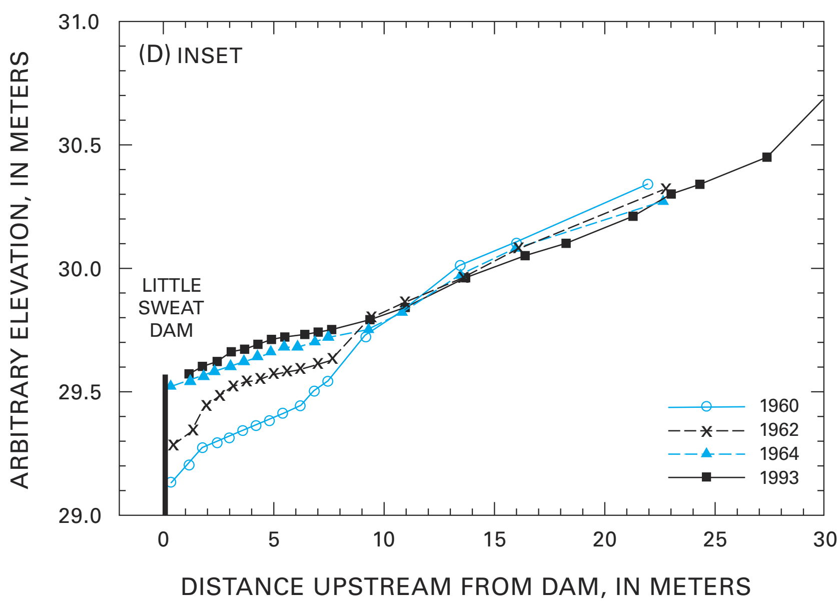


Figure 17. (C) Entire length of channel upstream from Little Sweat Dam. (D) Profiles of the channel within 30 meters of the dam showing locations of resurveyed channel cross sections.

Table 9. Weighted slopes of channel upstream from Big Sweat Dam and Little Sweat Dam near Santa Fe, New Mexico.

[--, no data]

(A)	Big Sweat Dam				
	Weighted slopes, in meters per meter				
Reach upstream from dam, in meters (figure 1)	1960 (original)	1964	1968	1974	1993
0 to 5.3	0.069	0.043	0.038	--	0.027
0 to 9.1	0.062	0.044	0.041	--	0.044
0 to 18.3	0.051	0.039	0.036	0.037	0.035
0 to 25.9	0.048	0.035	0.034	0.036	0.036
0 to 33.5	0.042	0.045	0.033	0.033	0.034
33.5 to 67.0	0.045	0.044	0.045	--	0.045
67.0 to 91.4	--	0.077	0.042	--	0.044
67 to 100.6	0.052	0.059	0.053	--	

(B)	Little Sweat Dam			
	Weighted slopes, in meters per meter			
Reach upstream from dam, in meters (figure 1)	1960 (original)	1962	1964	1993
0 to 7.6	0.058	0.049	0.028	0.028
0 to 11.0	0.066	0.055	0.029	0.027
11.0 to 22.9	0.047	0.024	0.028	0.034
11.0 to 61.0	--	--	--	0.093

disparity between Leopold and Bull's (1979) determination of deposition to 30.5 m upstream and the value of 20 m reported here is due to a general lowering of the profile from 1964 to 1993 (fig. 17). Although the trap efficiency of the dam was not calculated, the sediment wedge in 1993 was at the top of the dam; therefore, some sediment was transported downstream. The reaches close to the dam, within 5.3 m, indicate fluctuations in channel gradient through the period of record (table 9). Local steepening of the slope in these reaches may possibly have led to minor incision and thus the lowering of the profile in figure 17. The sinuosity of the thalweg has also increased over time and may have caused some local scour (fig. 18). Differences in locations through time used to survey the channel profile may also cause some error in duplication of the channel profile.

The changes in the profile of sediment deposited behind Big Sweat Dam were reported as the thalweg elevation of each cross section upstream from the dam. The stationing of each cross section was a straight-line distance up the middle of the channel. A plot of the thalweg location on each cross section shows an increase in sinuosity from 1960 to 1993 (fig. 18). Therefore, figure 17 is not a longitudinal profile of the channel over time because the stationing was not along the thalweg, but is rather a change in thalweg elevation at cross-sectional locations. Because of the reduced slope associated with the increased length of the thalweg, the profile in figure 17 would show a decrease in elevation over time if it were a longitudinal profile. The increase in sinuosity may have resulted in the reduction in channel gradient over time. As channel gradient decreases, sinuosity increases (Schumm, 1977). Many of the increases in sinuosity were observed in flumes or controlled experiments (Schumm and Khan, 1972). The same changes were observed at the scale of Big Sweat Dam.

Hillslope-Erosion Plots

All 65 pins in Coyote C. Arroyo were located and measured in 1993, but the tops of the pins were surveyed only once, in 1962. Surveys of the tops of the pins in 1961 showed elevation differences as large as 2.8 cm, averaging 0.1 cm with a standard deviation of ± 0.7 cm (U.S. Geological Survey,

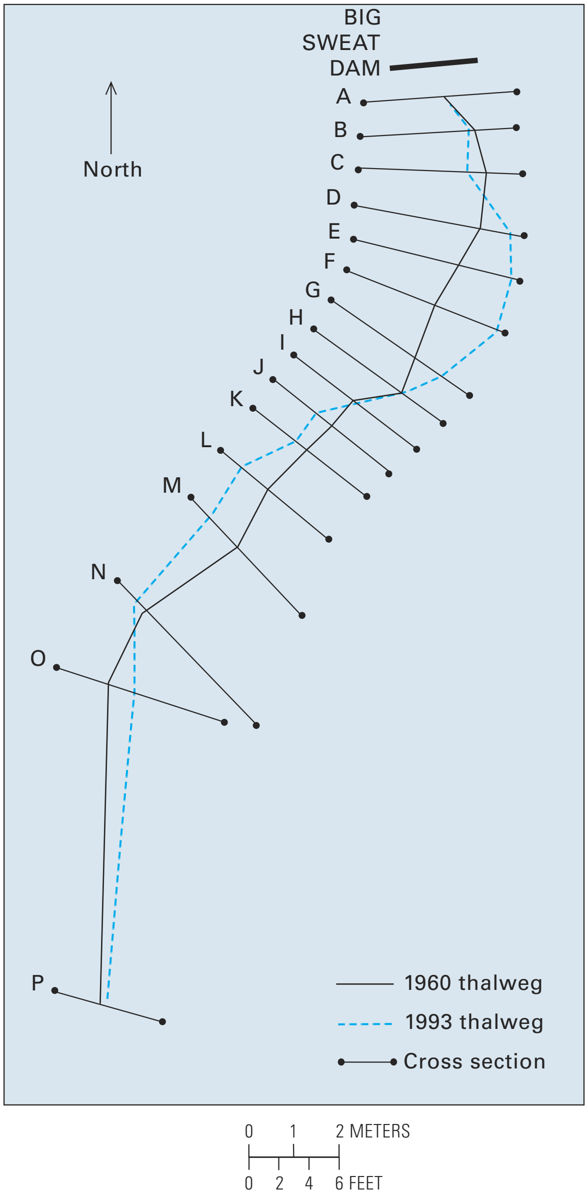


Figure 18. Planform diagram of 1960 and 1993 thalweg locations upstream from Big Sweat Dam. See photographs in figure 16.

unpublished data). Although this difference in pin elevations for 1 year is minimal, the changes in pin elevations after 30 years may be substantial if the direction of change in nail elevations is consistent over time.

Without level surveys to periodically check the elevations of short pins, factors such as soil heave and wetting and drying of the soil may result in erroneous readings. Therefore, the results presented in this report should be viewed with caution. Average deposition for the three erosion-pin lines ranged from 1.45 to 2.56 cm, and average erosion ranged from 2.64 to 4.54 cm (table 10). The average change in ground surface showed erosion for all three lines (table 10).

In 1993, 25 of the 61 pins were located, surveyed, and measured in Slopewash Tributary (fig. 19). Surveys of the top of the pins in 1993 indicated that most pins had changed in elevation and, therefore, that soil heave may have moved the pins. The maximum increase in pin-head elevation from soil heave from 1959 to 1993 was 1.31 cm, and the maximum decrease in elevation was 0.61 cm. The average change in the tops of all pin heads was a decrease in elevation of 0.02 cm. Erosion is measured from the bottom of the pin head to the top of the washer, and differences in pin-head elevation over time alter the erosion measurement. To correct for changes in pin-head elevation, the difference in elevation from the 1959 survey to the 1993 survey was either added to or subtracted from the measured erosion, depending on whether the pin-head elevation had increased or decreased over time. Deposition is the depth of sediment above the washer, and the washer was assumed to be unaffected by changes in the top of the pin.

Measurements at the Slopewash Tributary erosion plot indicate that average erosion at the 25 pins was 2.64 cm. The spacing of the pins was 1.524 m, and the total area was 2.322 m^2 for each square in the grid. Only 25 pins were recovered, resulting in a total area of about 58 m^2 for the erosion measurements. The total volume of eroded soil for the entire grid was estimated by averaging the change in ground surface for all pins and multiplying by 58 m^2. The total volume of eroded material from 1959 to 1993 was 0.377 m^3 or 0.011 m^3/yr. By using a dry density of 1,603 kg/m^3, the total

Table 10. Summary of erosion-pin measurements at hillslope-erosion plots at Coyote C. Arroyo and Slopewash Tributary.

[cm/yr, centimeters per year]

Site	Original date	Average erosion (cm)	Average deposition (cm)	Average change in land surface (cm)	Average change in surface erosion (cm/yr)
Coyote C. Arroyo, line BA	1961–93	-4.54	1.45	-3.09	-0.096
Coyote C. Arroyo, line BC	1961–93	-4.52	2.13	-2.39	-0.075
Coyote C. Arroyo, line ED	1961–93	-4.43	2.56	-1.87	-0.058
Slopewash Tributary, plot A	1959–93	-2.64	1.99	-0.65	-0.019

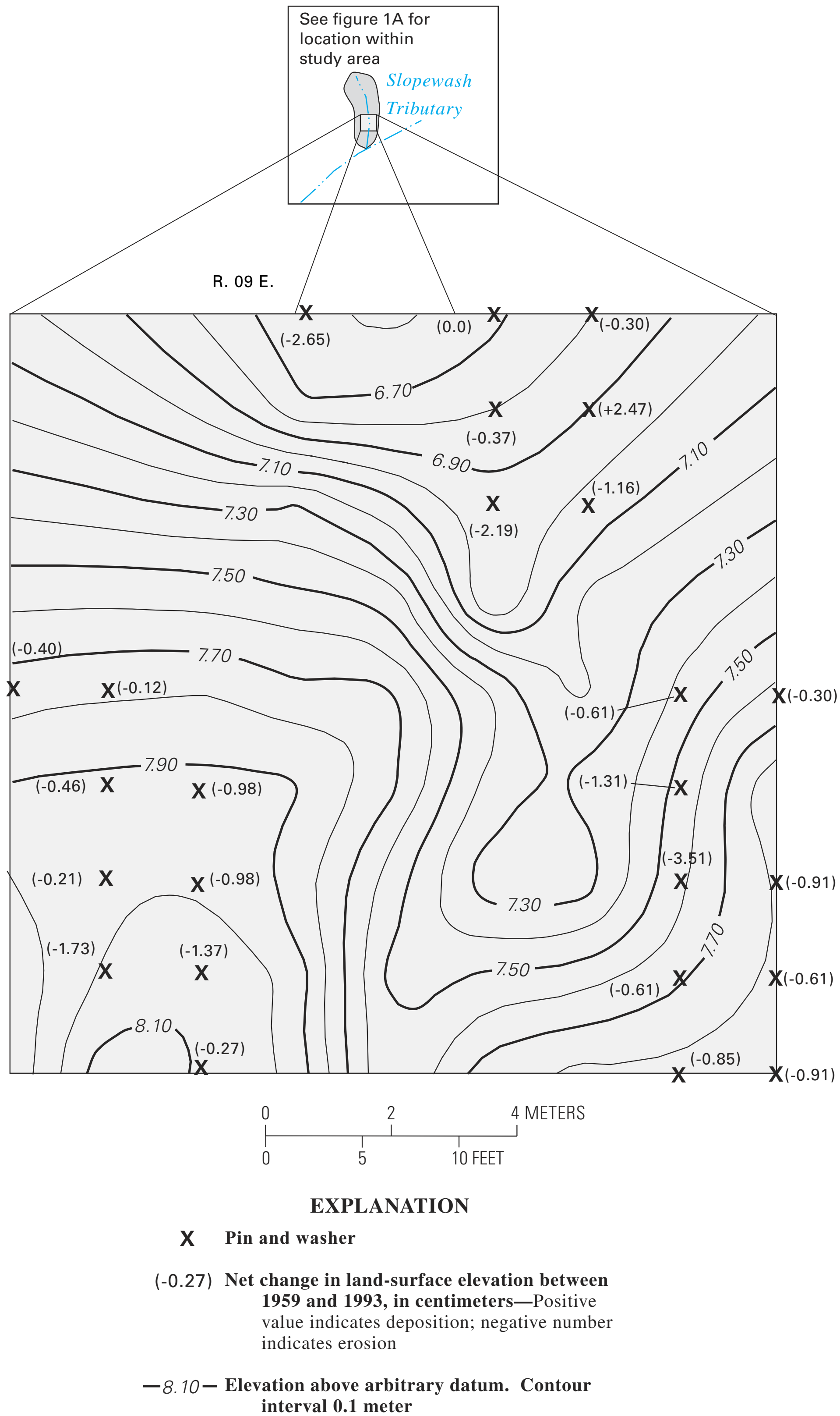


Figure 19. Hillside containing pin and washer lines in an erosion plot on Slopewash Tributary. Location of tributary shown in figure 1.

mass of sediment eroded was about 604 kg or 17.8 kg/yr. This value divided by the 58-m^2 area of the erosion plot results in an annual sediment yield of about 307 metric tonnes/km^2/yr at the Slopewash Tributary plot.

The average values of surface erosion reported here are within those of surface erosion and denudation rates reported for the Southwest, which range from 0.005 to 7.3 mm/yr (table 11). The erosion rates from this study are generally higher than the denudation rates reported at a geologic time scale (greater than 1 million years) (table 11) and may be due to differences in measurements over different time scales. On a geologic time scale, periods of erosion may be interrupted by periods of stability. A high surface-erosion rate (7.3 mm) (table 11) followed the 1977 La Mesa fire in the Jemez Mountains, New Mexico (fig. 1) (White and Wells, 1979).

Changes in Land Use

The Main Project reach in Arroyo de los Frijoles (fig. 1) is only 6.5 km from the downtown plaza in Santa Fe. Because of its proximity to Santa Fe, the study area has become increasingly residential since the Leopold and others' (1966) study. The 1952 and 1953 USGS topographic maps (1:24,000 scale) for the Arroyo de los Frijoles watershed show one house in the watershed; the 1993 maps (1:24,000 scale) show 52 houses. The number of houses may now (2001) be greater because of housing construction observed during the 1993 and 1997 resurveys.

The population of Santa Fe County in 1950 was 38,153 (U.S. Department of Commerce, 1952) and in 1990 was 98,928 (U.S. Department of Commerce, 1990), a 159-percent increase. In 1950, the population of Santa Fe was 27,998 (U.S. Department of Commerce, 1952) and in 1990 was 55,859 (U.S. Department of Commerce, 1990), nearly a 100-percent increase.

Road changes from 1952 to 1987 in the Arroyo de los Frijoles watershed, determined from aerial photographs (1:19,800 scale) taken in 1952–53 and aerial photographs (1:24,000 scale) taken in 1987 indicate an increase in total road length (fig. 20). Total road length in the watershed in 1952 was 11,980 m and in 1987 was 27,790 m, a 132-percent increase. With an increase in population, an increase in roads is expected. On the basis of field work in the area from 1993 to 1998, most roads appear to have been built for access to housing subdivisions.

Road crossings are affecting degradation and aggradation of the main channel Arroyo de los Frijoles (fig. 21). The change in channel elevation over the resurvey period clearly

Table 11. Surface-erosion and denudation rates reported from studies conducted in the Southwest.

[mm/yr, millimeters per year; Ma, million years]

Location	Time period analyzed	Erosion/ denudation rate (mm/yr)	Geology	Method of analysis	Reference
Jemez Mountains, New Mexico	1.14 Ma	0.005 to 0.011	Rhyolitic volcanic rocks	Cosmogenic nuclides	Albrecht and others, 1993
Jemez Mountains, New Mexico	10/1977 to 11/1978	0.8 to 7.3	Rhyolitic volcanic rocks	Erosion pins	White and Wells, 1979
Western Espa–ola Basin, New Mexico	1.1 Ma	0.1	Weakly lithified sandstone	Hypsometric	Dethier and others, 1988
Western Espa–ola Basin, New Mexico	1.1 Ma	0.07	Indurated tuff/boulder gravel	Hypsometric	Dethier and others, 1988
Western Espa–ola Basin, New Mexico	1.1 Ma	0.04	Indurated tuff/basalt	Hypsometric	Dethier and others, 1988
Red River Basin, Texas	3 Ma	0.47	Poorly consolidated shale, siltstone, and sandstone	Hypsometric	Gustavson and others, 1981
Red River Basin, Texas	10/1978 to 9/1979	0.13 to 1.27	Poorly consolidated shale, siltstone, and sandstone	Suspended-sediment analysis	Gustavson and others, 1981
Four reservoirs in the Rolling Plains area, Texas	9 to 33 years	0.61 to 2.97	Poorly consolidated shale, siltstone, and sandstone	Reservoir sedimentation rates	Gustavson and others, 1981
Rio Puerco Basin, New Mexico	10,000 years	0.1	Sandstone	Cosmogenic nuclides	Clapp and others, 1997
Arroyo de los Frijoles watershed, Santa Fe, New Mexico	1961–93	0.19 to 0.96	Unconsolidated gravel, sand, and silt	Erosion pins	Current study

was largest where human effects are noticeable on the main channel Arroyo de los Frijoles (fig. 21). The effect of road crossings can be observed in the channel cross-sectional resurveys. The greatest degradation of the main channel Arroyo de los Frijoles, 1.53 m, and the greatest aggradation, 0.38 m, are downstream and upstream, respectively, from a culvert in a dirt road (fig. 21). Five of the resurveyed cross sections were located downstream from this culvert (fig. 21). Field inspection of eight of the nine roads crossing the main channel Arroyo de los Frijoles indicated that four of the roads had a noticeable effect of either degradation or aggradation on the channel.

Summary

Detailed documentation of geomorphic changes in the landscape of more than a few years is rarely possible. The Vigil Network was established for such a purpose. In the 1950's and 1960's, channel cross sections, sediment deposition behind dams, and hillslope-erosion plots in several small watersheds near Santa Fe, New Mexico, were monumented using concepts established in the Vigil Network to measure erosion and deposition. These geomorphic features were resurveyed in the 1990's and provided the opportunity to assess

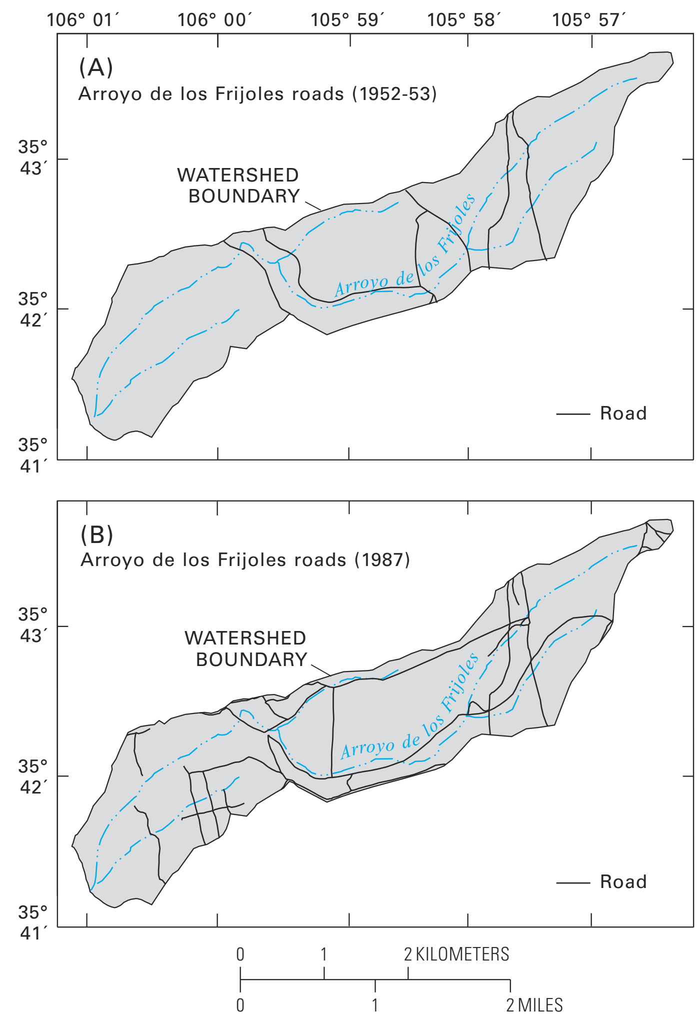


Figure 20. Roads in Arroyo de los Frijoles (A) in 1952–53 and (B) in 1987.

(A)

(B)

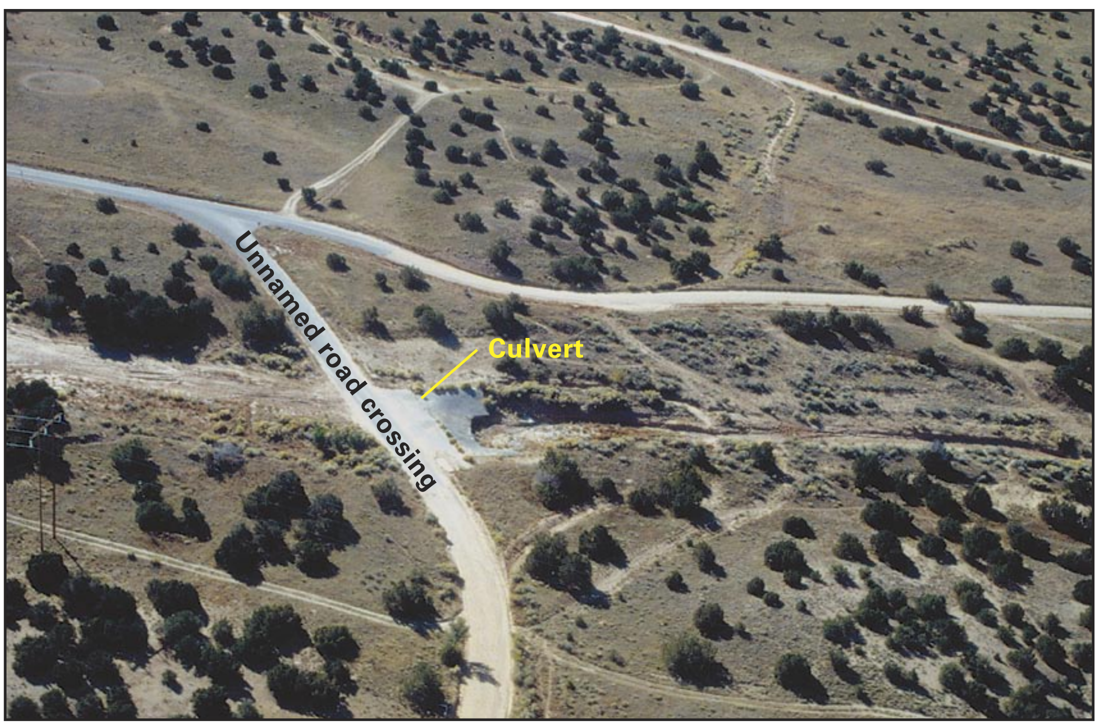


Figure 21. Road crossings over the main channel Arroyo de los Frijoles. (A) Buckman Road 6,662 meters downstream from the Slopewash Tributary watershed divide. (B) Unnamed road crossing with culvert 2,700 meters downstream from Slopewash Tributary. This crossing contained the cross section with highest aggradation upstream and downstream from the culvert.

more than 30 years of geomorphic change. In addition to the resurveys in the 1990's, data are presented that were collected in the original study on channel scour but never published.

In 1993 and 1997, 51 of the original 79 cross sections were located and resurveyed, from which 32 cross sections were used to measure changes in cross-sectional area and 19 cross sections were used to measure changes in thalweg elevation for the cross sections. The cross sections were originally monumented with steel bars. Elevation of the steel bars had not changed much over 30 years, averaging 0.8 cm for the 41 cross sections, within the normal surveying error of 1.5 cm. A comprehensive study of Arroyo de los Frijoles in 1966 concluded that the main channel Arroyo de los Frijoles was aggrading. Results from mid-1990's resurveys of many of the same locations show that this trend did not continue. The average change in cross-sectional area for 32 resurveyed cross sections was erosion of 0.27 m^2 or a 4-percent increase in cross-sectional area. The average net change in thalweg elevation for 51 resurveyed cross sections was degradation of 0.04 m. Aggradation and degradation of the channel appear to vary through the watershed where several adjoining cross sections have the same trend in net thalweg elevation changes over time. Infiltration in the channel bed allows sites of deposition, and sites of heavy localized rainfall and tributary runoff may cause local scour. A 1978 study that used data from flume studies and field data from Arroyo de los Frijoles concluded that scour occurs locally at all flows and may be due to bedform migration of antidunes.

Unpublished data (1964–68) for the scour chains showed that 371 chains had an average scour of 0.14 ± 0.14 m. About 50 percent of the scour measurements were less than 0.10 m, and 10 percent were greater than 0.32 m. Fill measured at 372 chains shows an average of 0.13 ± 0.11 m. Forty-seven percent of the fill was less than 0.10 m, and 11 percent was greater than 0.25 m. Scour, found in the original study (1958–64) to be proportional to the square root of discharge, was confirmed with the addition of the 1964–68 unpublished data. In 1993, 33 of the original scour chains were located in 20 cross sections in the Arroyo de los Frijoles watershed. In the 25–29 years since the scour chains were last read, scour ranged from 0 to 0.52 m and averaged 0.24 ± 0.13 m. Deposition atop the scour chains ranged from 0.08 to 0.54 m and averaged 0.29 ± 0.12 m. Observed changes in scour and fill have no consistent trend related to distance from the watershed divide.

Arroyo de los Frijoles is 6.5 km from Santa Fe, and an increase in housing and population has led to an increase in roads between 1952–53 and 1987. Channel degradation is more noticeable at road crossings. The greatest degradation of the main channel Arroyo de los Frijoles, 1.53 m, and the greatest aggradation, 0.38 m, occur downstream and upstream, respectively, from a culvert in a dirt road.

Average annual rainfall intensities were high in the 1853–80 period that immediately preceded late 19th century arroyo incision and another period of high-intensity rainfall beginning in 1967. On the basis of a previous method used to interpret average annual rainfall intensity, rainfall since 1967 may indicate that climatic factors are again favorable for arroyo incision in this part of New Mexico. However, data from the channel surveys for this study do not support evidence for a renewed cycle of erosion.

For a 1930's Civilian Conservation Corps-constructed earthen dam on Coyote C. Arroyo, sediment yield measured from 1966 to 1993 was 139 metric tonnes/km^2/yr. Sediment yields have decreased over time from a decrease in the trap efficiency of the reservoir during the measurement period and(or) from a decrease in sediment delivery due to upstream channel storage. The effects of base-level rise on the channel profile behind two small dams, Big Sweat and Little Sweat, built in 1960, were documented through resurveys in 1993. The resurveys showed that deposition extended 20 and 9.3 m upstream, respectively, and that the final sediment gradient is nearly the same as the unaffected channel upstream. Big Sweat Dam showed fluctuations in channel gradient within 5.3 m of the dam, which may be due to local scour following complete filling of the dam, scour due to increased sinuosity, or differences in surveying stations over time. The sinuosity of the channel has increased over time, presumably from a reduction in slope. Channel gradients 0 to 11.0 m upstream from Little Sweat Dam have remained constant at about 0.028 from 1964 to 1993.

Hillslope erosion was measured in the original study at a site in the Coyote C. Arroyo watershed and a site in Slopewash Tributary: three lines with a total of 65 erosion pins in Coyote C. Arroyo and a total of 61 erosion pins in Slopewash Tributary. All 65 erosion pins in Coyote C. Arroyo were located and measured in 1993. Average deposition ranged from 1.45 to 2.56 cm. Also in 1993, 25 of the 61 pins at Slopewash Tributary were located, surveyed, and measured. Most of the pins had changed in elevation. The maximum increase in pin-head elevation from soil heave was 1.31 cm, and the maximum decrease in elevation was 0.61 cm. Average erosion was 2.64 cm, and average deposition was 1.99 cm. The sediment yield from this plot was 307 metric tonnes/km^2/yr.

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Appendix 1

Appendix 1. Summary of difference in elevations in closing the 1993 and 1997 resurveys to the original surveys.

[cm, centimeter; --, difference in elevation could not be determined or no remarks]

Cross-section label (locations in figure 1B)	Cross-section name	Difference in elevation (cm)	Remarks
1	SWT-CS-1		Left-bank pin missing
2	SWT-CS-2	3	--
3	SWT-CS-3	0	--
4	LW-Chain 4	0	--
5	NFA-Upper		Right-bank elevation not shown in original survey
6	NFA-Lower	2	--
7	Chain Section 15	1	--
8	LW-16		Right-bank pin was moved
9	LW-17		Right-bank elevation not shown in original survey
10	LW-18	1	--
11	LW-19	1	--
12	LTR 20-24	0	--
13	LTR 30-33	1	--
14	LW-35	1	--
15	LW-37	1	--
16	CS-40		Left-bank pin found on ground
17	CS-45	1	--
18	CH49	0	--
19	Frijoles Range 1	1	--
20	CH51	2	--
21	MPR 52-59	1	--
22	Frijoles Range 3		Right-bank pin missing
23	CH61	2	--
24	Frijoles Range 4	1	--
25	Frijoles Range 5		Right-bank pin missing
26	Frijoles Range 6	0	--
27	LW-64	1	--
28	Frijoles Range 7	1	--
29	LW-75	0	--
30	LW-76	1	--
31	LW-77	1	--
32	LW-79	1	--
33	LW-82	0	--
34	HMR-83	0	--
35	SPR 84-88	1	--

Appendix 1. Summary of difference in elevations in closing the 1993 and 1997 resurveys to the original surveys.—Continued

[cm, centimeter; --, difference in elevation could not be determined or no remarks]

Cross-section label (locations in figure 1B)	Cross-section name	Difference in elevation (cm)	Remarks
36	ACC-6	1	--
37	ACC-5	0	--
38	ACC-4	1	--
39	ACC-3	2	--
40	ACC-2	0	--
41	ACC-1	0	--
42	Gunshot Arroyo Station 468	3	--
43	Gunshot Arroyo Station 417 top of headcut	0	--
44	Gunshot Arroyo Station 417 bottom of headcut	0	--
45	Gunshot Arroyo Station 230	0	--
46	Gunshot Arroyo Station 25	0	--
47	Morning Walk Wash Upper	0	--
48	Morning Walk Wash Lower		--

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