TWENTIETH CENTURY ARROYO CHANGES IN CHACO CULTURE NATIONAL HISTORICAL PARK

U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 01-4251

Prepared in cooperation with the

NATIONAL PARK SERVICE

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By Allen C. Gellis

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Albuquerque, New Mexico
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U.S. DEPARTMENT OF THE INTERIOR
GALE A. NORTON, Secretary

U.S. GEOLOGICAL SURVEY
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CONVERSION FACTORS AND DATUMS

Multiply	By	To obtain
millimeter (mm)	0.03937	inch (in.)
centimeter (cm)	0.06102	inch (in.)
centimeter per year (cm/yr)	0.06102	inch per year (in./yr)
meter (m)	3.281	foot (ft)
meter per year (m/yr)	3.281	foot per year (ft/yr)
kilometer (km)	0.6214	mile (mi)
square meter (m^2)	10.76	square foot (ft^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
cubic meter (m^3)	35.31	cubic foot (ft^3)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
foot (ft)	0.3048	meter (m)
acre	4,047	square meter (m^2)

Historical data collected and stored as National Geodetic Vertical Datum of 1929 have been converted to North American Vertical Datum of 1988 (NAVD 88) for this publication.

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Vertical Datum of 1983 (NAD 83).

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ABSTRACT

Chaco Wash arroyo channel changes in the 20th century have become a major concern of the National Park Service. Several archeologic and cultural sites are located in the Chaco Wash corridor; thus, increased erosional activity of Chaco Wash, such as channel incision and increased meandering, may affect these sites.

Through field surveys, photogrammetric analyses, and reviews of existing reports and maps, arroyo changes at Chaco Culture National Historic Park were documented. Arroyo changes were documented for the inner active channel and the entire arroyo cross section. The inner channel of Chaco Wash evolved from a wide, braided channel in the 1930's to a narrower channel with a well-developed flood plain by the 1970's. From 1934 to 1973 the active channel narrowed an average of 26 meters, and from the 1970's to 2000 the channel narrowed an average of 9 meters. Overall from 1934 to 2000, the inner channel narrowed an average of 30 meters.

From 1934 to 2000, the top of Chaco Wash widened at four cross sections, narrowed at one, and remained the same at another. The top of Chaco Wash widened at a rate of 0.4 meter per year from the 1970's to 2000 compared with 0.2 meter per year from 1934 to 1973. At 50-percent depth or halfway down the arroyo channel, four cross sections widened and two cross sections narrowed from 1934 to 2000. Rates of widening at 50-percent depth decreased from 0.2 meter per year from 1934 to 1973 to 0.1 meter per year from the 1970's to 2000. From 1934 to 2000, arroyo depth decreased at five of six cross sections and increased at one cross section. Arroyo depth between 1934 and 1973 decreased an average 1.4 meters from aggradation and between the 1970's and 2000 increased an average 0.4 meter from channel scour.

From 1934 to 2000, arroyo cross-sectional area decreased at all six cross sections. Cross-sectional areas in Chaco Wash decreased from 1934 to 1973 as a result of sediment deposition and both decreased and increased from the 1970's to 2000. The cross-sectional area decreased by the 1970's due to channel narrowing and flood-plain formation. Increases in cross-sectional area are from channel scour and channel widening. Photogrammetric analyses of volumetric changes for a 1.7-kilometer reach of Chaco Wash showed sediment deposition from 1934 to 1973 of 64 square meters per unit length of channel over 1.7 kilometers to erosion from 1973 to 2000 of 7 square meters per unit length of channel.

Chaco Wash evolved from a braided channel in the 1930's to a narrow, sinuous inner channel by the 1970's. Chaco Wash was widening in the 1930's, leading to sediment deposition and formation of an inner flood plain. Channel narrowing resulted from increased sediment deposition on the flood plain. Sediment deposition may be related to a decrease in peak flows, an increase in flood-plain vegetation, or an increase in the transport of fine-grained sediment. Increases in bankfull depth of Chaco Wash between the 1970's and 2000 were due to aggradation of the flood plain and channel scour. Thus, rates of aggradation and cross-sectional filling were greater from 1934 to the 1970's than from the 1970's to 2000.

INTRODUCTION

Chaco Wash channel changes in the 20th century have become a major concern of the National Park Service (NPS). Many of the cultural sites at Chaco Culture National Historical Park (CCNHP) are situated on the alluvial valley floor near Chaco Wash. The alluvial valley floor can erode from changes in the geometry of Chaco Wash and sheetwash erosion, soil piping, and gullying on the alluvial valley. Changes in the geometry of Chaco Wash from channel incision, widening, and sinuosity can lead to bank collapse and erosion of the alluvial valley floor. Erosion of the alluvial valley floor from any of these processes may affect cultural sites. To address the concern of 20th century arroyo changes in Chaco Wash and their effect on archeologic sites, the U.S. Geological Survey (USGS), in cooperation with the NPS, conducted a study to examine 20th century channel changes in Chaco Wash near the CCNHP. This report was prepared in cooperation with the NPS.

Purpose and Scope

This report summarizes the changes in Chaco Wash from 1935 to 2000. Changes in arroyo channel geometry for the entire arroyo and for the inner channel were compared from 1934 to 1973 and for selected years from the 1970's to 2000. Channel geometry in 1934 was quantified from 1931 and 1934 1-ft contour maps and in 1973 was quantified from aerial photography. Channel geometry in the 1970's was determined from an average of channel dimensions from 1972, 1974, 1976, and 1977 field surveys conducted by Malde (1977) or from interpretations from the 1973 aerial photographs. Channel geometry in 2000 was determined from either field surveys or aerial photographs.

Description of Study Area

The 33,989-acre CCNHP (fig. 1) in northwestern New Mexico, formerly known as Chaco Canyon National Monument, is a renowned site for archeology and is listed by the United Nations Educational Scientific and Cultural Organization as a World Heritage site. Chaco Canyon begins 1 km west of Cañada Alemita Junction and extends for 32 km to the junction with Escavada Wash (DeAngelis, 1972). Chaco Wash drains 11,500 km^2 at its confluence with the San Juan River and is 220 km long (Love, 1980). Chaco Wash is sinuous and incised and in places is as much as 10 m below the alluvial valley floor. After its junction with Escavada Wash, Chaco Wash takes on the appearance of Escavada Wash: unincised and braided. Bedrock in Chaco Canyon is mostly sandstone and shale; grain-size distribution of sediment in the inner-channel Chaco Wash is predominantly fine sand (Love, 1980).

Climate and Runoff

Climate in the CCNHP is semiarid. Average annual precipitation recorded at the NPS Headquarters from 1934 to 1999 is 226 mm (U.S. Department of Commerce, 1934-99) (fig. 2A). Annual precipitation appears to have increased 21 percent from 1934 to 1999 (fig. 2A). About half the average annual precipitation results from convective storms from July through October (fig. 2B).

Monthly runoff measured at the USGS streamflow-gaging station Chaco Wash at Chaco Canyon National Monument from March 1976 to April 1990 is highly variable (fig. 3A). From 1976 through 1990, all months recorded some flow (fig. 3B). Mean monthly runoff was largest in February and July through September (fig. 3C). The highest monthly runoff was recorded in February 1979 (8.88×10^6 m^3) and August 1988 (5.38×10^6 m^3). Instantaneous peak flows from 1976 to 1990 ranged from 0.5 to 54.4 m^3/s (fig. 3D). Average monthly precipitation (fig. 2) shows a similar pattern to mean monthly runoff for summer to fall (June to November) but not for the winter and spring months (December to May). This difference may be due to the influence of snowmelt on runoff.

Geomorphic Description of Arroyos at Chaco Canyon

Arroyos are stream channels incised into valley alluvium and colluvium (Elliott and others, 1999). Geologic evidence exists for past episodes of arroyo incision in the American Southwest during the Holocene (Webb and Hereford, 2001) and recently in the late 19th century (Cooke and Reeves, 1976). The causes for arroyo incision in the late 19th century can be separated into three arguments: (1) arroyos were incised following a change in precipitation intensity (Leopold, 1951; Balling and Wells, 1990), (2) arroyos were incised as a result of overgrazing (Cooke and Reeves, 1976; Aby, 1997), and (3) arroyos were incised because of internal adjustments of slope, sediment transport, and hydrology. In argument 3, climate and grazing are triggers for arroyo development (Schumm and Hadley, 1957; Gellis and Elliott, 2001). Whatever the causes of arroyo incision in the Southwest, the result is that valley floors, which formerly supported small, unincised channels or discontinuous channels, were incised, in some places more than 10 m.

The stratigraphic record exposed along the walls of arroyos shows numerous paleoarroyos, indicating that arroyos have incised and filled during the late Quaternary. The cycle of incision and filling is called arroyo evolution (Schumm and others, 1984; Gellis and others, 1991; Elliott and others, 1999). A generalized model of arroyo evolution, depicting the stages that an arroyo goes through following incision, is shown in figure 4. These changes in arroyo cross section are observed through time at one selected location in the arroyo (fig. 4A). Generally, the arroyo changes through time from a narrow, V-shaped gully (stage B) with low width-to-depth ratios to a wide, U-shaped gully with

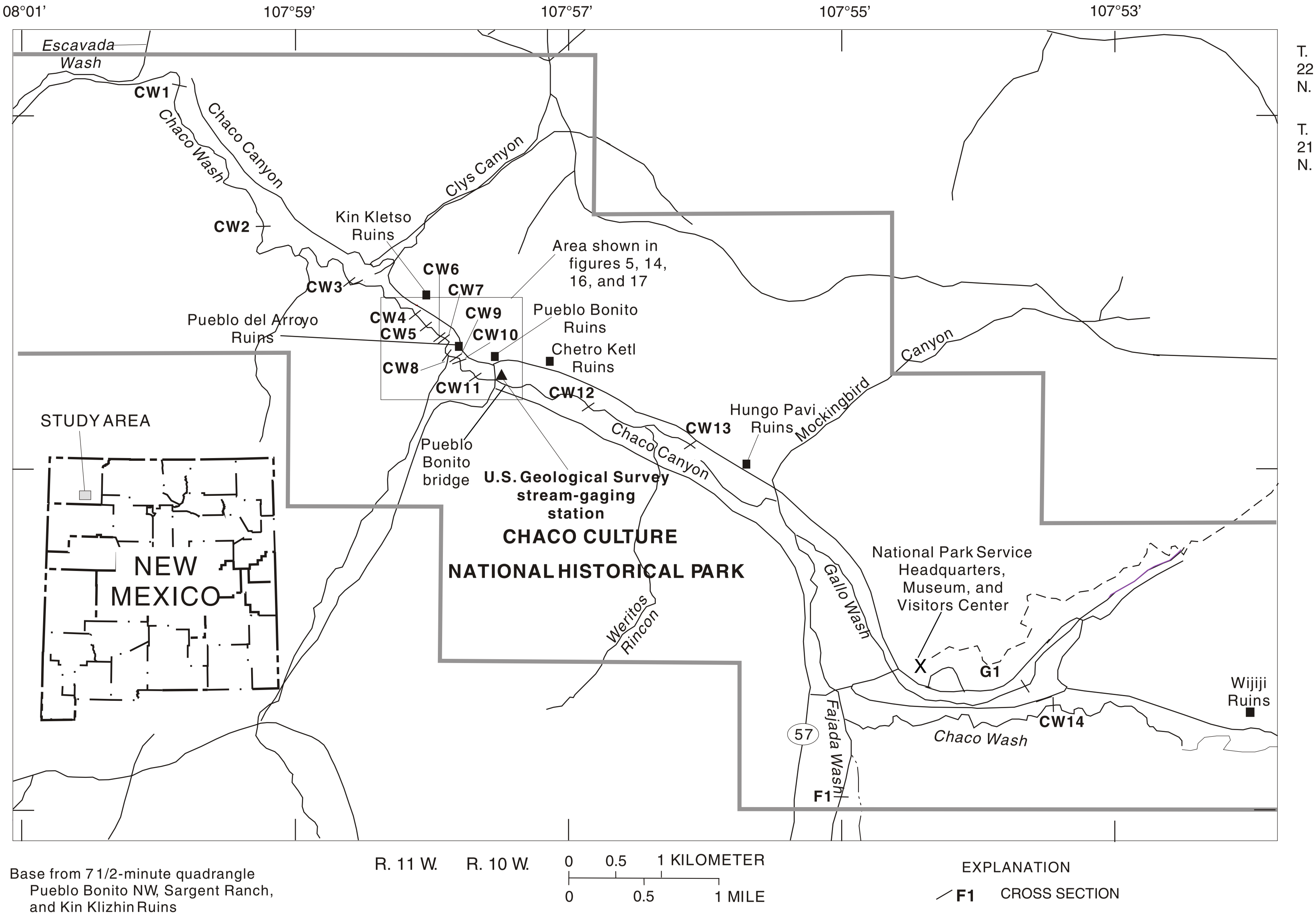
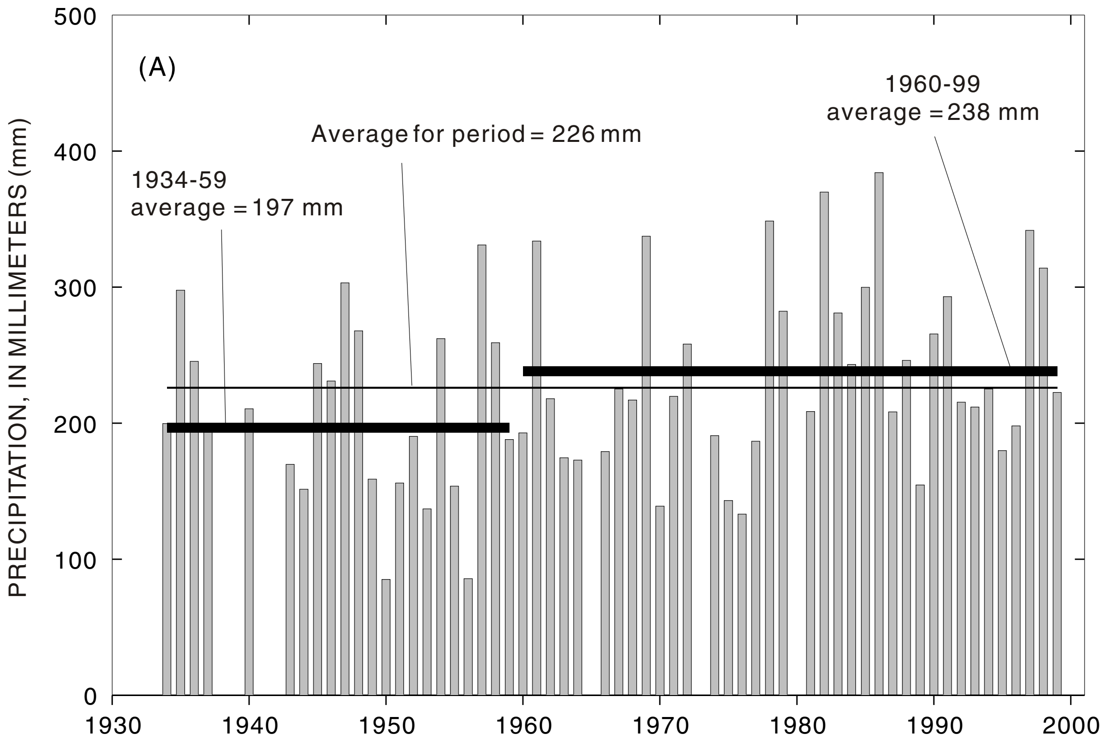


Figure 1. Location of study area and cross sections measured along Chaco Wash and selected tributaries in Chaco Canyon, New Mexico.



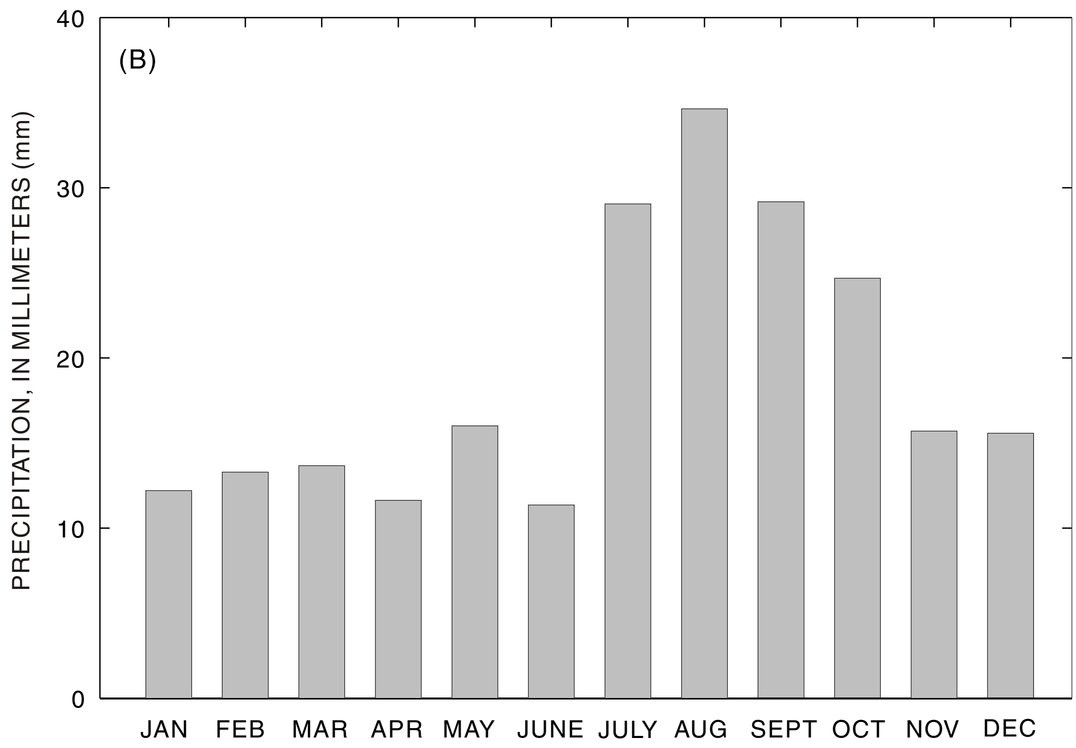


Figure 2. Precipitation at Chaco Culture National Historical Park Headquarters, 1934-99. (A) Annual precipitation and (B) average monthly precipitation.

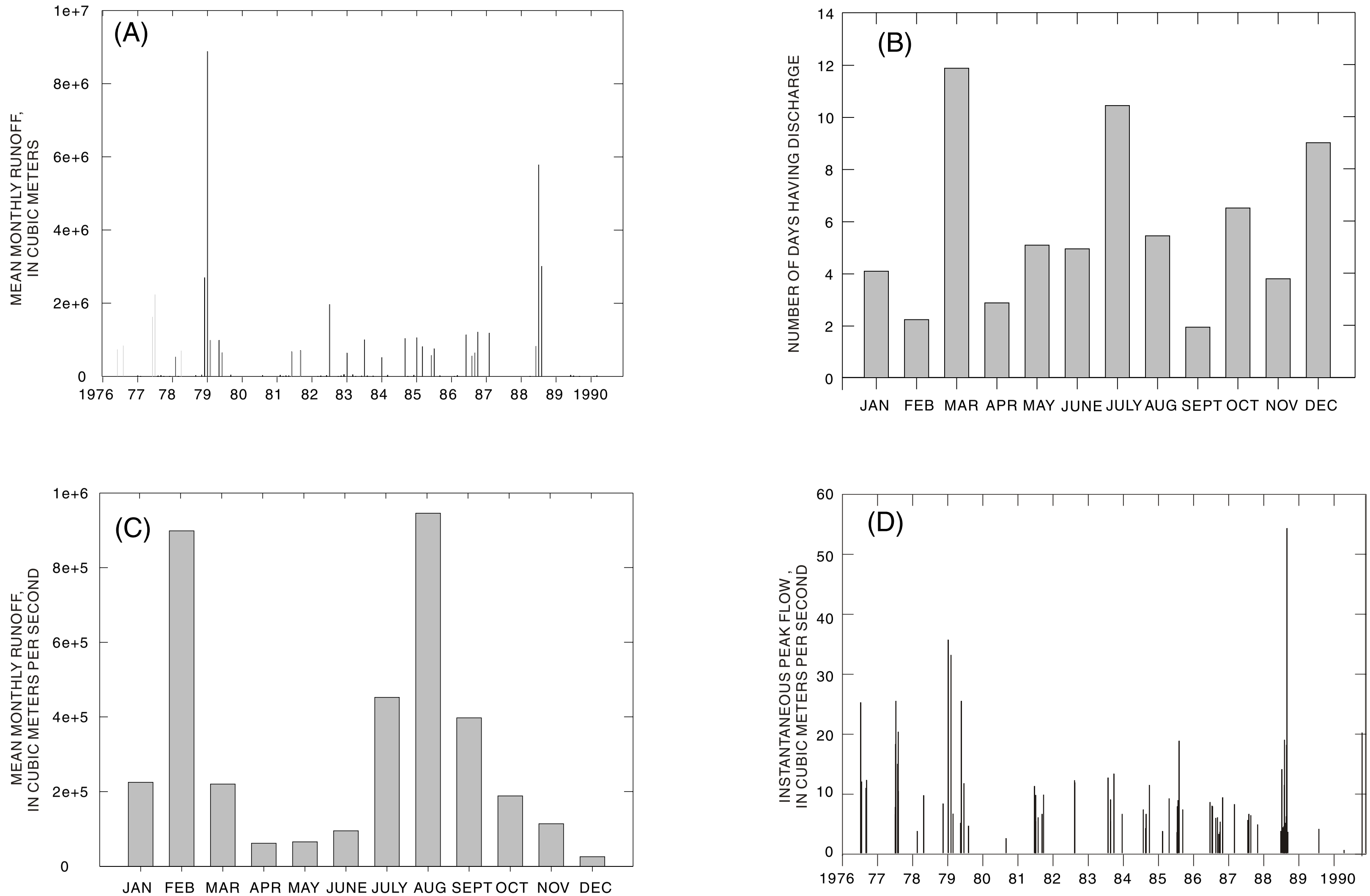


Figure 3. (A) Mean monthly runoff at streamflow-gaging station Chaco Wash near Chaco Canyon National Monument, May 1976 to April 1990, (B) number of days in a month with discharge, (C) mean monthly runoff, and (D) instantaneous peak flow, 1976-90.

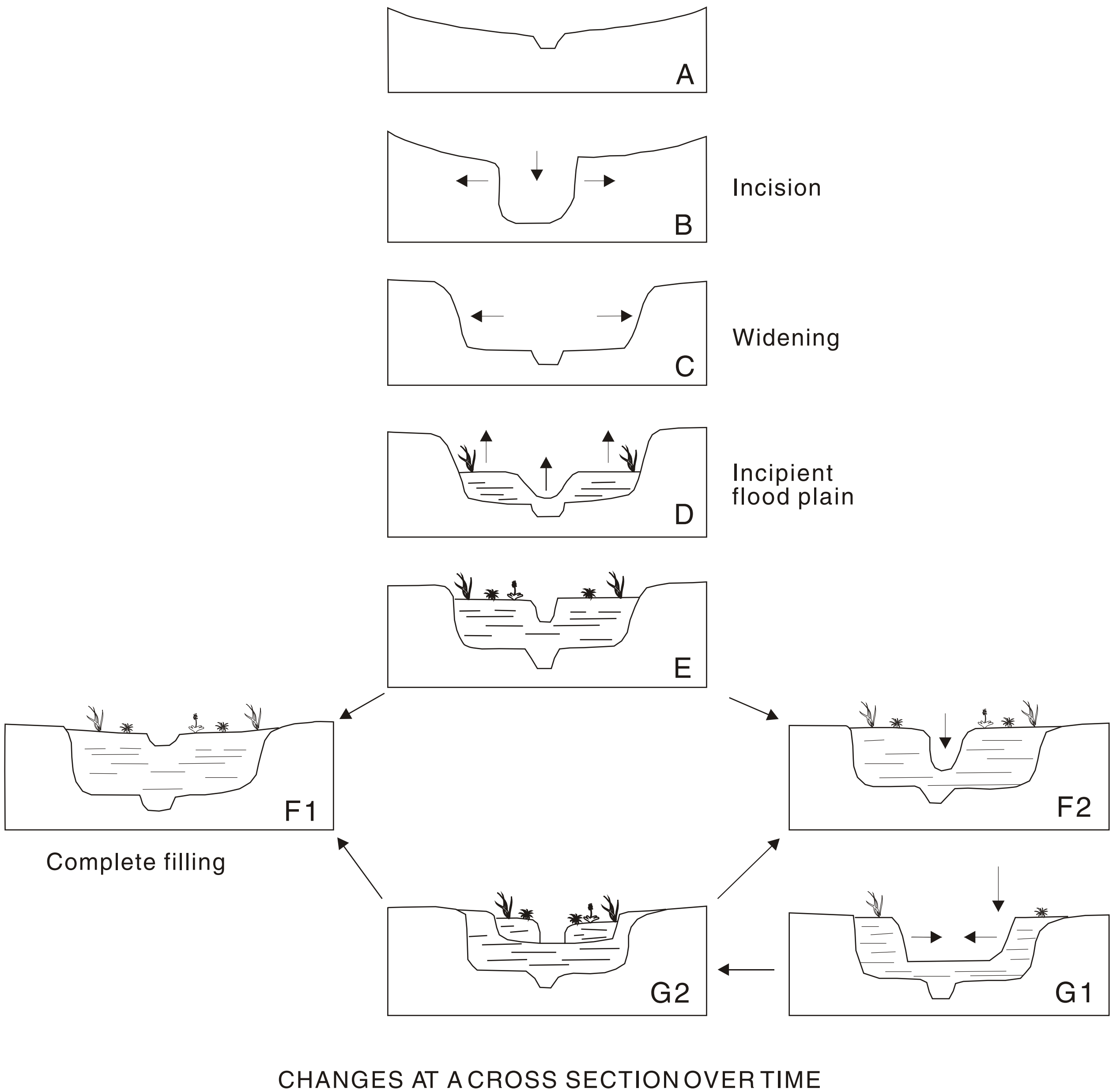


Figure 4. Model of arroyo evolution depicting changes at a cross section over time following channel incision (from Gellis, 1992).

high width-to-depth ratios (stages B and C). Arroyo widening decreases flow depth, which decreases streampower, thereby promoting sediment deposition and formation of an incipient flood plain (stage D) (Elliott and others, 1999). Decreases in runoff during this stage may promote vegetation colonization because seedlings are not removed by higher flows (Hereford, 1984). Vegetation that becomes established on the flood plain increases hydraulic roughness and promotes increased sediment deposition (stage E). At stage E, the inner channel narrows as a result of flood-plain formation. Eventually the channel may aggrade and completely fill the cross section (stage F1) or become reincised from narrowing of the channel, which decreases the channel width-to-depth ratio, increases streampower, and causes reincision.

Previous Studies

Many geologists, geographers, and engineers have documented channel width and depth in Chaco Wash since the 1800's (table 1). Bryan (1954) estimated 1860 as the date of channel incision in Chaco Wash. Love (1980) suggested an earlier date of incision in the 1830's to 1840's, formation of a flood plain between 1877 and the early 1890's, and renewed incision in the 1890's. In the 1920's to 1930's, Chaco Wash was flat floored, braided, and devoid of vegetation (DeAngelis, 1972; Simons, Li, and Associates, 1982); by 1965, Chaco Wash had changed dramatically, having a sharply defined inner channel with dense vegetation (Lagasse and Eggert, 1983). Love (1980) attributed increases in the width of Chaco Wash to a wet period from 1900 to 1934 and to overgrazing. The increase in width led to a decrease in slope, resulting in sediment deposition and development of an incipient inner channel. From the 1930's to the 1950's, precipitation decreased, discharge decreased, and sediment was deposited next to the inner channel. Erosion-control structures built during this time helped stabilize sediment (Love, 1980).

Aerial photographs taken in 1971 show continued stabilization of the inner channel and more frequent channel cutoffs from 1965 to 1971 (Simons, Li, and Associates, 1982). From 1934 to 1972, Chaco Wash widened from 4 to 35 percent of its 1934 width at an average rate of 5 to 15 cm/yr, whereas between 1924 and 1972, the depth of the channel changed little (DeAngelis, 1972). Leopold (1976) reported aggradation of the Chaco Wash flood plain from 1961 to 1974, about 1.0 km upstream from the visitors center at CCNHP. Aggradation of Chaco Wash from the 1930's to the 1970's was followed by incision of the inner channel (DeAngelis, 1972; Love, 1980; Simons, Li, and Associates, 1982). In 1979, many tributary arroyos along Chaco Wash were actively eroding headward (Love, 1980).

Channel erosion is a major problem affecting the cultural resources of the CCNHP. Pueblo del Arroyo was threatened by lateral erosion of Chaco Wash in the early 1920's (Simons, Li, and Associates, 1982). Chauvenet (1935) examined channel erosion, its possible effect on archeologic sites, and erosion protection; he reported that several structures, Kin Kletso, Pueblo del Arroyo, Wijiji, Hungo Pavi, and Chetro Ketl (fig. 1), were affected by a variety of erosion processes, including undermining by lateral erosion of Chaco Wash, sheetwash action on the exposed banks, gullying, and tributary erosion. In 1981, Simons, Li, and Associates (1982) reported that gullies and soil piping were affecting Pueblo del Arroyo and Wijiji and that channel erosion was affecting Kin Kletso.

Chauvenet (1935) also described some erosion structures built of wood, rock, and wire to control channel erosion. Love (1980) reported that the Civilian Conservation Corps, Soil Conservation Service, and the NPS planted more than 1 million trees and shrubs for erosion control in the CCNHP in the 1930's. Other erosion-control strategies since the 1930's include jetties, earth dams, and contour furrowing (Simons, Li, and Associates, 1982). For flood-control purposes, the NPS straightened some sections of Chaco Wash in the 1960's (Love, 1980).

METHODS FOR ANALYSIS OF ARROYO CHANGES

Sixteen arroyo cross sections in the CCNHP were used to measure arroyo and inner-channel geometry and to describe changes in Chaco Wash and selected tributaries (fig. 1). Five of these cross sections were established in 1972 and resurveyed in 1974, 1976, and 1977 using a survey level (Malde, 1972, 1977); three of the cross sections (CW3, CW13, and CW14) were on Chaco Wash, and two of the cross sections (F1 and C1) were on the tributaries Fajada Wash and Gallo Wash (fig. 1). Original field notes of Malde's five cross

Table 1. 19th and 20th century Chaco Wash channel dimensions

[--, no data]

Date	Location	Arroyo depth (meters)	Arroyo width (meters)	Observer	Reference
1849	Una Vida	0.46	2.4	Lt. Simpson	Bryan, 1954
1849	Wijiji	0.5	2.4	Lt. Simpson	Chauvenet, 1935
1860	Pueblo Bonito	1.5	--	Local Navajo	Bryan, 1954
1877	Pueblo Pintado	3.0-3.6	--	William H. Jackson	Bryan, 1954
1877	Pueblo del Arroyo	4.9	12.2-18.3	William H. Jackson	Bryan, 1954
1925	Escavada Wash	3.0	46-91	Bryan	Bryan, 1954
1925	Pueblo Bonito	9.1	--	Bryan	Bryan, 1954
1925	Pueblo del Arroyo	9.1	46-91	Bryan	Bryan, 1954
1925	Wijiji	6.1	--	Bryan	Bryan, 1954
1934	Entire Chaco Canyon	3.6-7.6	15-76	Chauvenet	Chauvenet, 1935
1934	Kin Kletso	6.7	76	Chauvenet	Chauvenet, 1935
1965	Pueblo del Arroyo	5.2	--	Tuan	Simons, Li, and Associates, 1982
1972	Entire Chaco Canyon	3.8-9.6	28-126	DeAngelis	DeAngelis, 1972
1972	Pueblo Pintado	5.5-6.4	--	DeAngelis	DeAngelis, 1972
1972	Pueblo del Arroyo	7.3	--	DeAngelis	DeAngelis, 1972
1974	1.0 kilometer upstream from museum at Chaco Canyon National Historical Park	About 9	About 47	Leopold	Leopold, 1976
1979	Entire Chaco Canyon	3-12	--	Love	Love, 1980
1979	Entire Chaco Canyon (inner channel)	1-3 m	10-30	Love	Love, 1980

sections were obtained from USGS archives. The five cross sections were resurveyed in August 2000, in conjunction with this study, with a total station survey and survey level. Two new cross sections (CW1 and CW7) also were surveyed in August 2000 using a total station survey. An additional nine cross sections (CW2, CW4, CW5, CW6, CW8, CW9, CW10, CW11, and CW12) (fig. 1) were analyzed using aerial photographs. Photogrammetric cross sections CW4, CW5, CW6, CW8, CW10, and CW11 were selected for analysis because of their proximity to Pueblo del Arroyo (fig. 1).

One-foot contour maps of the CCNHP (1:480 scale) were surveyed by the NPS in 1931 and 1934. The contour maps were digitized into a geographical information system (GIS). The accuracy of the NPS contour maps to the true surface of the Earth is dependent on the amount of data collected and the experience of the survey crew. Black and white aerial photographs of the CCNHP were obtained for 1973 (1:6,000 scale) and 2000 (1:3,000 scale). By using a GIS, 0.3-m contour maps were generated from the 1973 and 2000 aerial photographs.

Analysis of Photogrammetric Cross Sections

The 1973 photogrammetric analysis was modeled with software using discrete stereo pairs, meaning that the stereo model (georeferencing and exterior camera orientationQ—or the position of the camera relative to a horizontal plane and in real x, y, z space) is set up on the basis of individual stereo pairs. The orientation of the camera lens relative to the plane on which the photographic file sits and the camera metrics (except for calibrated focal length) were set automatically by the software using the location of the camera fiducial marks. Centimeter Global Position System (GPS) data were used for georeferencing. Some error is associated with the georeferencing because the exact point location on a photo taken 27 years earlier is difficult to identify. Maximum estimated vertical errors for the 1973 1:6,000 aerial photograph interpretations average less than ±0.75 m with a maximum error of ±2.0 to ±2.5 m (Rich Friedman, McKinley County GIS, written commun., 2001). Maximum estimated horizontal errors average ±0.66 m with a maximum error of ±2.0 m (Rich Friedman, written commun., 2001).

The 2000 photogrammetric analysis was modeled using software (*http://erdas.com*) that allowed for the creation of stereo models across multiple stereo pairs, used block-bundle adjustment, and allowed for importation of exterior orientation data from flight-recording systems. In block-bundle adjustment, all tie points and georeference information for each photo in the flight line(s) are used to calculate the orientation parameters for the entire block of photos instead of two at a time; this achieves superior consistency and accuracy. The images were georeferenced using the same data that were used to georeference the 1973 images. Maximum estimated vertical errors for the 2000 1:3,000 aerial photograph interpretations average less than ±0.5 m with a maximum error of ±1.5 to ±2.0 m (Rich Friedman, written commun., 2001). Maximum estimated horizontal errors average less than ±0.5 m with a maximum error of ±1.5 to ±2.0 m (Rich Friedman, written commun., 2001).

For the georeference points collected for image registration, the High Accuracy Reference Network station established by the National Geodetic Survey just south of Pueblo Bonito, Chaco Canyon, was used as the base location; rapid, static data-collection procedures were used to acquire the position readings for the point locations. The expected errors with these data should be less than 10 cm vertical (z) and from 2 to 5 cm horizontal (x,y).

Errors reported in this study's photogrammetric analysis are similar to errors reported for other geomorphic studies on erosion and deposition. Dymond and Hicks (1986) used 1950 aerial photographs at a scale of 1:17,500 and 1981 aerial photographs at a scale of 1:12,000 to obtain volumetric measurements of erosion and deposition in mountainous areas of New Zealand. Accuracy of elevation using their photogrammetric technique ranged from ±0.5 to ±4.0 m. Coe and others (1997) used Digital Elevation Models (DEM's) derived from 1982 pre-debris-flow aerial photography (scale 1:8,000) and 1991 post-debris-flow aerial photography (scale 1:3,000) to volumetrically calculate net erosion and deposition from a modern debris flow near Yucca Mountain, Nevada. Based on their photogrammetric mapping configuration, the vertical accuracy derived between the two sets of photos was ±0.14 m. Fryer and others (1994) reported that the accuracy of vertical measurements using aerial photographs is ±1 to ±3 parts per 10,000 m of flying height. For a flying height of 1,500 m the vertical precision is ±0.15 m. Miller (1986) analyzed channel changes using aerial photographs between 1971 (scale 1:20,000) and 1983 (scale 1:24,000) for Smoky Creek, Tennessee, and found horizontal displacement errors of ±1 to ±5 m.

Volumetric changes in Chaco Wash also were quantified through photogrammetric techniques. Chaco Wash was divided into six reaches covering approximately 1.7 km of channel (fig. 5). The area of the reaches ranged from 15,600 to 30,300 m^3. The volume in each reach was calculated to the same elevation for 1934, 1973, and 2000. The areas for the volume calculations overlapped to ensure that orientations of the plane in three-dimensional space were placed in locations that had not changed from 1934 to 2000 for each data set. Four points defined the orientation of each plane in three-dimensional space and were placed in locations that had not changed from 1934 to 2000. Because the elevations were not the same across all three data sets, greater accuracy for volume comparisons was achieved by defining unique elevation planes for each of the three elevation sets rather than trying to adjust the data sets to the same elevation. The change of volume in each reach is related to sediment deposition and erosion. Deposition decreases the volume, and erosion increases the volume. The planimetric area or the area of the reach at the top of the arroyo was calculated over time. Increases in planimetric area over time indicate arroyo widening. The average arroyo depth for a reach was calculated as the volume of the reach divided by the planimetric area.

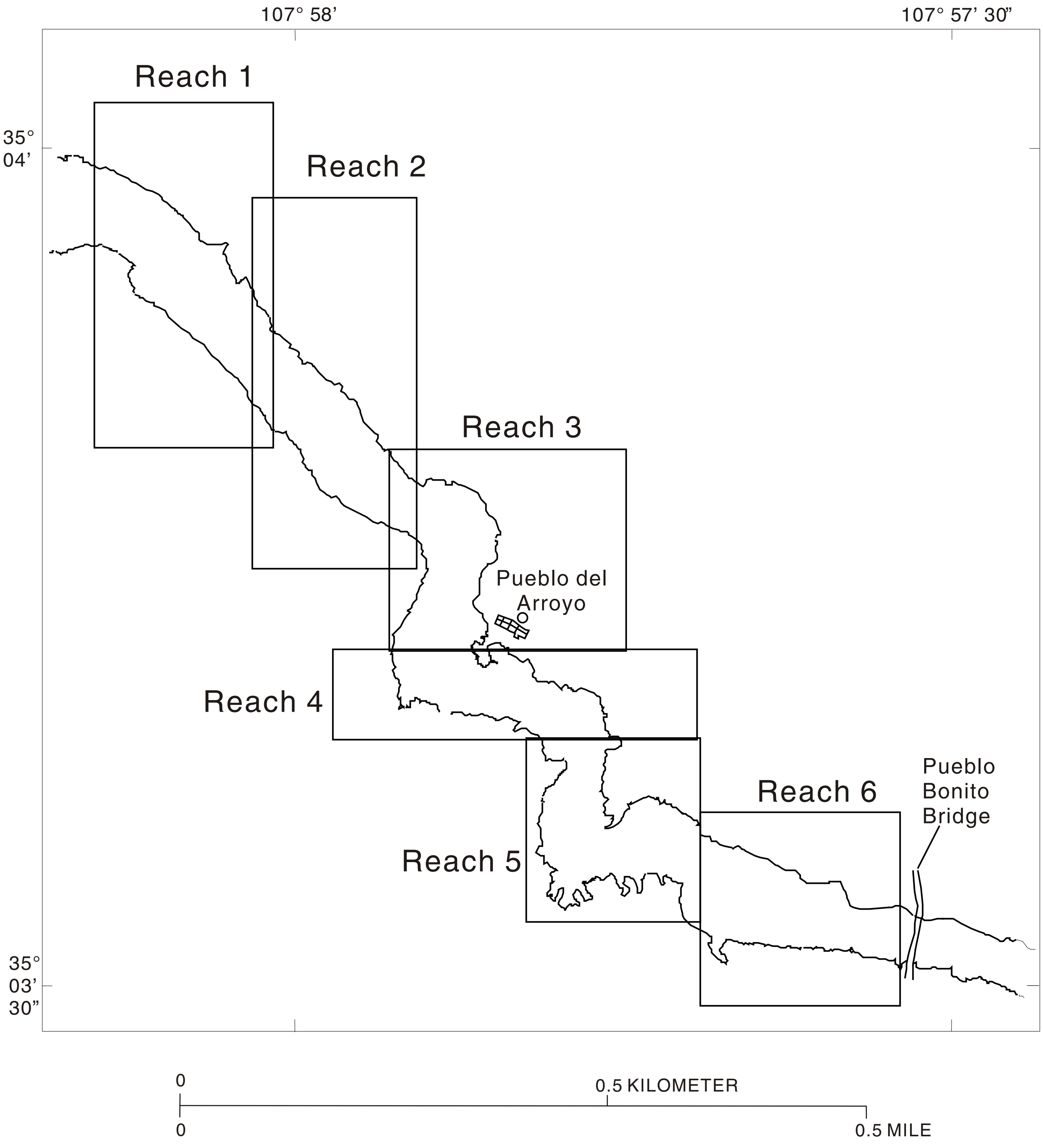


Figure 5. Reaches used to measure volumetric changes over time in Chaco Wash.

Delineation of Arroyo Geometry

To present a coherent description of channel geometry, features along the arroyo cross section are defined. Arroyos at Chaco Canyon are typically characterized by two distinct geomorphic features (fig. 6): (1) the entire arroyo channel confined by the arroyo walls and the top height of the alluvial valley floor and (2) a sinuous, active inner channel characterized by levees, flood plains, and point bars (Love, 1983). In this report the term "channel" signifies the inner channel within the arroyo.

Changes in the entire arroyo were evaluated by analyzing the top width and the width at 50-percent depth (fig. 6). The top edge of the arroyo, where width and depth are measured, is the abrupt break in slope of the alluvial valley floor and arroyo wall. The alluvial valley floor is the highest elevation of the arroyo. Top depth was measured as the distance from the top edge of the arroyo to the lowest part of the channel or thalweg (fig. 6). If the alluvial valley floor had different elevations on either side of the arroyo, the lowest elevation was used. Selecting the top edge of the arroyo can be subjective, but the first abrupt break in slope of the arroyo wall and the alluvial valley floor was usually selected. Fifty-percent arroyo depth is measured from half of the top-depth elevation to the thalweg (fig. 6). Width, depth, and cross-sectional area were quantified for these two elevations in the entire arroyo channel. To compare width changes over time, the elevation in the channel used to define width was kept constant for each year. The cross-sectional area is defined as the area under a line drawn across the top of the entire arroyo from the left bank to the right bank.

For the inner channel, channel top width and depth and cross-sectional area were quantified. The width and depth of the channel are synonymous with bankfull. Bankfull is a morphologic feature in the channel that generally is the top of the levee or the break in slope of a point bar as it flattens (fig. 6). Channel changes that were analyzed included bankfull width and depth.

Widening of the entire arroyo top width is caused by processes on the alluvial valley floor, such as sheetwash, gullying, and soil piping, that may lead to erosion and bank failures. Increased in-channel sinuosity also may result in an increase in arroyo width as the active channel undercuts the arroyo walls, leading to bank failures. Changes to bankfull width and depth are affected by in-channel flows and sediment deposition.

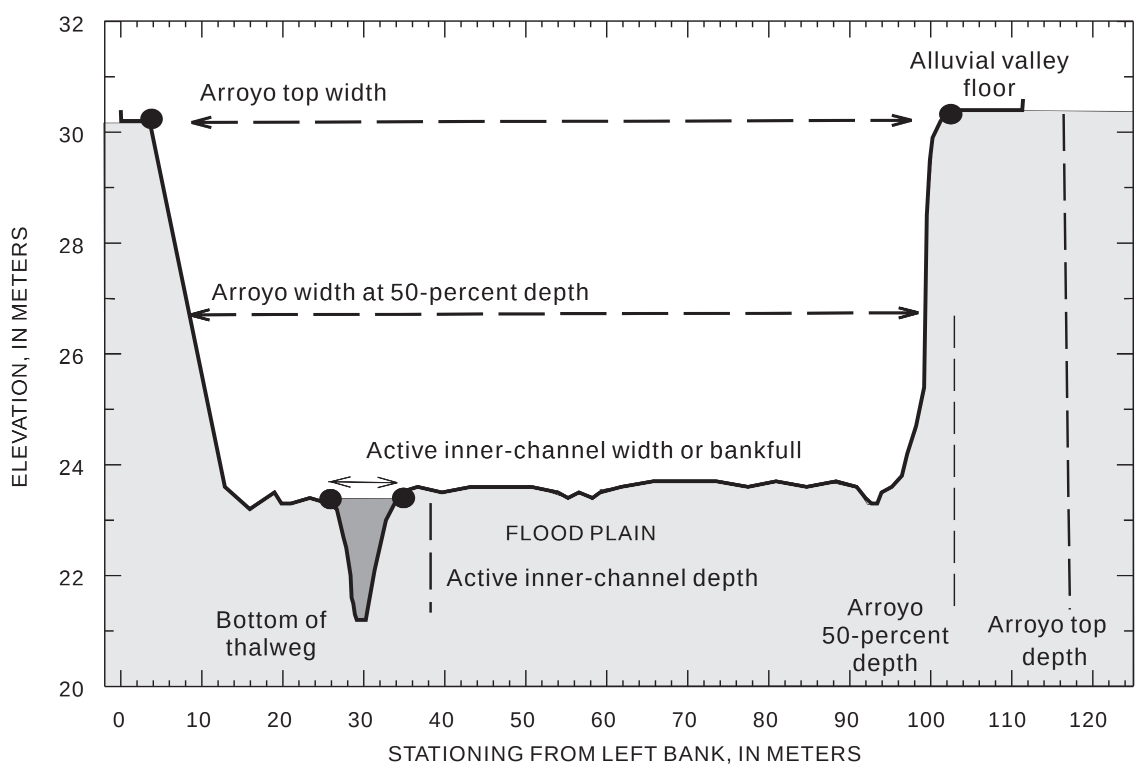


Figure 6. Schematic of channel width and depth features in a typical arroyo channel.

Aggradation is an increase in the thalweg elevation over time, and degradation is a decrease in the thalweg elevation over time. Longitudinal profiles of the channel thalweg were created from the 1934 topographic maps and 1973 and 2000 aerial photogrammetry.

RESULTS

This section describes the results of arroyo changes at CCNHP from 1934, 1973, and 2000. Errors encountered in the field surveys and photogrammetric interpretations are presented. Changes in width and depth are discussed for select arroyos and the inner channel. Longitudinal and planform changes of Chaco Wash in 1934, 1973, and 2000 are also discussed.

Analysis of Errors in Field Surveys and Photogrammetric Data Interpretation

Analyses of 16 arroyo cross sections through time were used to quantify arroyo geometry and changes in Chaco Canyon (fig. 7). Accuracy of the field resurveys was determined as the error in closing the survey and the difference between elevation of the cross-sectional end points in 2000 and Malde's 1972-77 surveys. Accuracy in closing the 2000 resurveys ranged from 0.3 to 2.4 cm. Accuracy in elevation of the cross-sectional end points in 2000 compared to Malde's surveys ranged from 0.7 to 5.9 cm. Because CW3 had an end-point steel bar bent on the left bank and CW13 had one end point missing on the left bank, accuracy in elevation between the cross-sectional end points in the 2000 resurvey of CW3 and CW13 and Malde's 1972-77 surveys could not be determined.

Difficulty was encountered when trying to register the three cross sections (CW4, CW5, and CW6) generated from the 1934 topographic maps and 1973 and 2000 aerial photographs to the same vertical datum. Differences in elevation among the 3 different years were due to differences in the data source and photogrammetric techniques. The 1973 data are closest to the actual elevation based on the North American Vertical Datum of 1988. The 2000 photography was acquired at a nominal scale of 1:3,000 with a digital camera. The primary source of differences in elevation between the 1973 and 2000 data sets may be the exterior orientation parameters (GPS location data and camera and (or) plane orientation information) from the in-flight recording system, which is assumed to be at the centimeter level. The higher elevation in the 2000 data was in part due to the exterior orientation of the 2000 data, which seemed to carry a heavier weight in the elevation solutions than the georeference points do (12 georeference points were used compared to more than 50 elevations generated from the exterior orientation data).

To correct for this error in elevation for the 1934, 1973, and 2000 coverages, the surface of the alluvial valley floor at a distance of at least 3 m from the edge was used as the datum for all 3 years. Processes that may affect the elevation of the alluvial valley floor over time are erosion and deposition associated with sheetwash and eolian activity. The rates of elevation change on the alluvial valley floor associated with sheetwash and eolian activity are relatively small compared with elevation changes in the channel. The vertical adjustments made to register CW4, CW5, and CW6 to the same datum are listed in table 2. Some difficulty was encountered when interpreting elevations of the inner channel during photogrammetric analysis. Elevation data are difficult to determine in photographs that show featureless areas and dark shadows. This problem is especially true where the elevation suddenly changes. One area where this was a constant problem was the active inner channel, which appears as a homogeneous area that is almost white. This source of error was encountered in both the 1973 and 2000 data.

Table 2. Vertical adjustments made to register cross sections to the same datum

Cross section (fig. 1)	Year	Vertical adjustment (meters)
CW4	1934	1.43
CW4	2000	1.15
CW5	1934	0.68
CW5	1973	1.62
CW6	1934	1.02
CW6	2000	1.45

Comparison of Photogrammetric Techniques to Field Surveys

The geometry of three cross sections (CW3, CW8, and CW10) was generated using the 2000 field surveys and the 2000 aerial photogrammetric interpretations and, therefore, can be used to compare the accuracy of photogrammetric techniques to field

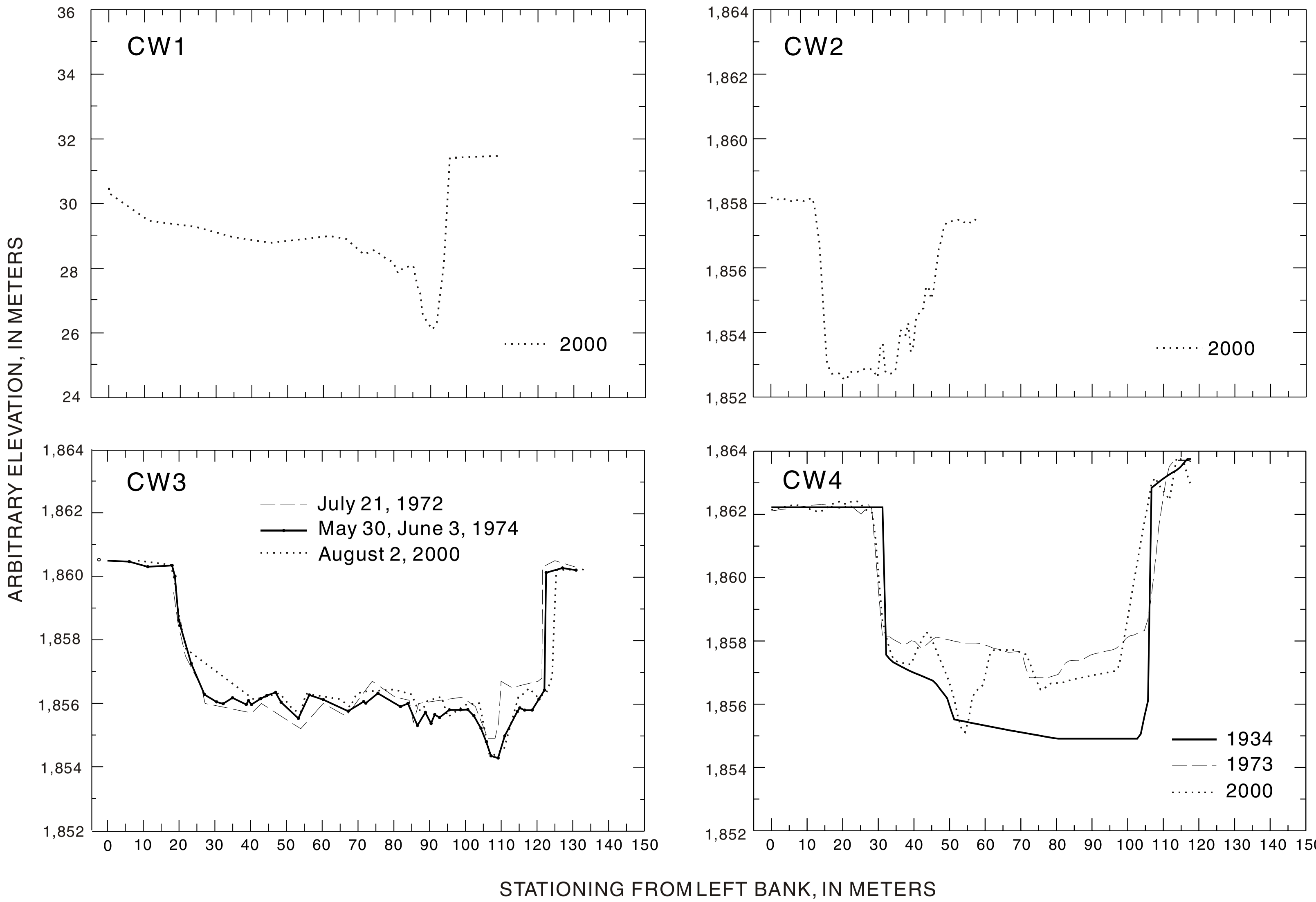


Figure 7. Channel cross-sectional measurements along Chaco Wash and selected tributaries in Chaco Culture National Historical Park, 1934-2000. Locations of cross sections shown in figure 1.

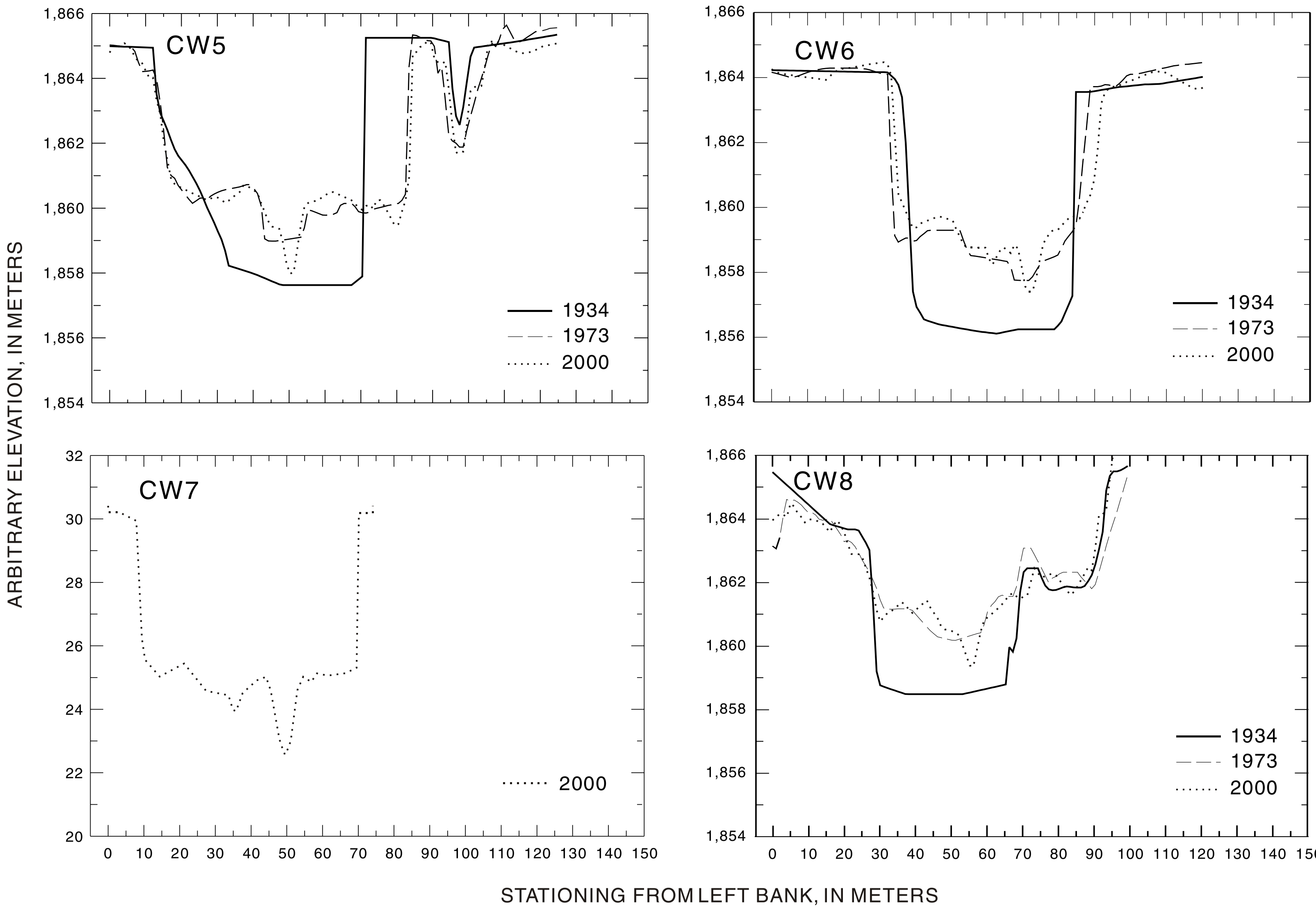


Figure 7. Channel cross-sectional measurements along Chaco Wash and selected tributaries in Chaco Culture National Historical Park, 1934-2000. Locations of cross sections shown in figure 1--Continued.

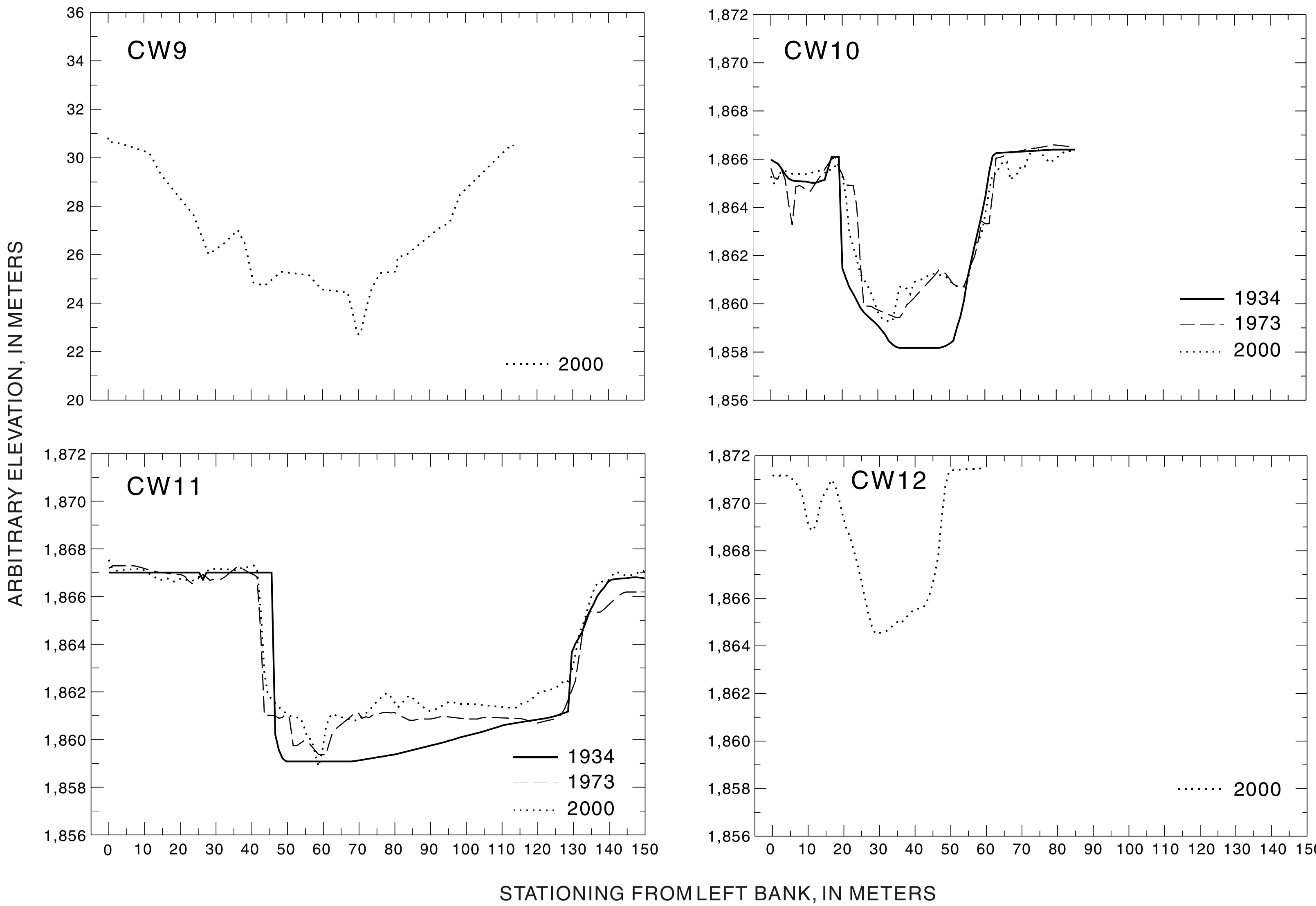


Figure 7. Channel cross-sectional measurements along Chaco Wash and selected tributaries in Chaco Culture National Historical Park, 1934-2000. Locations of cross sections shown in figure 1--Continued.

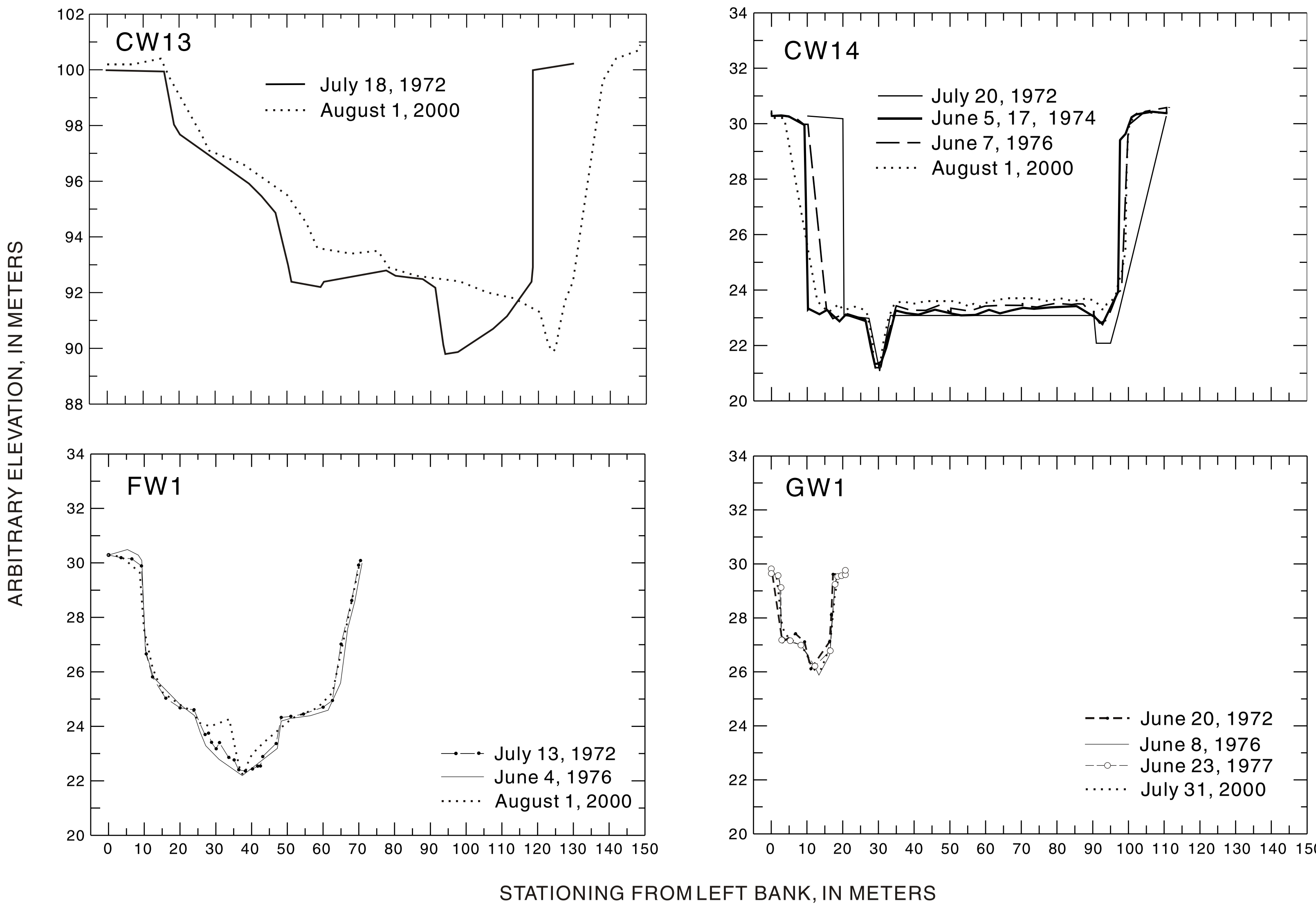


Figure 7. Channel cross-sectional measurements along Chaco Wash and selected tributaries in Chaco Culture National Historical Park, 1934-2000. Locations of cross sections shown in figure 1--Concluded.

surveys. The latitude and longitude of the cross-sectional end points at CW3, CW8, and CW10 were obtained from a GPS. The accuracy of the latitude and longitude measurements ranged from ±4 to ±8 m.

The cross sections obtained from the photogrammetric interpretations had a different vertical datum than the surveyed cross sections. To correct for this difference in elevation, the field survey and photogrammetric cross sections were registered to a common surface, either the alluvial valley floor or the flood plain. Because of error in the GPS readings, the horizontal stationing had to be adjusted to the break in slope of the alluvial valley floor and the arroyo wall or edge of bankfull.

Comparisons of photogrammetric techniques to field surveys illustrate some similarities and differences in the methods. In general, the channel shape obtained from photogrammetric techniques (fig. 8) is similar to that obtained from the surveyed cross sections. Differences exist in arroyo widths and depths (table 3). The arroyo top widths derived from the two methods were within 10 and 18 m at CW3 and CW8, respectively. At CW10 the arroyo top widths differed by 40 m (close to 100 percent). At CW8 and CW10, bankfull width was less than 2 m but at CW3 differed by 7 m (60 percent). For all three cross sections, arroyo top depths differed by as much as 2.9 m and bankfull depth differed by as much as 0.9 m (table 3).

Differences in channel geometry between the photogrammetric techniques and field surveys may be due to differences in the precise location of cross sections and scale. Channel geometry may change within a few meters upstream or downstream from the cross section. Changes may be greater in more sinuous reaches where channels alternate from impinging on the arroyo walls to being in a broad flood plain. Differences also are due to inherent errors in the photogrammetric techniques used to generate the elevations. Scale is an important consideration in the difference between the photogrammetric techniques and field surveys. Field surveys are done on a scale of 1:1, which allows for great detail and very little error. In contrast, the measurements from the photogrammetric sources were done from scales of either 1:6,000 (1973) or 1:3,000 (2000). Although measurements can be very good at these scales, achieving the same detail or accuracy that can be achieved at a 1:1 scale is extremely difficult.

For interpretive purposes, the 2000 field surveys were not compared to earlier photogrammetric interpretations of the same cross section. However, the relative changes in channel geometry at the same cross section in 1934, 1973, and 2000 using photogrammetric techniques and the contour map are acceptable.

Arroyo Geometry Changes

Arroyo geometry in 1934 at CW4, CW5, CW6, CW8, CW10, and CW11 was quantified from GIS interpretations of the 1931 and 1934 NPS contour maps (tables 4 and 5). Arroyo geometry in 1973 at CW4, CW5, CW6, CW8, CW10, and CW11 was quantified from photogrammetric interpretations. Field surveys at CW3, CW13, CW14, F1, and G1 were conducted between 1972 and 1977 (tables 4 and 5). Arroyo geometry in the 1970’s was based on an average of all measurements in the 1970’s. In the 2000 survey at cross section CW1, the survey was not completed far enough along the left bank to accurately define the arroyo top width and top depth. Changes of channel geometry in Chaco Wash for the 2000 survey upstream from Escavada Wash are shown in figure 9. No trend is evident in arroyo top width or area in an upstream direction. Top depth increases slightly upstream from Escavada Wash (fig. 9).

Table 3. Comparison of channel geometry using 2000 surveys and 2000 photogrammetric analysis for cross sections CW3, CW8, and CW10

[m, meter; m^2, square meter]

Method	Cross section (fig. 1)	Arroyo top width (m)	Arroyo top depth (m)	Arroyo top area (m^2)	50-percent width (m)	Bank-full width (m)	Bank-full depth (m)	Bank-full area (m^2)
Survey	CW3	115	6.0	435	104	10	1.6	11
Photogrammetry	CW3	125	5.0	416	98	17	1	9
Survey	CW8	91	7.5	457	85	8.3	1.9	8
Photogrammetry	CW8	73	4.6	182		7	1	5
Survey	CW10	83	7.7	309	47	7.1	1.7	7
Photogrammetry	CW10	43	6.1	177	37	8.8	1	8

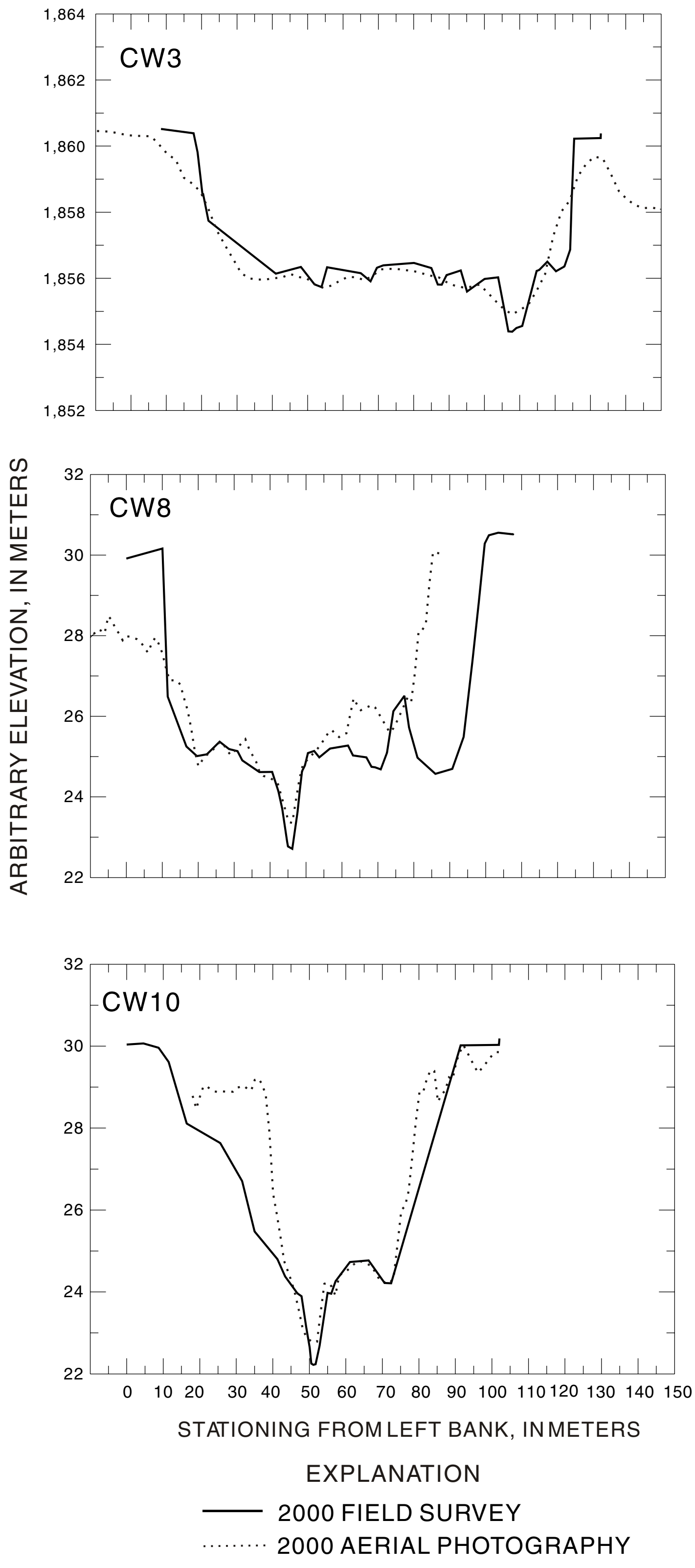


Figure 8. Comparison of surveyed channel cross sections to photogrammetric interpretations at Chaco Wash cross sections CW3, CW8, and CW10. Location of cross sections shown in figure 1.

Table 4. Arroyo geometry of Chaco Wash and selected tributaries: (A) 1934, (B) 1970's, and (C) 2000

[GIS, Geographical Information System; --, no data]

(A) 1934

Cross section (fig. 1)	Method used to quantify arroyo geometry	Arroyo top width, in meters	Arroyo top depth, in meters	Arroyo top cross-sectional area, in square meters
CW4	GIS	76	7.2	519
CW5	GIS	59	7.1	362
CW6	GIS	52	7.4	344
CW8	GIS	68	5.5	279
CW10	GIS	43	7.2	272
CW11	GIS	95	6.4	600

(B) 1970's

Cross section (fig. 1)	Method used to quantify arroyo geometry	Arroyo top width, in meters				
		1972	1973	1974	1976	1977
CW3	Survey	104	--	104	--	--
CW4	Photogrammetry	--	87	--	--	--
CW5	Photogrammetry	--	79	--	--	--
CW6	Photogrammetry	--	56	--	--	--
CW8	Photogrammetry	--	78	--	--	--
CW10	Photogrammetry	--	45	--	--	--
CW11	Photogrammetry	--	94	--	--	--
CW13	Survey	102	--	--	--	--
CW14	Survey	--	--	90	96	--
F1	Survey	61.6	--	--	61.3	--
G1	Survey	17.0	16.7	--	16.7	15.3

Table 4. Arroyo geometry of Chaco Wash and selected tributaries: (A) 1934, (B) 1970's, and (C) 2000--Concluded

(B) 1970's--Concluded

Cross section (fig. 1)	Arroyo top depth, in meters					Arroyo top cross-sectional area, in square miles				
	1972	1973	1974	1976	1977	1972	1973	1974	1976	1977
CW3	5.5	--	6.1	--	--	428	--	440	--	
CW4	--	5.3	--	--	--	--	414	--	--	--
CW5	--	5.8	--	--	--	--	355	--	--	--
CW6	--	5.8	--	--	--	--	244	--	--	--
CW8	--	3.8	--	--	--	--	136	--	--	--
CW10	--	6.0	--	--	--	--	204	--	--	--
CW11	--	6.1	--	--	--	--	477	--	--	--
CW13	10.6	--	--	--	--	672	--	--	--	
CW14	--	--	9.0	9.1	--	--	--	587	595	--
F1	7.6	--	--	7.5	--	345	--	--	330	
G1	3.3	--	--	3.2	3.6	36.8	--	--	40.4	35.6

(C) 2000

Cross section (fig. 1)	Method used to quantify channel geometry	Arroyo top width, in meters	Arroyo top depth, in meters	Arroyo top cross-sectional area, in square meters
CW1	Survey	Not surveyed	Not surveyed	Not surveyed
CW2	Photogrammetry	38	4.9	143
CW3	Survey	115	6.0	435
CW4	Photogrammetry	82	5.3	391
CW5	Photogrammetry	179	6.8	338
CW6	Photogrammetry	62	6.1	273
CW7	Survey	62.3	7.4	324
CW8	Photogrammetry	73	4.6	182
CW9	Survey	102	7.5	383
CW10	Photogrammetry	43	6.1	177
CW11	Photogrammetry	94	6.6	476
CW12	Photogrammetry	33	6.5	147
CW13	Survey	127	10.5	765
CW14	Survey	99.2	9.1	624
F1	Survey	61.5	7.6	308
G1	Survey	17.1	3.4	39.7

Table 5. Arroyo cross-sectional geometry at 50-percent depth

[--, no data]

(A) 1934

Cross section (fig. 1)	Width at 50-percent depth, in meters	Depth at 50-percent depth, in meters	Cross-sectional area at 50-percent depth, in square meters
CW4	75	5.0	319
CW5	55	4.8	210
CW6	47	5.1	220
CW8	55	3.8	147
CW9	--	--	--
CW10	38	4.9	147
CW11	83	4.2	284

(B) Selected years during the 1970's

Cross section (fig. 1)	Width at 50-percent depth, in meters			
	1977	1976	1974	1973
CW3	--	--	101	--
CW4	--	--	--	77
CW5	--	--	--	68
CW6	--	--	--	53
CW8	--	--	--	53
CW10	--	--	--	35
CW11	--	--	--	86
CW13	--	--	--	--
CW14	--	86.3	87.6	--
F1	--	54.7	--	--
G1	14.6	14.5	--	--

Table 5. Arroyo cross-sectional geometry at 50-percent depth--Continued

(B) Selected years during the 1970's--Concluded

Cross section (fig. 1)	Width at 50-percent depth, in meters				
	1977	**1976**	**1974**	**1973**	**1972**
CW3	--	--	3.9	--	3.3
CW4	--	--	--	3.0	--
CW5	--	--	--	3.5	--
CW6	--	--	--	3.4	--
CW8	--	--	--	2.1	--
CW10	--	--	--	3.6	--
CW11	--	--	--	3.9	--
CW13	--	--	--	--	6.0
CW14	--	5.6	5.4	--	--
F1	--	4.7	--	--	4.9
G1	2.4	2.0	--	--	2.1

Cross section (fig. 1)	Cross-sectional area at 50-percent depth, in meters				
	1977	**1976**	**1974**	**1973**	**1972**
CW3	--	--	229	--	209
CW4	--	--	--	163	--
CW5	--	--	--	162	--
CW6	--	--	--	128	--
CW8	--	--	--	52	--
CW10	--	--	--	85	--
CW11	--	--	--	214	--
CW13	--	--	--	--	281
CW14	--	301	321	--	--
F1	--	160	--	--	169
G1	22	21	--	--	15

Table 5. Arroyo cross-sectional geometry at 50-percent depth--Concluded

(C) 2000

Cross section (fig. 1)	Width at 50-percent depth, in meters	50-percent depth, in meters	Cross-sectional area at 50-percent depth, in square meters
CW1	45.8	2.7	21
CW2	29.7	2.4	49
CW3	104	3.8	204
CW4	72	3.0	192
CW5	69	4.5	161
CW6	55	3.8	112
CW7	60	3.7	91
CW8	58	2.9	61
CW9	50	3.7	74
CW10	37	3.8	80
CW11	87	4.4	166
CW12	23.2	3.2	52
CW13	86.7	5.9	263
CW14	90.9	5.6	291
F1	54.7	4.8	146
G1	14.8	2.2	21

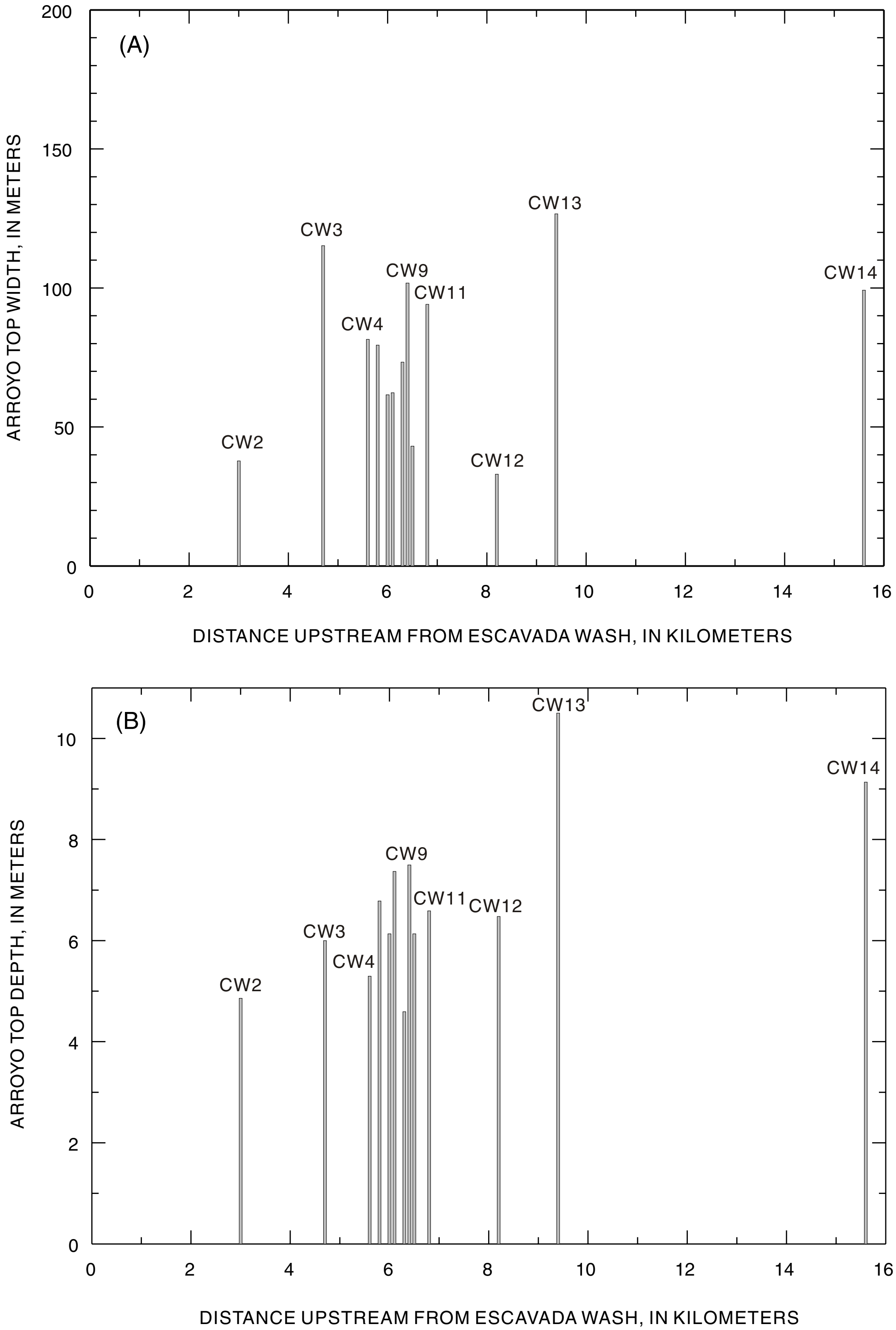


Figure 9. (A) Chaco Wash top width measurements from 2000 field surveys and photogrammetry and (B) top depth measurements from 2000 data. Location of cross sections shown in figure 1.

Arroyo Top Width

From 1934 to 1973, Chaco Wash arroyo top width increased at five of six cross sections (CW4, CW5, CW6, CW8, and CW10) (fig. 10A) and decreased 1 m at CW11. Widening at the five cross sections ranged from 2 to 20 m and averaged about 9 m. From the 1970's to 2000, changes in Chaco Wash top width were more variable, with increases at four of nine cross sections (CW3, CW6, CW13, and CW14), narrowing at three cross sections (CW4, CW8, and CW10), and no change in arroyo top width at CW5 and CW11 (fig. 10A). Widening at the four cross sections ranged from about 6 to 24 m and averaged 12 m. Narrowing of the channel ranged from 2 to 5 m. The largest increase in arroyo top width for any resurvey was 24 m at CW13 measured from the 1970's to 2000. Tributary arroyos F1 and G1 showed a small amount of widening from the 1970's to 2000, 0.1 and 0.8 m, respectively (fig. 10A). Overall, from 1934 to 2000 Chaco Wash widened at four of six cross sections on Chaco Wash (CW4, CW5, CW6, and CW8), narrowed at CW11, and remained the same at CW10. Widening at the four cross sections ranged from 5 to 20 m and averaged about 10 m.

An arroyo can narrow if sediment such as talus is deposited along arroyo walls. A decrease in arroyo top width is not expected because deposition is not possible on a vertical or near-vertical arroyo wall; the channel can narrow, however, if it is modified by human activity such as adding fill material to the channel. The narrowing of channel top widths at cross sections CW4, CW8, CW10, and CW11 was interpreted from aerial photography and may be due to inherent errors in photogrammetric examination of the data.

Arroyo Width at 50-Percent Depth

From 1934 to 1973, arroyo width at 50-percent depth increased at four of six cross sections (CW4, CW5, CW6, and CW11) (fig. 10B; table 5) and narrowed at two cross sections (CW8 and CW10). Widening at the four cross sections ranged from 3 to 13 m and averaged about 6 m. Narrowing was 2 m at CW8 and 3 m at CW10. From the 1970's to 2000, arroyo width at 50-percent depth increased at eight of nine cross sections (CW3, CW5, CW6, CW8, CW10, CW11, CW13, and CW14) and narrowed 6 m at CW4 (fig. 10B). Widening in these eight cross sections ranged from about 1 to 9 m and averaged about 3 m. The greatest increase in width at 50-percent depth was 13 m at CW5 from 1934 to 1973. Tributary arroyo F1 narrowed 0.7 m from the 1970's to 2000, and G1 widened 0.9 m (fig. 10B). Overall, measured changes at 50 percent of arroyo depth from 1934 to 2000 indicate widening in four of six cross sections (CW5, CW6, CW8, and CW11) on Chaco Wash and narrowing in two cross sections (CW4 and CW10). Widening in the four cross sections ranged from 3 to 14 m and averaged about 7 m. Narrowing was 3 m at CW4 and 1 m at CW10.

Overall widening at 50-percent depth is generally less than at the top of the arroyo, which may be due to colluvial deposits (talus aprons) developing along the arroyo walls from upslope bank failures. The narrowing at CW4 and CW10 from 1934 to 2000 may be due to talus deposits. Rates of widening at the top of the channel doubled from 0.2 m/yr during 1934-73 to 0.4 m/yr during the 1970's-2000 (fig. 11A). Rates of widening at 50-percent depth decreased from 0.2 m/yr (1934-73 cross sections) to 0.1 m/yr (1970's-2000) (fig. 11A).

Arroyo Top Depth

Changes in arroyo top depth were measured at selected cross sections from 1934 to 1973 and from the 1970's to 2000 (table 4). From 1934 to 1973, all six cross sections showed a decrease in depth, ranging from 0.3 to 1.9 m and averaging 1.4 m. From the 1970's to 2000, arroyo top depth increased at seven of nine cross sections (CW3, CW5, CW6, CW8, CW10, CW11, and CW14), decreased 0.1 m at CW13, and showed no change at CW4 (fig. 10C). The increase in depth at the seven cross sections ranged from 0.1 to 1.0 m and averaged 0.4 m. Tributary arroyos F1 and G1 showed no appreciable change in depth from the 1970's to 2000 (fig. 10C). The average rate of decreasing arroyo depth from 1934 to 1973 (0.04 m/yr) was higher than that from 1934 to 2000 (0.02 m/yr) (fig. 11B). Overall, from 1934 to 2000, arroyo top depth decreased at five of six cross sections (CW4, CW5, CW6, CW8, and CW10) and increased 0.2 m at cross section CW11 (fig. 10C; table 4). The decrease in depth ranged from 0.3 to 1.9 m and averaged 1.1 m.

Decreases in arroyo top depth are related to changes in the channel thalweg. Changes of the arroyo top surface are related to sheetwash and eolian activity and generally are negligible. The major cause for the decrease in depth is aggradation of the thalweg. In the Rio Puerco channel, an arroyo draining central New Mexico, the channel aggraded 2.55 m between 1936 and 1995 (Gellis and Elliott, 2001).

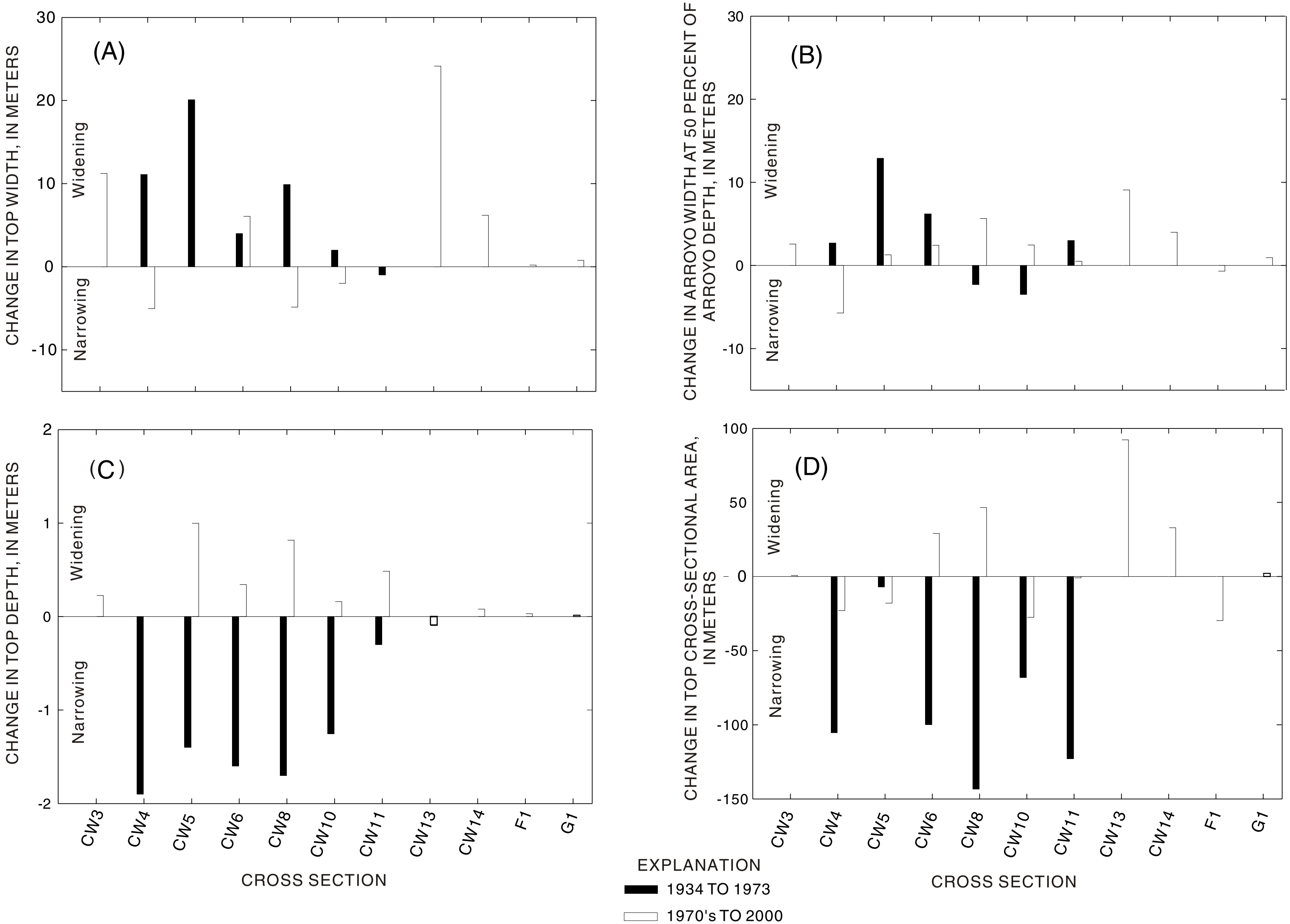


Figure 10. Changes in arroyo top geometry at selected cross sections along Chaco Wash and selected tributaries. (A) Top width, (B) top width at 50 percent of arroyo depth, (C) arroyo top depth, and (D) top cross-sectional area. Location of cross sections shown in figure 1.

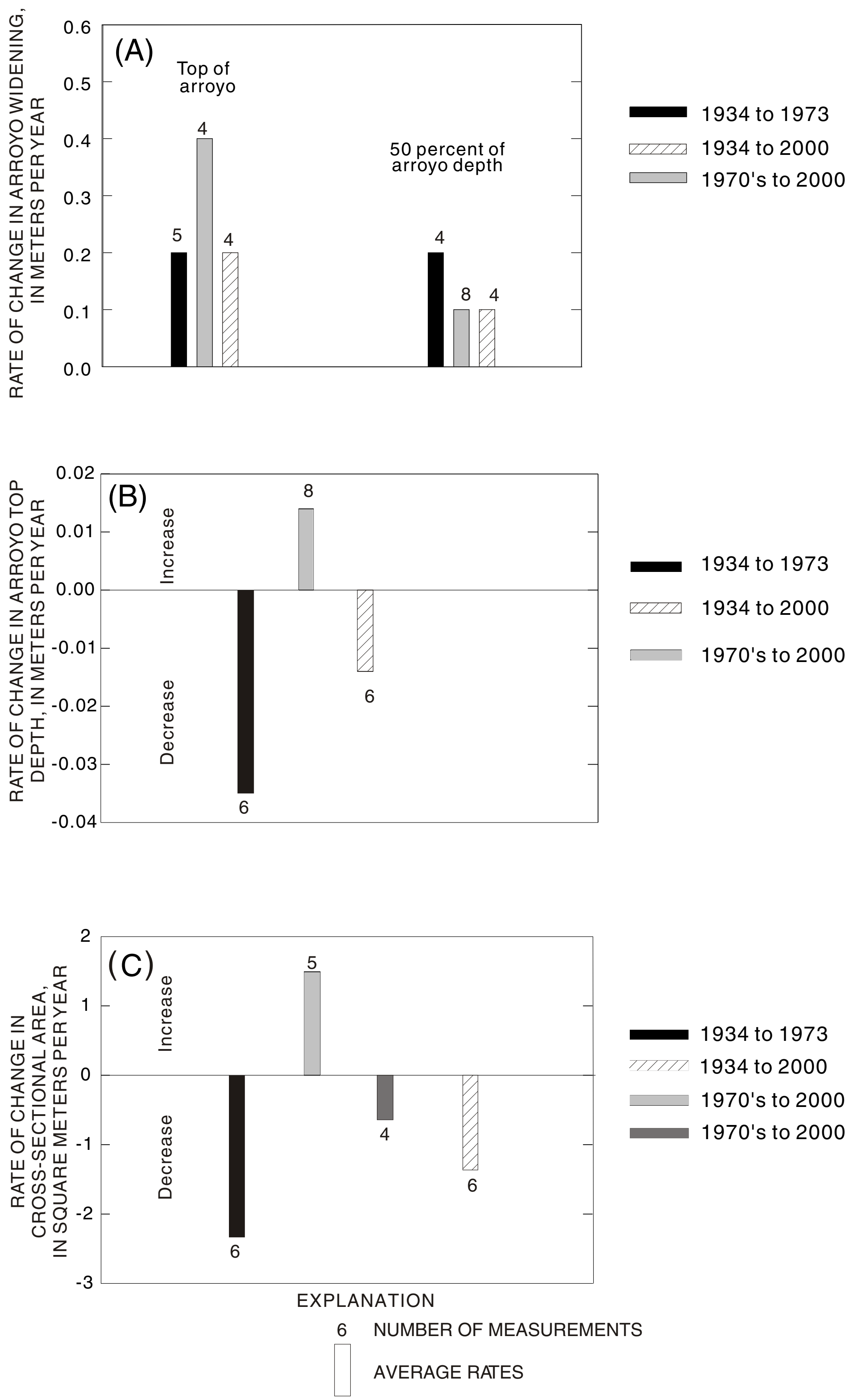


Figure 11. Average rates of (A) arroyo widening, (B) arroyo top depth, and (C) top cross-sectional area at selected cross sections along Chaco Wash and selected tributaries.

Arroyo Cross-Sectional Area

Changes in cross-sectional area are an informative way to determine erosion and deposition for the arroyo. From 1934 to the 1970's, all six cross sections showed a decrease in arroyo top cross-sectional area, ranging from 7 to 143 m^2 and averaging 91 m^2 (fig. 10D). Between the 1970's and 2000, changes in arroyo top cross-sectional area varied, increasing at five cross sections (CW3, CW6, CW8, CW13, and CW14) and decreasing at four cross sections (CW4, CW5, CW10, and CW11) (fig. 10D). Increases in area at the five cross sections ranged from 1 to 92 m^2 and averaged 40 m^2. Decreases in area for the four cross sections ranged from 1 to 28 m^2 and averaged 17 m^2. The greatest decrease in arroyo top cross-sectional area was 143 m at CW8 from 1934 to 1973. The greatest increase in arroyo top cross-sectional area was 92 m at CW13 from the 1970's to 2000. Tributary arroyo F1 showed a decrease in arroyo top cross-sectional area of 30 m^2 from the 1970's to 2000, and G1 showed no appreciable change in the same period (fig. 10D). Overall, from 1934 to 2000, arroyo top cross-sectional area decreased at six cross sections (CW4, CW5, CW6, CW8, CW10, and CW11) (fig. 10D). Decreases in arroyo top cross-sectional area ranged from 24 to 128 m^2 and averaged 90 m^2.

The average rate of decrease in cross-sectional area from 1934 to 1973 was 2.3 m^2/yr (fig. 11C). This rate decreased to 0.6 m^2/yr for the four cross sections (CW4, CW5, CW10, and CW11) that continued to decrease in cross-sectional area from the 1970's to 2000 (fig. 11C). The average rate of increase in cross-sectional area was 1.6 m^2/yr at the five cross sections where area increased from the 1970's to 2000 (fig. 11C).

Volumetric Changes in Chaco Wash

Changes in the volume of the six reaches shown in figure 5 were quantified over time. From 1934 to 1973, sediment was deposited in all six reaches and ranged from 6,700 to 26,600 m^3. By dividing the volume filled (109,200 m^3) from 1934 to 1973 over the length of channel (1.7 km), the cross-sectional area filled per unit length of channel of 64 m^2 or 1.65 m^2/yr can be calculated. From 1973 to 2000, four of the six reaches showed erosion or an increase in volume (table 6) ranging from 3,300 to 4,500 m^3 and two of the reaches showed deposition of 400 and 1,800 m^3. The cross-sectional area eroded 7 m^2 per unit length of channel or 0.27 m^2/yr. Overall, volume calculations along six reaches of Chaco Wash from 1934 to 2000 (table 6) showed sediment deposition in all reaches ranging from 8,500 to 23,200 m^3. For the entire 1.7 km, the arroyo filled about 96,900 m^3 or 57 m^2 per unit length of channel (0.87 m^2/yr). The volume decreased at a rate of 130 to 350 m^3/yr at all reaches.

Changes in planimetric area show widening of the channel for all reaches from 1934 to 2000 (table 6). Five of six reaches show greater rates of widening from 1973 to 2000 than from 1934 to 1973. Reaches 3 and 4, near Pueblo del Arroyo (fig. 5), show greater increases in planimetric area, 87 and 62 m^2/yr, respectively, from 1973 to 2000 than the rates of 6 and 21 m^2/yr from 1934 to 1973.

Inner-Channel Changes

In 1934, Chaco Wash channel was a broad, braided channel without a well-defined inner channel (DeAngelis, 1972). Because of this lack of a well-defined inner channel, determining bankfull geometry is difficult. A well-defined inner channel is evident from the 1970's to 2000; thus, bankfull geometry is easier to discern. Bankfull width in 1934 was generally selected along the arroyo wall near the bottom of the channel where a break in slope is observed. Bankfull depth and cross-sectional area were not quantified.

Geometry for the bankfull channel for 1934, selected years during the 1970's, and 2000 is shown in table 7. From 1934 to 1973 all six cross sections showed a decrease in bankfull width, ranging from 0.4 to 45 m and averaging 26 m (fig. 12A). Narrowing continued at seven of nine cross sections from the 1970's to 2000, ranging from 1.9 to 19.3 m and averaging 9 m (fig. 12A). From the 1970's to 2000, CW4 showed widening of 8 m and CW5 showed little change (fig. 12A). Overall, from 1934 to 2000, narrowing was the dominant form of change in bankfull width and occurred in all six cross sections on Chaco Wash (fig. 12A). Narrowing ranged from 13 to 55 m (table 7) and averaged 30 m. Rates of channel narrowing from 1934 to 1973, averaging 0.7 m/yr, were generally greater than rates from the 1970's cross-sectional survey to 2000, averaging 0.3 m/yr (fig. 13).

Because of the problems discussed earlier in defining bankfull depth from the 1934 cross sections, changes in bankfull depth and cross-sectional area are shown only from the 1970's to 2000 (fig. 12B,C). From the 1970's to 2000, bankfull depth increased at six of nine cross sections on Chaco Wash (CW3, CW5, CW6, CW8, CW11, and CW14), ranging from 0.2 to 1.2 m and averaging 0.5 m (fig. 12B). From the 1970's to 2000, CW4 showed no change in bankfull depth. Depth in tributary arroyos F1 and G1 showed an increase of 0.1 m and a decrease of 0.1 m, respectively (fig. 12B).

Table 6. Change in sediment volume, area, and depth of the arroyo channel at selected reaches in Chaco Wash

[--, no data]

Location-year (fig. 5)	Volume, in cubic meters	Planimetric area, in square meters	Change in volume, in cubic meters/year			Difference in planimetric area, in square meters/year		
			1934-73	1973-2000	1934-2000	1934-73	1973-2000	1934-2000
Reach 1-2000	83,200	25,300	-450	160	-200	43	218	115
Reach 1-1973	78,700	19,500	--	--	--	--	--	--
Reach 1-1934	96,400	17,800	--	--	--	--	--	--
Reach 2-2000	103,600	30,300	-170	-70	-130	0	6	2
Reach 2-1973	105,400	30,100	--	--	--	--	--	--
Reach 2-1934	112,100	30,100	--	--	--	--	--	--
Reach 3-2000	70,900	18,600	-550	120	-270	6	87	39
Reach 3-1973	67,600	16,300	--	--	--	--	--	--
Reach 3-1934	89,000	16,000	--	--	--	--	--	---
Reach 4-2000	70,000	18,100	-600	130	-300	21	62	38
Reach 4-1973	66,600	16,400	--	--	--	--	--	--
Reach 4-1934	89,900	15,600	--	--	--	--	--	--
Reach 5-2000	83,100	24,500	-350	-10	-210	68	88	76
Reach 5-1973	83,500	22,100	--	--	--	--	--	--
Reach 5-1934	97,000	19,500	--	--	--	--	--	--
Reach 6-2000	91,400	24,000	-680	120	-350	89	16	59
Reach 6-1973	88,000	23,500	--	--	--	--	--	--
Reach 6-1934	114,600	20,000	--	--	--	--	--	---
Combined reaches 2000	502,200	140,800	-2,800	460	-1,470	227	478	330
Combined reaches 1973	489,800	127,900	--	--	--	--	--	--
Combined reaches 1934	599,100	119,000	--	--	--	--	--	--

Table 7. Bankfull geometry of Chaco Wash and selected tributaries: (A) 1934, (B) 1970's, and (C) 2000

[--, no data]

(A) 1934

Cross section (fig. 1)	Bankfull width, in meters	Bankfull depth, in meters	Bankfull cross-sectional area, in square meters
CW4	59	1.7	86
CW5	36	0.6	16
CW6	44	1.1	41
CW8	38	1.5	51
CW10	22	0.9	17
CW11	64	1.5	67

(B) 1970's

Cross section (fig. 1)	Bankfull cross-sectional area, in square meters				
	1977	**1976**	**1974**	**1973**	**1972**
CW3	--	--	10.5	--	7.2
CW4	--	--	--	8	--
CW5	--	--	--	11	--
CW6	--	--	--	4	--
CW8	--	--	--	14	--
CW9	--		--	--	--
CW10	--	--	--	28	--
CW11	--	--	--	19	--
CW13	--	--	--	--	38.7
CW14	--	9.9	8.9	--	--
F1	--	29.5	--	--	31.8
G1	5.1	3.7	--	--	6.0

Table 7. Bankfull geometry of Chaco Wash and selected tributaries: (A) 1934, (B) 1970's, and (C) 2000--Concluded

(C) 2000

Cross section (fig. 1)	Bankfull width, in meters	Bankfull depth, in meters	Bankfull cross-sectional area, in square meters
CW1	8.5	2.0	10.8
CW2	21.3	1.6	24.9
CW3	10.4	1.6	11.1
CW4	28	0.8	17
CW5	13	2.2	13
CW6	8	1.4	6
CW7	10.4	2.5	12.9
CW8	7	1.2	5
CW9	6.5	1.8	6.1
CW10	9	1.4	8
CW11	9	2.1	8
CW12	11	0.8	5
CW13	6.3	1.4	5.1
CW14	6.9	2.0	7.3
F1	17.6	2.0	15.8
G1	8.8	1.0	5.1

From the 1970's to 2000, bankfull cross-sectional area changes were variable (fig. 12C); four cross sections (CW3, CW4, CW5, and CW6) showed increases in area ranging from 2 to 9 m^2 and averaging 4 m^2. Cross-sectional area at five sites (CW8, CW10, CW11, CW13, and CW14) showed decreases ranging from 2 to 34 m^2 and averaging 15 m^2 (fig. 12C). Tributary arroyo F1 showed filling of 15 m^2, and G1 showed no appreciable change in area (fig. 12C).

Love (1979) documented the adjustment of Chaco Wash from a braided channel in the 1930's to a channel with a well-defined flood plain by the 1970's. The braided form of the channel in the 1930's may have been a response to increased discharge (Love, 1980) or to an increase in sediment supply (Schumm, 1977). Love (1980) speculated that periods of less than average rainfall were favorable for deposition and that periods of greater than normal rainfall favored erosion. Channel narrowing resulted from the development of the modern flood plain, which began by 1939 (Love, 1979). Following incision, the arroyo channel widens (fig. 4C). The arroyo channel may widen to a width at which it can no longer transport sediment; thus, sediment is deposited, the channel aggrades, and an incipient flood plain is developed (fig. 4D). Vegetation establishes itself on the flood plain, stabilizes the inner channel, and increases roughness, which further enhances sediment deposition on the flood plain. Similar changes in arroyo geometry from a braided channel to a well-developed inner channel have been documented for the lower reaches of the Rio Puerco (Elliott and others, 1999). The increase in bankfull depth is from aggradation of the flood plain. Scour of the channel also increases bankfull depth. Because arroyo top depth increased at seven of nine cross sections from the 1970's to 2000 (fig. 10C), channel scour or lowering of the thalweg elevation may also be a factor in the increase in bankfull depth. Because a decrease in cross-sectional area was observed in all cross sections from 1934 to 2000 (fig. 10D), channel scour alone cannot explain the increase in bankfull depth.

Longitudinal and Planform Changes

Contour maps created from the 1934 topographic maps and 1973 and 2000 aerial photographs (figs. 14A-C) were used to describe longitudinal profile changes and planform changes of the arroyo. Planform changes in the arroyo are viewed from above. The longitudinal profile extends from reach 1 to reach 6 (fig. 5). The longitudinal profile of the channel (fig. 15A) shows net aggradation of the channel for all reaches from 1934 to 1973. This matches the results of the photogrammetric interpretations (fig. 7). From 1973 to 2000, reaches from 0 to 1,000 m upstream showed degradation of the channel (fig. 15A). This includes cross sections CW3, CW4, CW5, CW6, CW8, CW10, and CW11, which showed decreases in channel depth (fig. 10C). From 1973 to 2000, reaches from 1,000 to more than 1,500 m upstream (fig. 15A) showed no appreciable change in channel elevation.

Elevations were averaged in 250-m increments to determine elevation changes through the six reaches. Average elevation increases (aggradation) of the channel from 1934 to 1973 ranged from 0.2 to 1.4 m (fig. 15B). Decreases in elevation from 0 to 1,000 m upstream showed degradation of 0.4 to 0.8 m (fig. 15B).

Planform changes in Chaco Wash show arroyo top width widening from 1934 to 1973 and little change from 1973 to 2000 (fig. 16). The planform changes closely match the interpretations of arroyo top width changes from the field resurveys and photogrammetric interpretations. Planform changes in Chaco Wash show bankfull width narrowing from 1934 to 1973 and from 1973 to 2000 (fig. 17). Most of the narrowing was between 1934 and 1973.

Changes near Pueblo del Arroyo

Three cross sections (CW6, CW8, and CW10) were used to assess changes in Chaco Wash geometry over time near Pueblo del Arroyo. From 1934 to 2000, the arroyo top widened at CW6 (10 m) and CW8 (5 m) and showed no change at CW10 (fig. 10A; table 4). From 1934 to 2000, CW6 widened 9 m, CW8 widened 3 m, and CW10 narrowed 1 m (fig. 10B) at 50-percent depth. From 1934 to 2000 near Pueblo del Arroyo, three cross sections (CW6, CW8, and CW10) showed decreasing arroyo depths close to 1 m (fig. 10C). From 1973 to 2000, these same three cross sections showed an increase in depth from 0.2 to 0.8 m (fig. 10C). From 1934 to 2000, CW6, CW8, and CW10 showed decreases in cross-sectional area of 71, 97, and 96 m^2, respectively (fig. 10D). From the 1970's to 2000, CW6 and CW8 showed increases in cross-sectional area of 29 and 46 m^2, respectively. CW10 decreased 27 m^2 in cross-sectional area from the 1970's to 2000 (fig. 10D). Chaco Wash geometry changes near Pueblo del Arroyo are similar to changes elsewhere in the CCNHP. Between 1934 and 2000, Chaco Wash widened and aggraded. In the more recent time period, 1973-2000, Chaco Wash near Pueblo del Arroyo incised and increased in cross-sectional area.

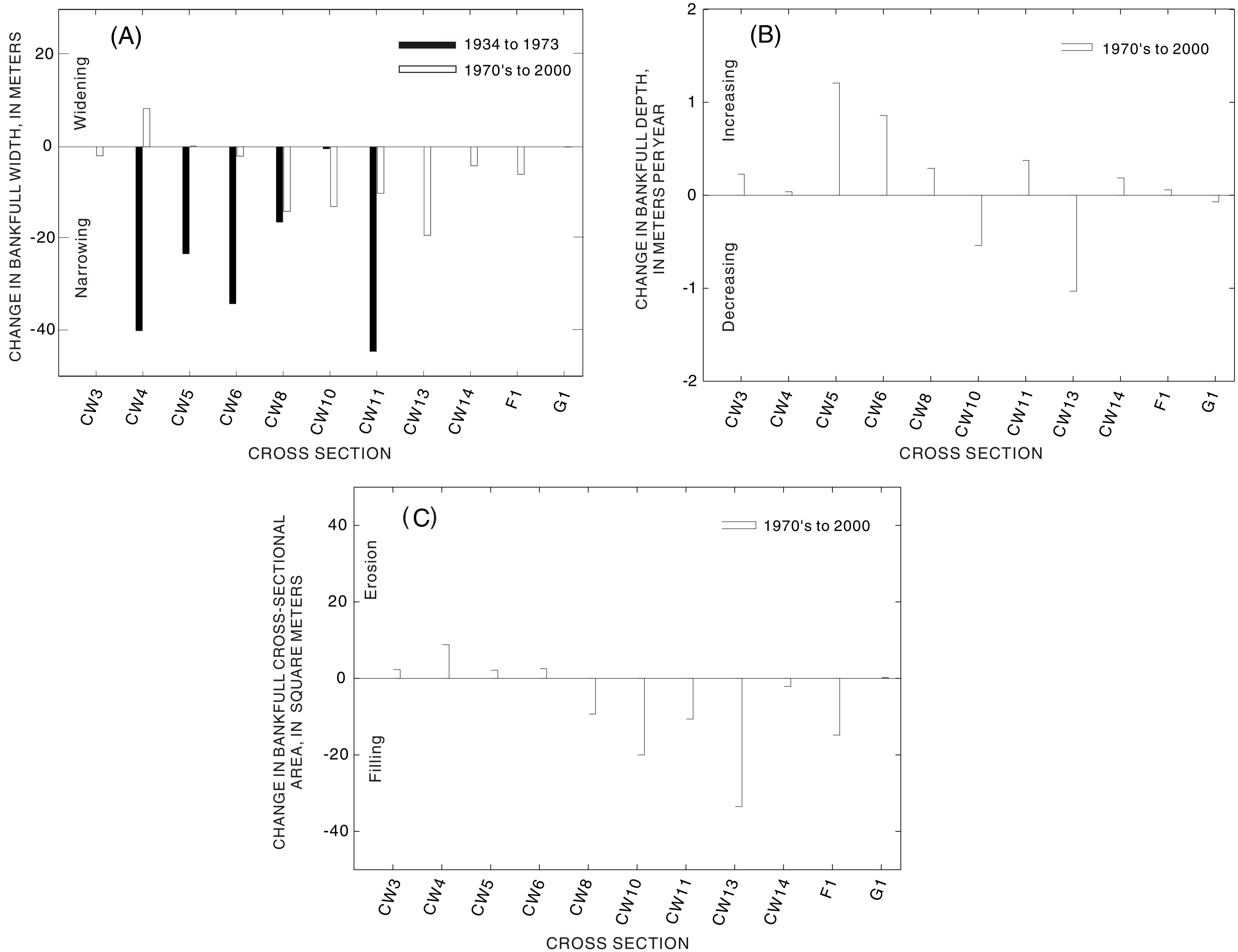


Figure 12. Changes in bankfull along Chaco Wash and selected tributaries. (A) Width, (B) depth, and (C) cross-sectional area. Location of cross sections shown in figure 1.

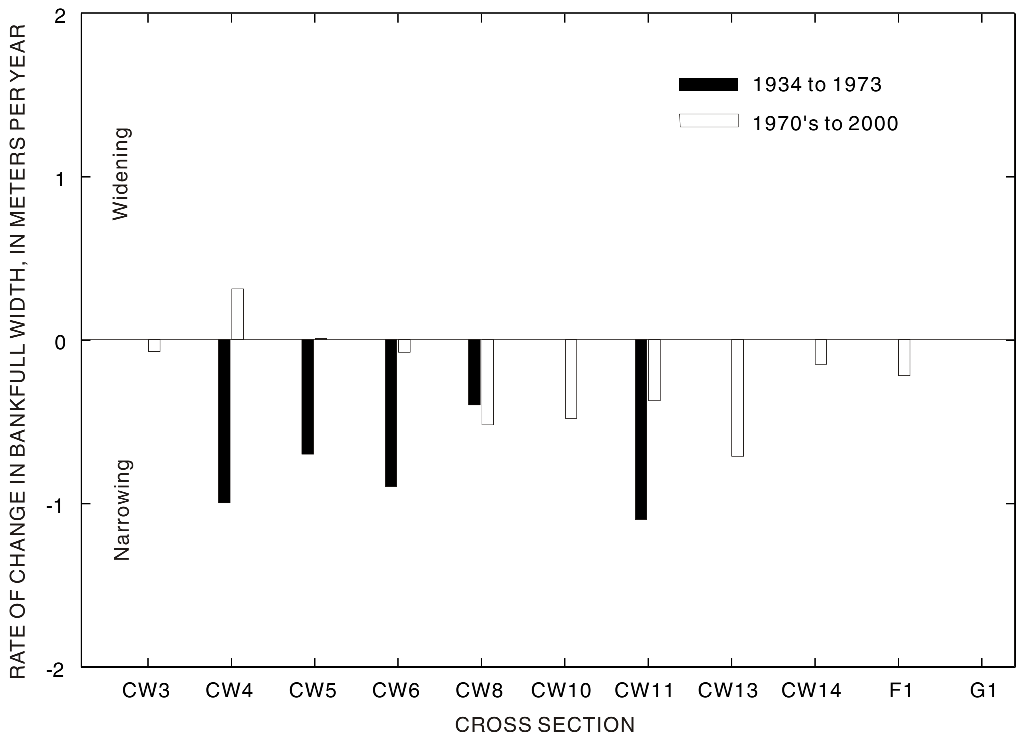


Figure 13. Rates of change in bankfull width from 1934 to 1973 and from the 1970's to 2000.

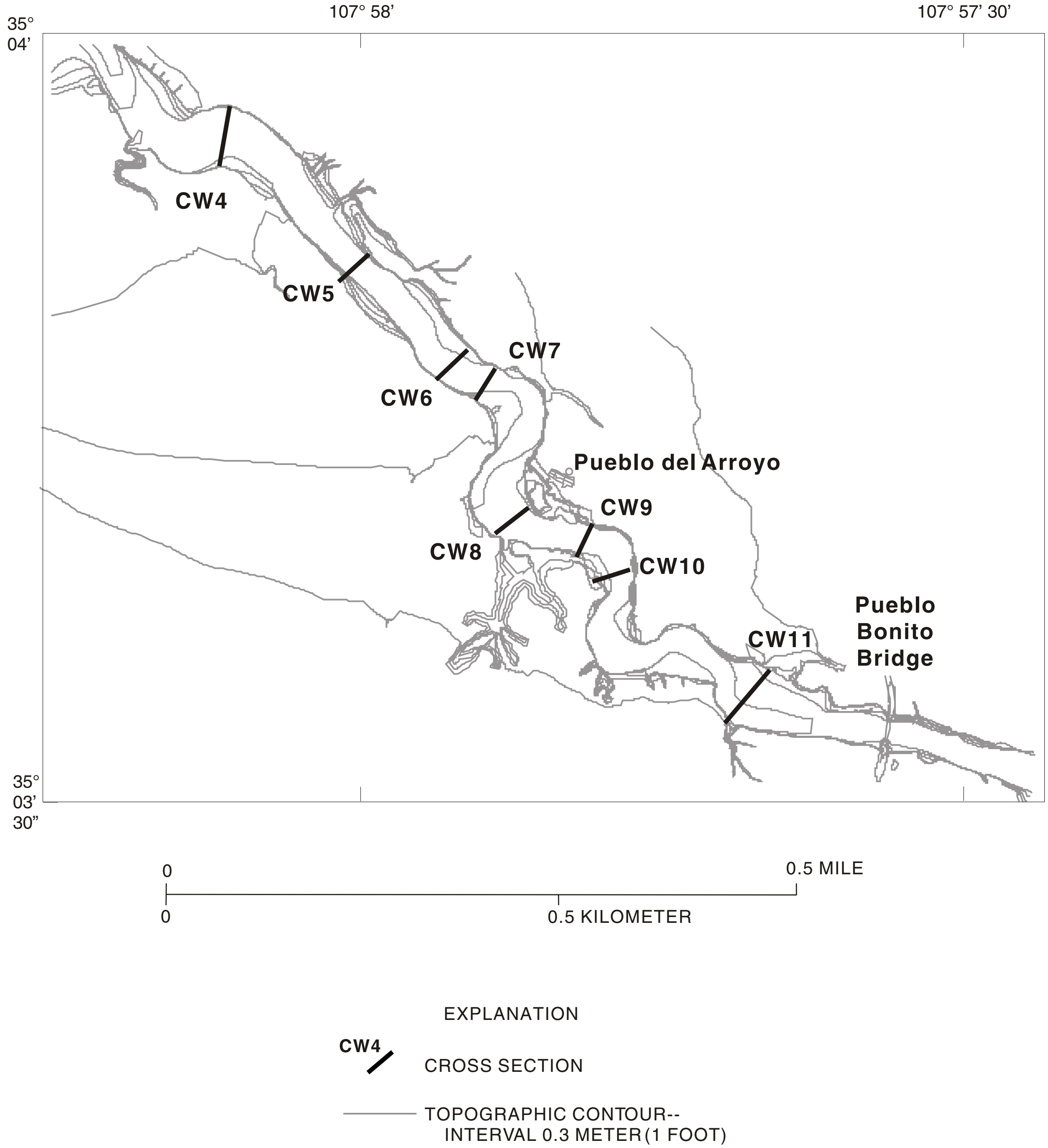


Figure 14A. Topographic contours in relation to selected cross sections along Chaco Wash in Chaco Culture National Historical Park. Contours generated from 1934 National Park Service 1:480 contour map. Location of this extent of Chaco Wash shown in figure 1.

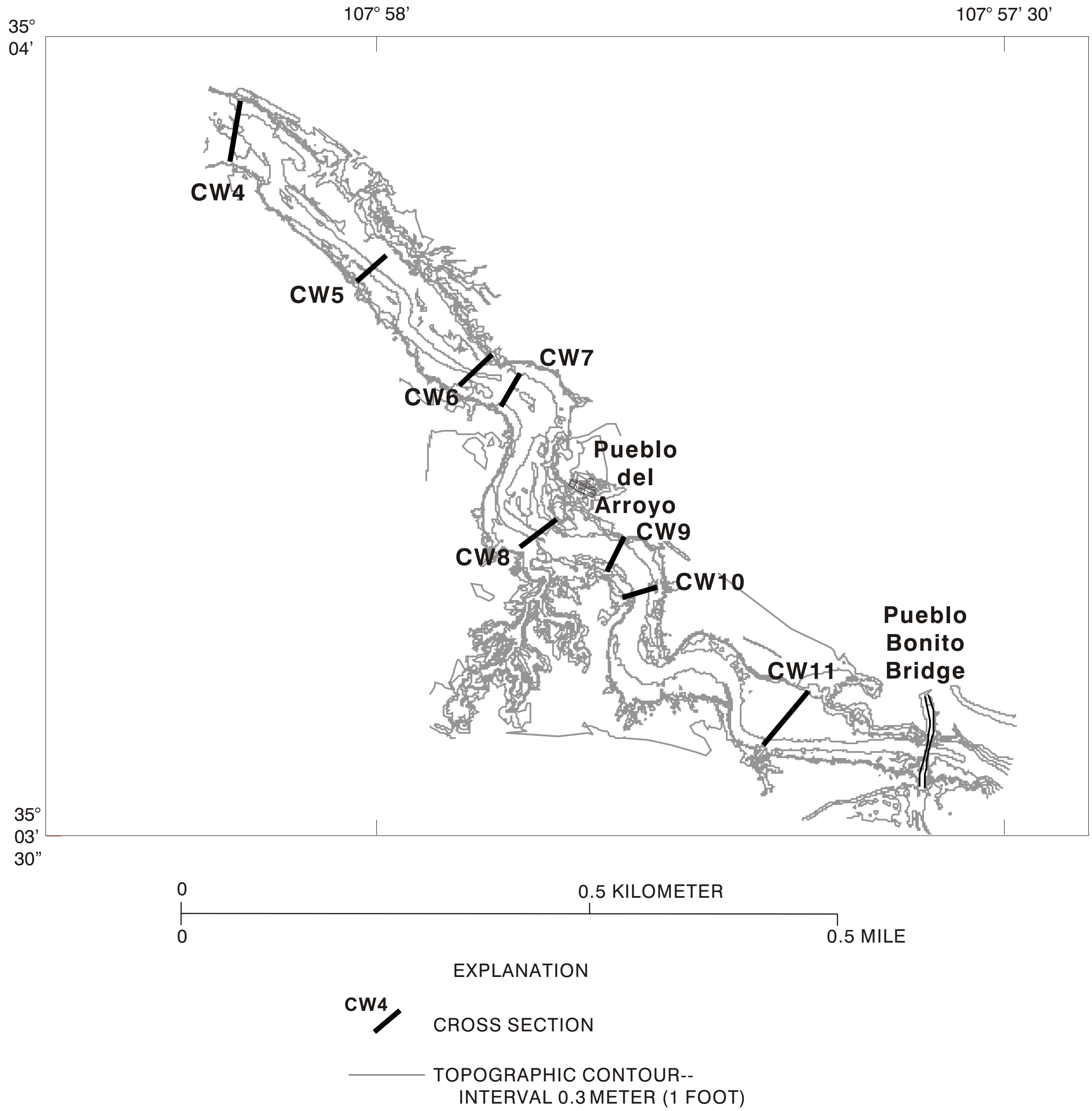


Figure 14B. Topographic contours in relation to selected cross sections along Chaco Wash in Chaco Culture National Historical Park. Contours generated from 1973 aerial photography. Location of this extent of Chaco Wash shown in figure 1.

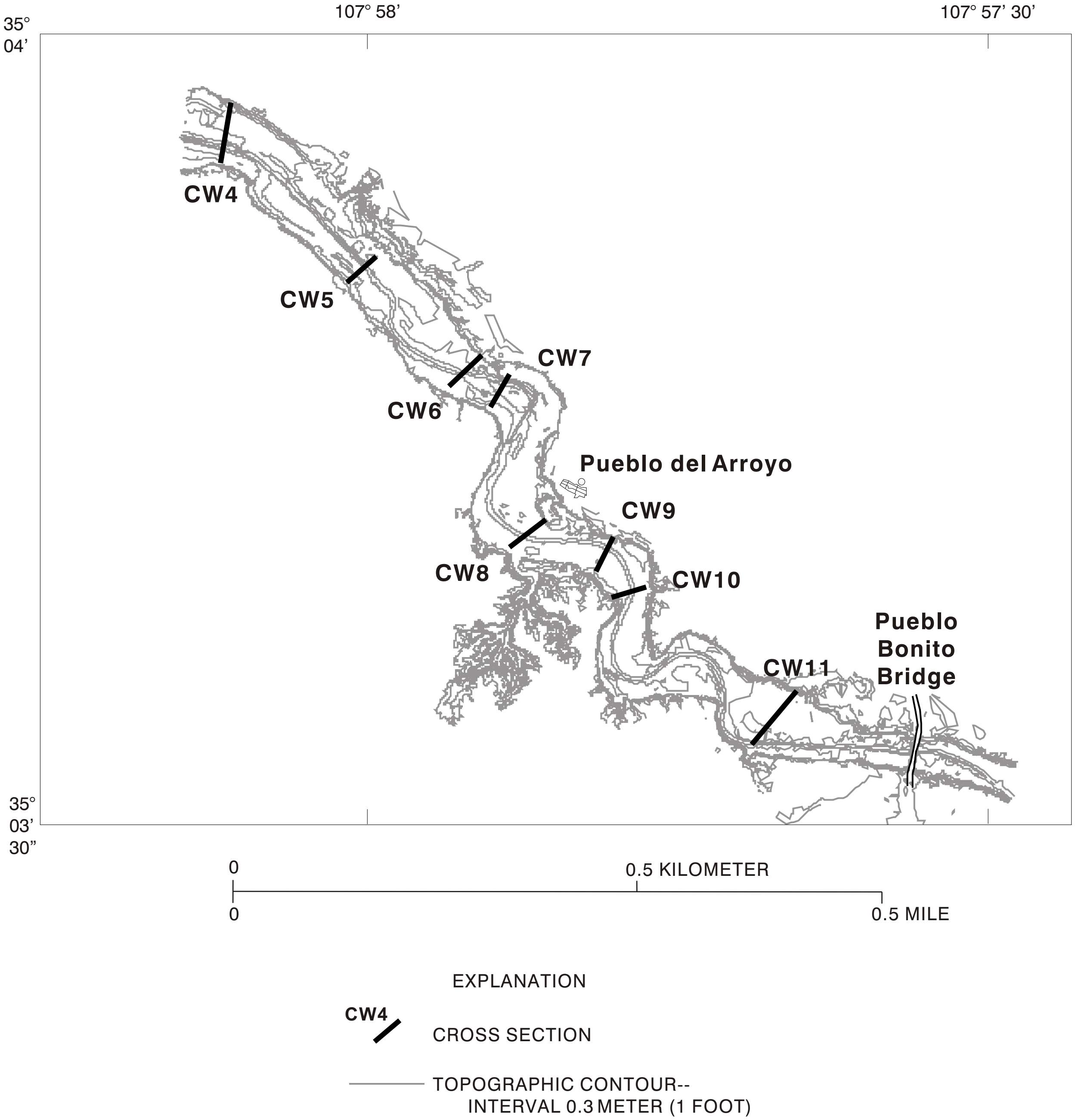


Figure 14C. Topographic contours in relation to selected cross sections along Chaco Wash in Chaco Culture National Historical Park. Contours generated from 2000 aerial photography. Location of this extent of Chaco Wash shown in figure 1.

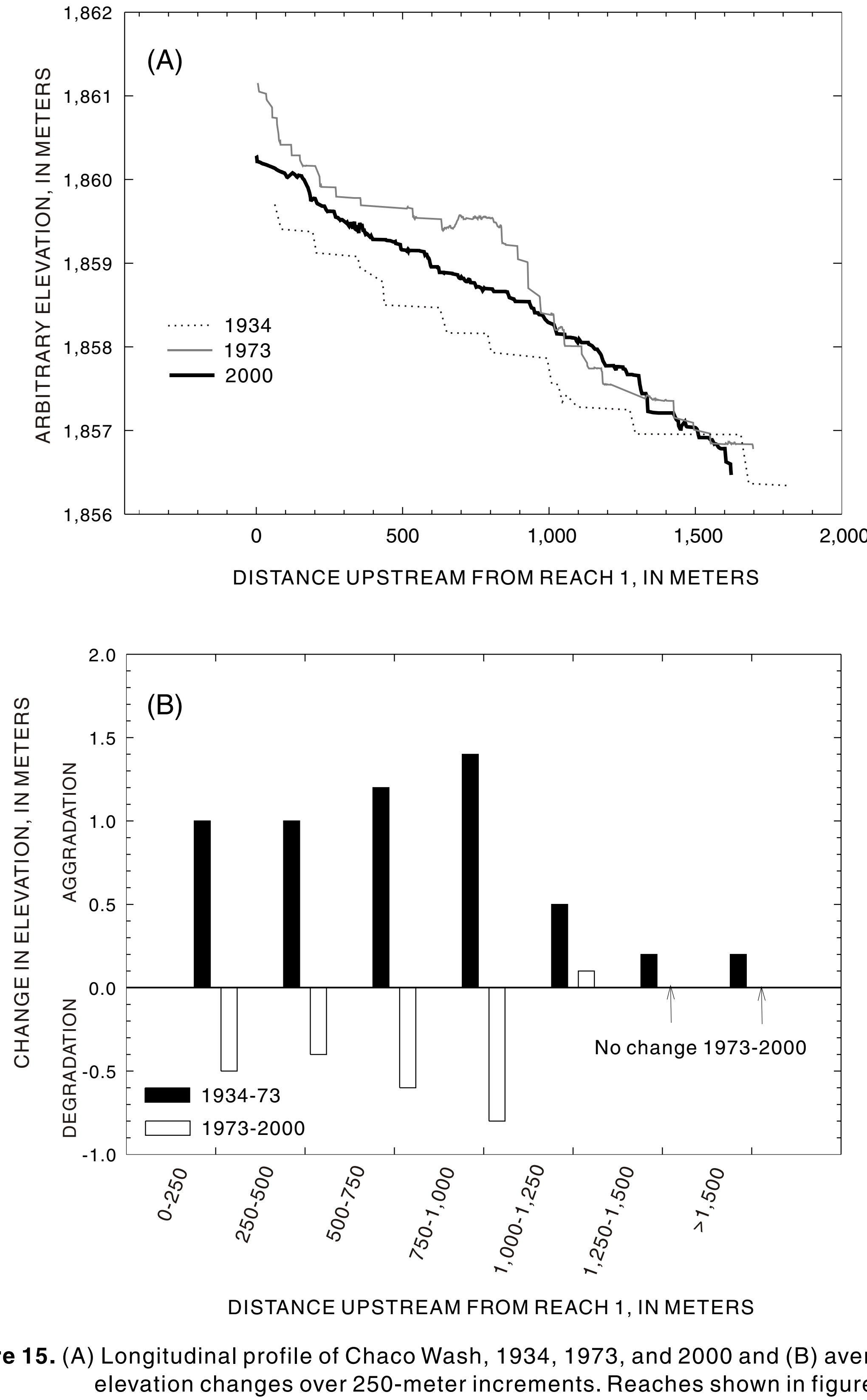


Figure 15. (A) Longitudinal profile of Chaco Wash, 1934, 1973, and 2000 and (B) average elevation changes over 250-meter increments. Reaches shown in figure 5.

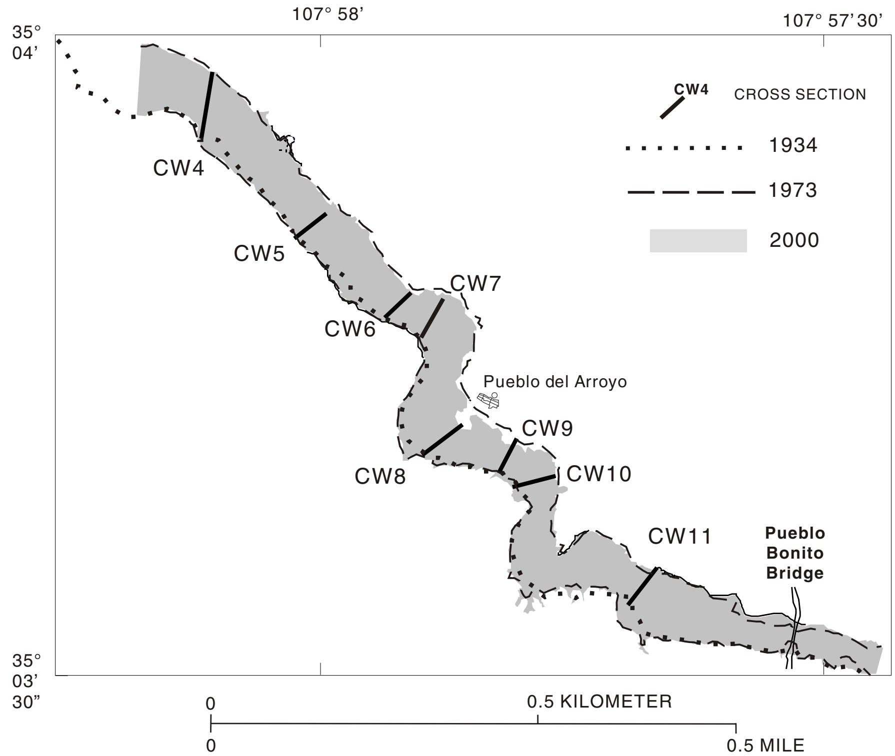


Figure 16. Top width cross-sectional measurements along Chaco Wash in 1934, 1973, and 2000. Location of this extent of Chaco Wash shown in figure 1.

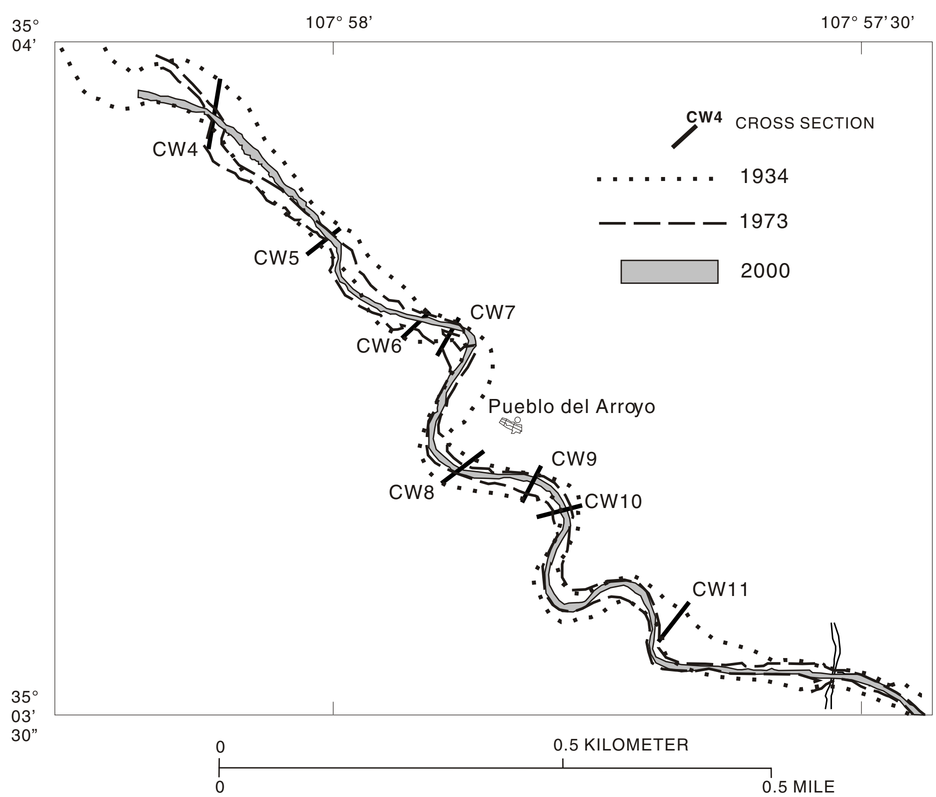


Figure 17. Bankfull width cross-sectional measurements along Chaco Wash in 1934, 1973, and 2000. Location of this extent of Chaco Wash shown in figure 1.

SUMMARY

Trends in arroyo channel geometry for Chaco Wash and selected tributaries were assessed through photogrammetric techniques and field resurveys for three time periods: 1934-2000, 1934-1973, and 1973-2000. Maximum vertical errors associated with photogrammetric techniques average less than ±0.75 m with a maximum error of ±2.0 to ±2.5 m. Maximum horizontal errors average ±0.66 m with a maximum error of ±2.0.

Five of the six photogrammetrically analyzed cross sections in Chaco Wash show net aggradation between 1934 and 2000 ranging from 0.4 to 1.9 m and averaging 1.1 m, with most of the aggradation occurring between 1934 and the 1970’s. Photogrammetric analysis at cross sections and reaches and field surveys indicate net widening from 1934 to 2000 at the top of Chaco Wash and at 50-percent depth.

The volume of the Chaco Wash arroyo decreased from filling with sediment at all reaches from 1934 to 2000 and ranged from 130 to 350 m^3/yr. For the entire 1.7 km, the arroyo filled 96,900 m^3 or 57 m^2 per unit length of channel. Similar results for the channel filling with sediment were obtained from the cross sections where the cross-sectional area decreased from 1934 to 2000, ranging from 25 to 128 m^2 and averaging 90 m^2. A decrease in cross-sectional area is due to aggradation on the channel bed and sediment deposition on the flood plain.

Channel changes of width, depth, and cross-sectional area are variable both in time and space. Five of six cross sections widened between 1934 and 1973, and four of nine cross sections widened between the 1970’s and 2000. At 50-percent depth, four of six cross sections widened between 1934 and 1973 and widened at eight of nine cross sections between the 1970’s and 2000. Rates of widening at the top of the channel doubled from 0.2 m/yr (1934 to 1973 cross sections) to 0.4 m/yr (1970’s to 2000 cross sections). The top of the channel widened from sheetwash, gullying, and soil piping on the alluvial valley floor and from bank collapse resulting from an increase in channel sinuosity. Widening at the top of the channel has the potential to affect cultural sites. Rates of arroyo widening at 50-percent depth decreased from 0.2 m/yr (1934 to 1973 cross sections) to 0.1 m/yr (1970’s to 2000 cross sections). Narrowing of the arroyo at 50-percent depth may be due to talus deposits.

All cross sections on Chaco Wash showed aggradation from 1934 to 1973 that ranged from 0.3 to 1.9 m and averaged 1.4 m. The aggradation trend reversed between the 1970’s and 2000; most cross sections (seven of nine) showed an increase in arroyo depth or degradation ranging from 0.1 to 1.0 m and averaging 0.4 m. Between 1934 and 1973, all six cross sections filled with sediment and decreases in cross-sectional area ranged from 7 to 143 m^2 and averaged 91 m^2. From the 1970’s to 2000 changes in cross-sectional area were variable, increasing at five cross sections and decreasing at four cross sections. The average rate of arroyo filling was greater between 1934 and 1973 (2.3 m^2/yr) than for cross sections that continued to fill between the 1970’s and 2000 (0.6 m^2/yr).

Bankfull depth increased over time as the flood plain developed. Bankfull width continued to narrow at six of nine cross sections between the 1970’s and 2000. The inner channel may have stabilized through colonization of vegetation, some of which was planted as part of erosion-control strategies in the CCNHP. After the 1970’s, channel depth increased at seven of nine cross sections through bed scour or flood-plain aggradation.

Changes in Chaco Wash since the 1930’s match interpretations from previous investigations. The inner channel of Chaco Wash evolved from a braided channel in the 1930’s to a narrower, well-defined inner channel by the 1970’s. Chaco Wash was widening in the 1930’s, leading to sediment deposition and formation of an inner flood plain. Bankfull width narrowed from 1934 to 2000, ranging from 13 to 55 m and averaging 30 m. All cross sections showed narrowing of the inner channel from 1934 to 1973, ranging from 0.4 to 45 m and averaging 26 m. Channel narrowing continued from the 1970’s to 2000, with six cross sections decreasing in bankfull width. Average rates of bankfull narrowing were greater from 1934 to 1973 (0.7 m/yr) than from the 1970’s to 2000 (0.3 m/yr). Channel narrowing resulted from increased sediment deposition on the flood plain related to a decrease in peak flows; an increase in flood-plain vegetation, some of which was planted as part of erosion-control strategies; or an increase in the transport of fine-grained sediment.

Bankfull depth increased in most cross sections (seven of nine) on Chaco Wash from the 1970’s to 2000, ranging from 0.04 to 1.2 m and averaging 0.5 m. The increase in bankfull depth may be due to formation of a flood plain or channel scour. Changes in bankfull area between the 1970’s and 2000 were variable, with four cross sections increasing in area and five cross sections decreasing in area.

Changes in arroyo and bankfull geometry of width, depth, and cross-sectional area in tributary cross sections F1 and G1 were minor compared with those in Chaco Wash. A decrease in cross-sectional area from the 1970's to 2000 was noticeable at F1.

Changes in arroyo top width, arroyo depth, and arroyo cross-sectional area near Pueblo del Arroyo are similar to changes for all the study area. Arroyo top width increased in two of three cross sections by 5 and 10 m, respectively. Arroyo width at 50-percent depth in the channel increased at two of three cross sections by 9 and 3 m, respectively. Near Pueblo del Arroyo, arroyo depths decreased between 1934 and 1973 and increased between 1973 and 2000. From 1934 to 2000, the arroyo depth near Pueblo del Arroyo had a net decrease. The net change in cross sections between 1934 and 2000 around Pueblo del Arroyo was a decrease in cross-sectional area. Cross-sectional area decreased between 1934 and 1973 and increased in two of three cross sections between the 1970's and 2000. The average rate of decrease in cross-sectional area was greater between 1934 and 1973 (2.3 m^2/yr) than between the 1970's and 2000 (0.6 m^2/yr).

Precipitation has been increasing in Chaco Canyon since records began in 1934. However, channel erosion has not increased. Runoff is generally correlated to rainfall, and runoff records exist only for 1976 to 1990. No discernible trend in runoff is apparent during this short time span. If runoff increased during this period when rainfall increased, the channel did not return to the braided pattern of the 1930's. The change of Chaco Wash to a narrow, sinuous inner channel is due to sediment deposition. Sediment deposition may be from a number of factors, including a decrease in peak flows, an increase of vegetation on the flood plain, or an increase in the transport of fine-grained sediment. A decrease in peak flows may be due to changes in rainfall intensity, changes in infiltration characteristics of the channel and watershed, or a response to changes in channel geometry and hydraulic parameters (width, depth, slope, and roughness). Increases in vegetation may be a response to decreases in peak flows that favor stable flood-plain sites for germination and growth or to trees planted for erosion control. Increases in fine-grained sediment may represent a change in sources. As tributary headward erosion and streampower decrease, more fine-grained sediment relative to sand is transported.

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