EFFECTS OF CHANNEL CHANGES ON GEOMORPHIC AND HYDRAULIC CHARACTERISTICS OF THE CANADIAN RIVER NEAR RATON, NEW MEXICO, 1965-2000

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

Water-Resources Investigations Report 03-4221

Prepared in cooperation with the

NEW MEXICO DEPARTMENT OF TRANSPORTATION

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Albuquerque, New Mexico
2003

U.S. DEPARTMENT OF THE INTERIOR
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CONTENTS

FIGURES

TABLES

CONVERSION FACTORS AND DATUMS

Multiply	By	To obtain
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square mile (mi^2)	259.0	hectare
square mile (mi^2)	2.590	square kilometer
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic foot per second per square mile ($ft^3/s/mi^2$)	0.01093	cubic meter per second per square kilometer
pound per foot squared (lb/ft^2)	0.04788	kilopascal

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8\ °C) + 32$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C = (°F - 32) / 1.8$$

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

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

Altitude, as used in this report, refers to distance above or below sea level.

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ABSTRACT

Following a 500-year flood in June 1965, New Mexico Highway 555 was constructed in its present (2000) configuration through the Canadian River Valley. During road construction, the river was channelized over several reaches. A 20-year recurrence-interval flood in 1999 damaged several sections of roadway. This study examines how changes in channel morphology associated with channelization may have contributed to damage caused by the 1999 floods by examining how different cross-sectional channel morphologies contribute to the effects of small- (bankfull and flood-prone) and larger (20-year recurrence-interval) magnitude discharges. The results indicate that in channelized reaches, channels that may effectively accommodate small-magnitude floods may be ineffective at containing larger magnitude floods. In addition, the 1999 stream channel overall had deepened since 1965. This deepening was most pronounced upstream from the most flow restrictive of the channelized reaches.

Geomorphologic and hydraulic data were derived from level-survey measurements at 10 channel cross sections and 10 channel slopes on the Canadian River and from digital elevation models developed from aerial photographs taken June 23, 1965, and June 1, 1999. A comparison of data derived from the 1965 and 1999 aerial photographs indicates that the Canadian River channel in the study area was shorter, deeper, steeper, and less sinuous in 1999 than in 1965. Prior to construction of New Mexico Highway 555, the zone of active-channel migration encompassed the entire width of the Canadian River Valley in the upper part of the study area. Streamflow-control structures designed to protect the road from erosion and deep, narrow stream channels built during construction of New Mexico Highway 555 now constrain the channel and have reduced the amplitude and frequency of channel meanders. Major channel modifications include channel straightening and elimination of meanders at cross sections CR4B and CR6B, gabion construction at cross sections CR3 and CR7, and construction of a bridge at cross section CR5.

The Coal Canyon debris-fan deposit, adjacent to the Canadian River channel where it parallels New Mexico Highway 555 downstream from cross section CR7, appears to effectively channelize the Canadian River along this reach, much like the artificially confined channel at cross section CR4. The deposit also causes consequences similar to the channelized reach at cross section CR4 in terms of increased potential sediment-transport capacity at large discharges.

INTRODUCTION

In the spring and summer of 1999, floods in the Canadian River damaged sections of New Mexico State Highway 555 (NM 555) west of Raton, New Mexico. NM 555, connecting Raton to coal mines in the Sangre de Cristo Mountains (fig. 1), was constructed in its present configuration in 1965, after a large flood in June of that year. During the 1965 road construction, the Canadian River channel was rerouted and (or) channelized in several locations, constricting the streambed in narrow channels adjacent to the highway. Because of the damage caused by the 1999 floods, the U.S. Geological Survey (USGS), in cooperation with the New Mexico Department of Transportation (NMDOT), conducted a study to examine how changes in channel morphology associated with channelization may have contributed to damage caused by the 1999 floods.

Purpose and Scope

This report presents the effects of channel changes on the geomorphic and hydrologic characteristics of the Canadian River near Raton, New Mexico. The report documents channel changes between June 23, 1965, and August 17, 2000, where NM 555 parallels the Canadian River upstream from Raton. A glossary is provided after the references to assist the reader with unfamiliar terms.

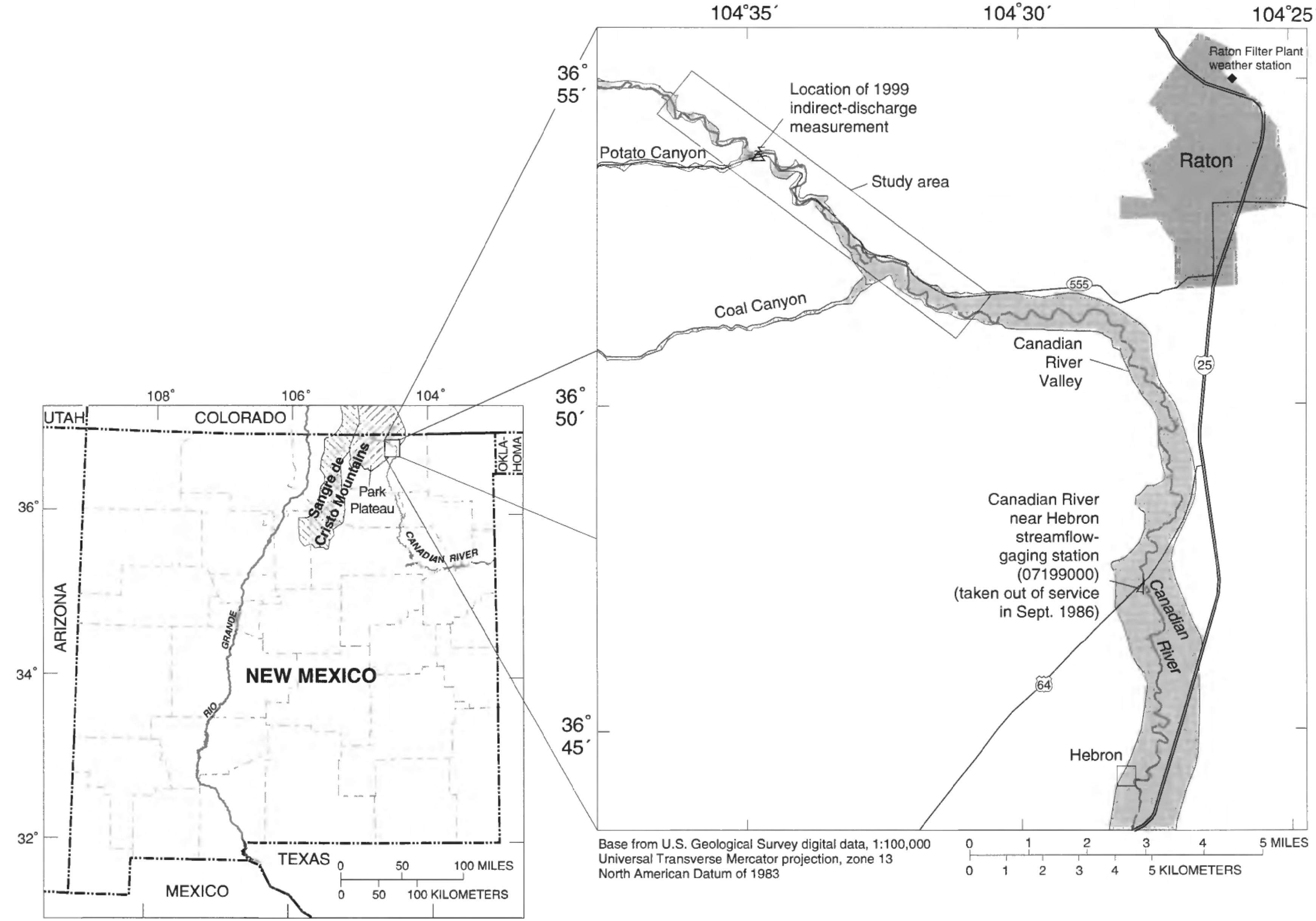


Figure 1. Geographic features near study area and locations of study area, indirect-discharge measurement site, streamflow-gaging station, and weather station.

Description of Study Area

The study area lies within the Park Plateau on the eastern flank of the Sangre de Cristo Mountains in northern New Mexico. The southeastern edge of the study area is located about 3.5 mi west of Raton, New Mexico (fig. 1). From its southeastern edge, the study area extends about 6.5 mi northwest along the Canadian River Valley.

The Canadian River arises in southern Colorado in the Sangre de Cristo Mountains and flows generally southeast toward Raton. The Canadian River drainage basin upstream from the southeastern edge of the study area is about 130 mi^2. The river dissects a sequence of fine-grained to conglomeratic sandstones with interbedded siltstones and coal, beginning with the Poison Canyon Formation of Tertiary age in the upper reaches and continuing down through the contact with the Pierre Shale of Cretaceous age near Raton (Pilmore, 1976). NM 555 parallels the Canadian River for about 8 mi from Potato Canyon to just south of Coal Canyon. From the headwaters to a point about 2 mi downstream from Potato Canyon, the Canadian River Valley is meandering and narrow (fig. 2), less than 500 ft wide in places, and bounded by steep, forested hillslopes of more than 50-percent grade. Further downstream, the valley straightens and widens to about 3,000 ft as it approaches the margins of the Park Plateau. The overall valley gradient within the study area is about 0.010. Local relief (from valley floor to the tops of the nearest mountains) is about 600 ft. Land-surface altitudes in the study area range from about 6,600 to 7,200 ft along the floor of the Canadian River Valley. The forest association is primarily piñon-juniper, characteristic of low moisture, shallow-soil areas. Ponderosa pine and Douglas fir generally are present on the north-facing slopes, where moisture is more plentiful and temperatures are lower.

Methods of Study

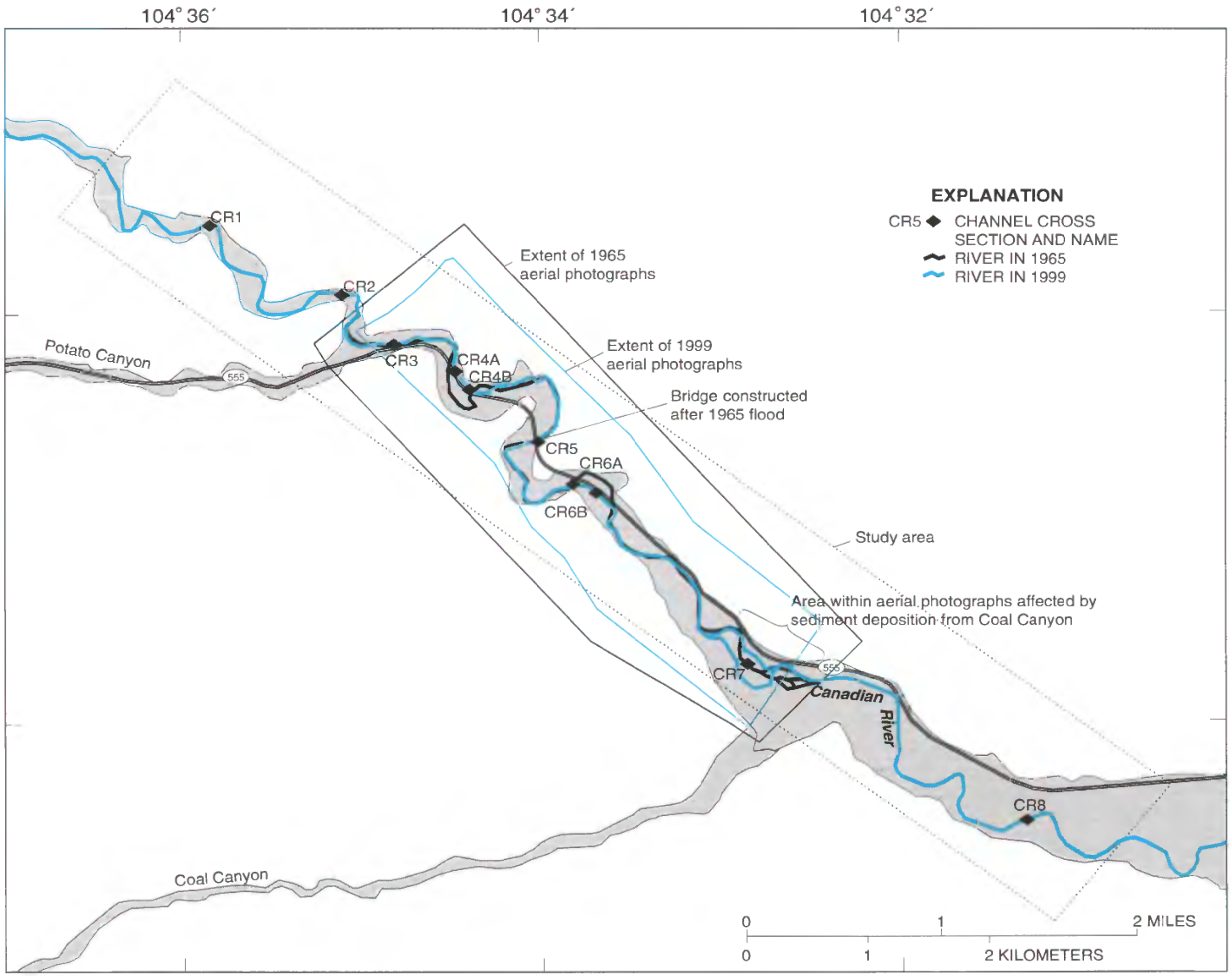
In August 2000, 10 channel cross sections and 10 channel slopes were surveyed on the Canadian River (fig. 2). Cross sections CR1 and CR2, located upstream from the reach where NM 555 is adjacent to the Canadian River, were selected to represent unchannelized conditions. Cross section CR3 was located across a gabion-stabilized reach of the river. Two cross sections (CR4B and CR6B) were located in channelized reaches, and two cross sections (CR4A and CR6A) were located just upstream from channelized reaches. Cross section CR5 was located just upstream from a highway bridge constructed after a 1965 flood. Cross section CR7 was located in a reach where the road was damaged in 1999, and cross section CR8 was located furthest downstream where the river valley widens relatively distant from NM 555.

The particle-size distribution of streambed material was analyzed using the pebble count method of Wolman (1954). Pebbles were counted at cross sections CR1, CR3, CR6A, CR6B, and CR8. The counts are not presented in this report.

Streamflow data were obtained from several sources. Forty years of streamflow data on file with the USGS in Albuquerque, New Mexico, were available for the Canadian River near Hebron streamflow-gaging station. This gaging station, located about 7 mi downstream from the study area (fig. 1), was operated from October 1, 1946, to September 30, 1986. Direct-discharge measurements for 1999 are not available for the Canadian River within the study area; however, an indirect-discharge measurement done on September 10, 1999, at cross section CR3 provided an estimate of the peak 1999 discharge. In addition, discharge for the peak 1999 flood was estimated for the channel at each cross section on the basis of Canadian River peak-frequency record and regional equations for discharge on an ungaged stream (Waltemeyer, 1996).

Precipitation data were obtained from the National Climatic Data Center (Asheville, North Carolina) for the weather station nearest the study area. This weather station (Filter Plant at Raton, New Mexico) has a precipitation record that extends from 1954 to the present and is located about 5 mi northeast of the downstream end of the study area.

Digital elevation models (DEM's) of the Canadian River Valley within the study area were photogrammetrically generated using 1965 and 1999 aerial photographs (Matt Jones, Bureau of Reclamation, oral commun., 2002). Topographic maps with a 2-ft contour interval were derived from 1965 and 1999 DEM's. The aerial photographs were taken on June 23, 1965, and June 1, 1999. The 1965 aerial photographs were taken at an altitude that rendered a scale of 1:14,000, and the 1999 aerial photographs were taken at an altitude that rendered a scale of 1:6,000 (Matt Jones, oral commun., 2003). Vertical datum control was established by using a global positioning satellite (GPS) receiver in the field at the



Base from U.S. Geological Survey digital data, 1:100,000
Universal Transverse Mercator projection, zone 13
North American Datum of 1983

Figure 2. Locations of surveyed cross sections and extent of 1965 and 1999 aerial photographs.

locations of natural features that were common to and identifiable in both the 1965 and 1999 aerial photographs (Matt Jones, oral commun., 2003). The absolute vertical error was estimated to be plus or minus 1.5 ft for the 1965 photographs and plus or minus 1.0 ft for the 1999 photographs (Matt Jones, oral commun., 2003). Surveyed cross sections were located on aerial photographs and maps using GPS coordinates and field descriptions.

The 1965 aerial photographs were taken 6 days after a 500-year recurrence-interval flood event, and show evidence of the flooding. In the absence of other pre-NM 555 construction data, the 1965 aerial photography was compared with the 1999 aerial photography to determine changes in Canadian River geomorphology between cross sections CR3 and CR7, the area common to both sets of photographs (fig. 2).

Previous Studies

Little geomorphic or hydraulic work has been published for the Canadian River. Fonstad and others (1999) reported that mean velocity, shear stress, stream power, and criticality were determined for an estimated 3,885-ft^3/s flood in the Canadian River headwaters in early May 1999. They reported large spatial heterogeneity in deposition and erosion patterns. Waltemeyer (1996) developed regional equations for New Mexico that can be used to estimate discharge for various recurrence-interval floods.

Acknowledgments

The authors thank Mike Ballew of the National Rifle Association and Jim Yarborough of the Vermejo Ranch for providing access to land in the study area. Allen Gellis of the U.S. Geological Survey coordinated the early part of and collected field data for this project.

PRECIPITATION, STREAMFLOW, AND RELATION TO AERIAL PHOTOGRAPHY

The mean annual precipitation recorded at the Raton Filter Plant weather station (fig. 1) was 17.68 in. for 1954 through 2000 (fig. 3A). The 30-yr (1961-90) normal annual precipitation computed by the National Climatic Data Center (2001) is 16.80 in. The 1954-2000 mean annual precipitation value is larger than the normal annual precipitation value because of the wetter than normal years of the late 1980's and 1990's (fig. 3A). Only 3 years (1993, 1998, and 2000) during the 1984 to 2000 time period had less than normal annual precipitation. Seasonally, 61 percent of annual precipitation during 1954-2000 fell from May through August (fig. 4).

A Canadian River flood in June 1965 (fig. 3B) was associated with above-average precipitation (fig. 4). Precipitation in June 1965 totaled 8.81 in., exceeding the monthly mean for June by about 450 percent. This precipitation caused a large flood on June 17, 1965, with an instantaneous discharge of 62,400 ft^3/s at the Canadian River near Hebron gaging station (fig. 1). The basin area that contributed to the discharge measured at the Canadian River near Hebron gaging station was 229 mi^2.

Floods in April and August 1999 also were associated with above-average precipitation (fig. 4). Precipitation in April and August 1999 totaled 4.20 and 5.72 in., respectively, exceeding the monthly mean for April and August by about 379 and 166 percent, respectively. Based on a September 10, 1999, indirect-discharge measurement at cross section CR3, the peak 1999 flood discharge was estimated to be about 7,000 ft^3/s. Because the Canadian River near Hebron gaging station was taken out of service in 1986, it is unknown if the indirect-discharge measurement documents the April or August 1999 flood. However, road damage did result from the April 1999 flood; thus, the April flood probably was the larger of the two floods. The basin area that contributed to the discharge measured at cross section CR3 was 110 mi^2.

The June 1965 flood unit discharge for the 229-mi^2 basin area upstream from the Canadian River near the Hebron gaging station was about 272 $ft^3/s/mi^2$. The 1999 flood unit discharge for the 110-mi^2 basin area upstream from the indirect-discharge measurement point was about 64 $ft^3/s/mi^2$. Based on the peak-frequency record for the Canadian River near Hebron gaging station (Waltemeyer, 1996), the June 1965 flood has an estimated recurrence interval of 500 years, whereas the 1999 peak flood has an estimated recurrence interval of about 20 years.

For the purposes of this geomorphic study, placing aerial photographs in the context of antecedent precipitation and streamflow conditions is important. The 1965 aerial photographs were taken on June 23, 6 days after the June 17, 1965, flood event.

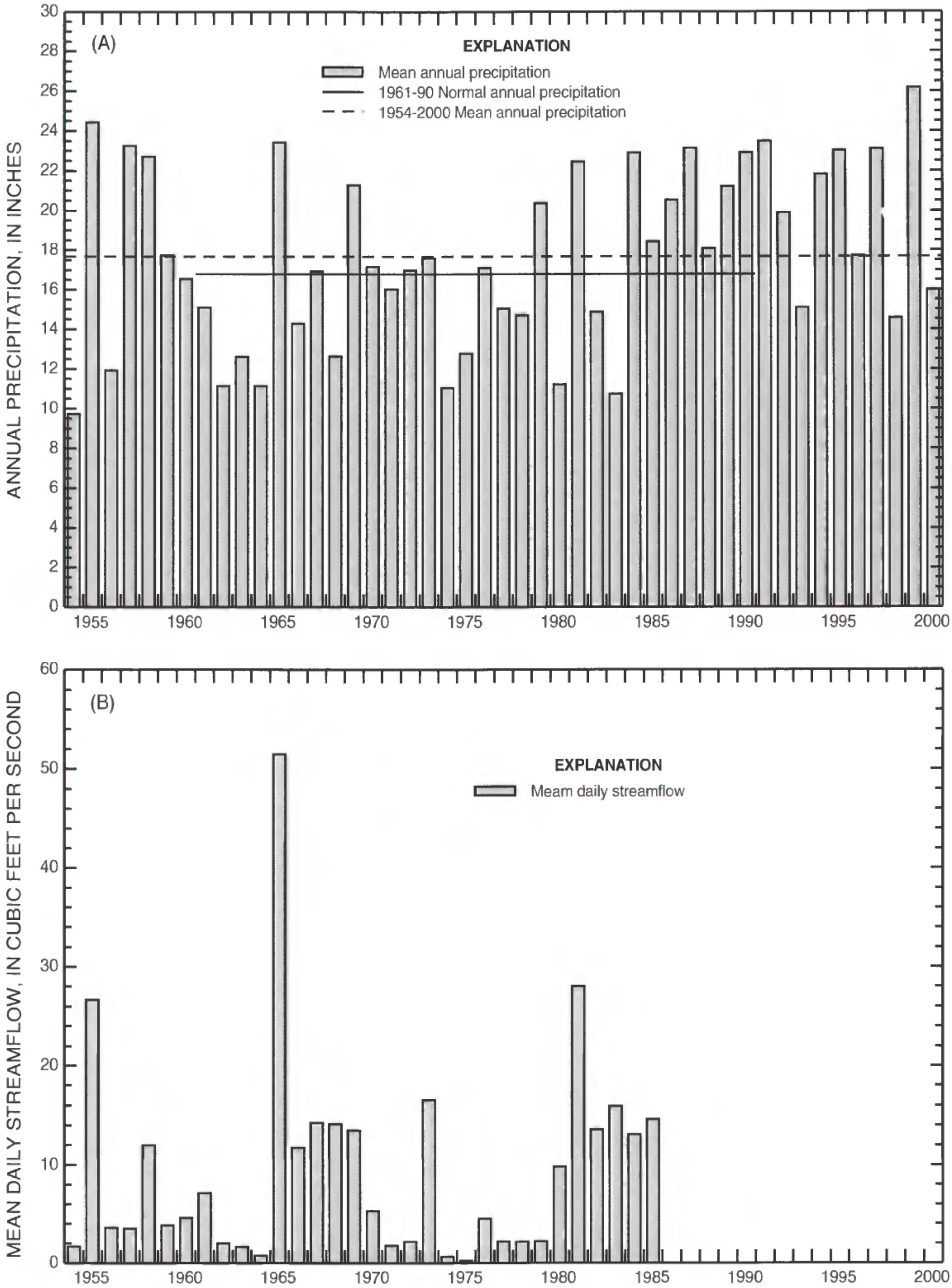


Figure 3. (A) Mean annual precipitation at Raton Filter Plant and (B) mean daily streamflow at Canadian River near Hebron. Precipitation data from National Climatic Data Center (2001). Streamflow data on file with U.S. Geological Survey, Albuquerque, New Mexico.

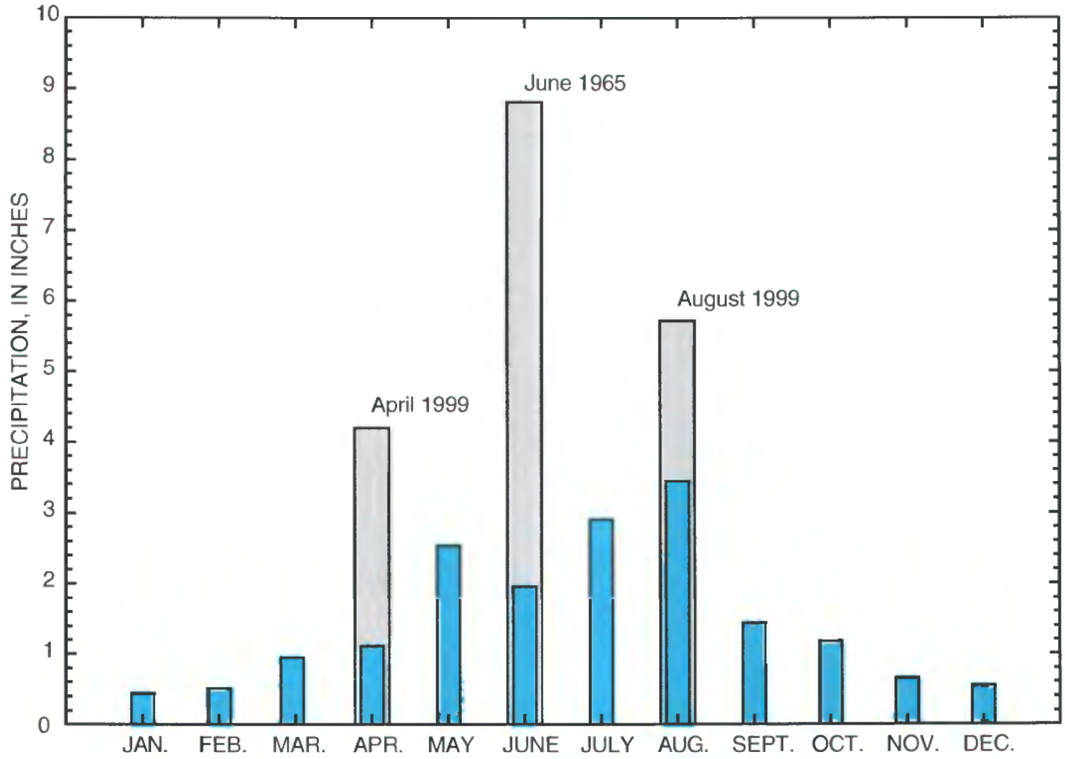


Figure 4. Monthly mean precipitation for 1954-2000 and total precipitation for June 1965, April 1999, and August 1999 at Raton Filter Plant weather station (National Climatic Data Center, 2001).

Consequently, the 1965 aerial photographs show abundant evidence of flooding in the form of large sand bars and unvegetated areas throughout the river valley in the study area (figs. 5A, 6A, 7A, 8A, 9A, and 10A). These sand bars and unvegetated areas probably resulted from scouring and later redeposition of sediment from the river channel. On the date of photography (June 23, 1965), however, the mean daily discharge at the Canadian River near Hebron streamflow-gaging station was 13 ft^3/s (see fig. 11), representing low-flow conditions.

The 1999 aerial photographs were taken June 1, about 1 month after the April 30, 1999, flood. The 1999 aerial photographs also show evidence of flooding (figs. 5B, 6B, 7B, 8B, 9B, and 10B), though not to the same extent as the 1965 aerial photographs. Although there is no 1999 record of streamflow for the Canadian River near Hebron (the gaging station was taken out of service in September 1986), precipitation records from the City of Raton Filter Plant indicate total precipitation of 1.2 in. during May 1999 and no precipitation during the 10 days prior to aerial photography. Thus, the river probably was at baseflow conditions at the time of the 1999 aerial photography.

EFFECTS OF CHANNEL CHANGES ON GEOMORPHIC AND HYDRAULIC CHARACTERISTICS

A river accommodates increasing discharge by relative changes in channel dimensions as the magnitude of flow increases. Channelization of the river can alter these relations from the natural channel configuration and may decrease the ability of a river to accommodate large discharges. The effect of channelization, in terms of basal shear stress (the shear stress on channel-bottom material) and sediment-transport capacity, depends on how the channel and the flood plain are altered by channelization and how channelization affects the stream's ability to accommodate discharge at both moderate and larger magnitude discharges.

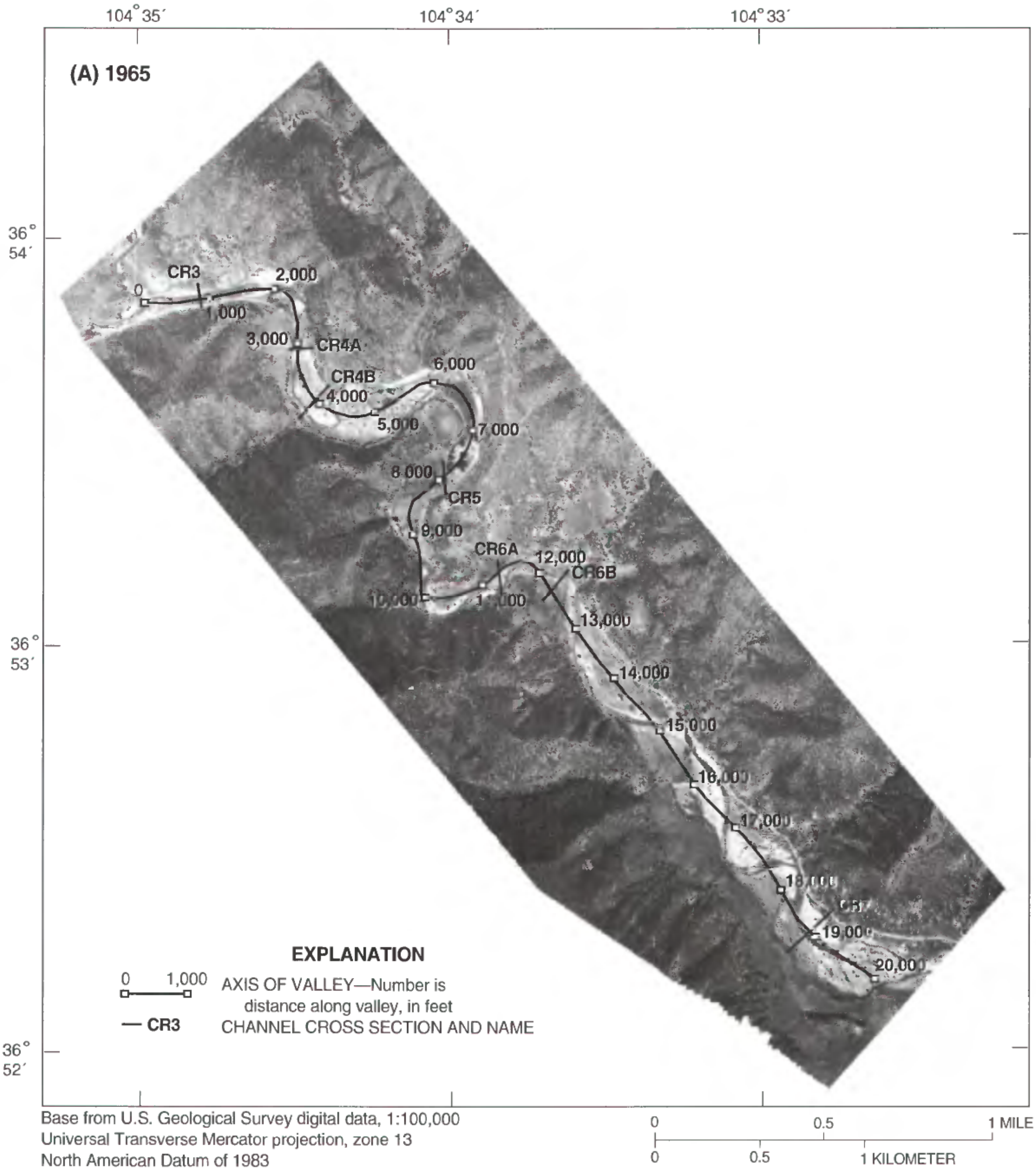


Figure 5A. Channel cross sections and distances along Canadian River Valley centerline superimposed on (A) 1965 and (B) 1999 aerial photographs.

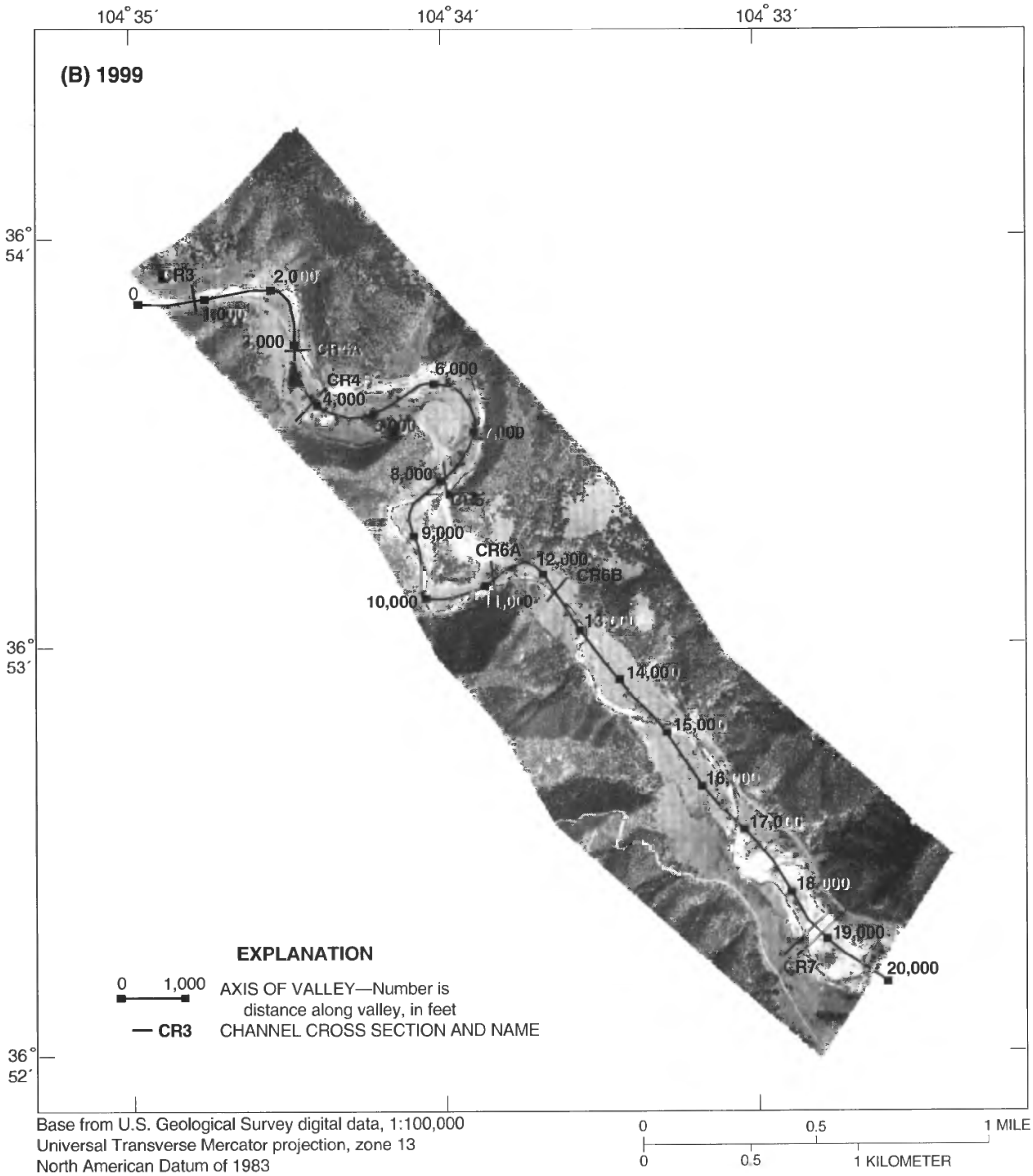
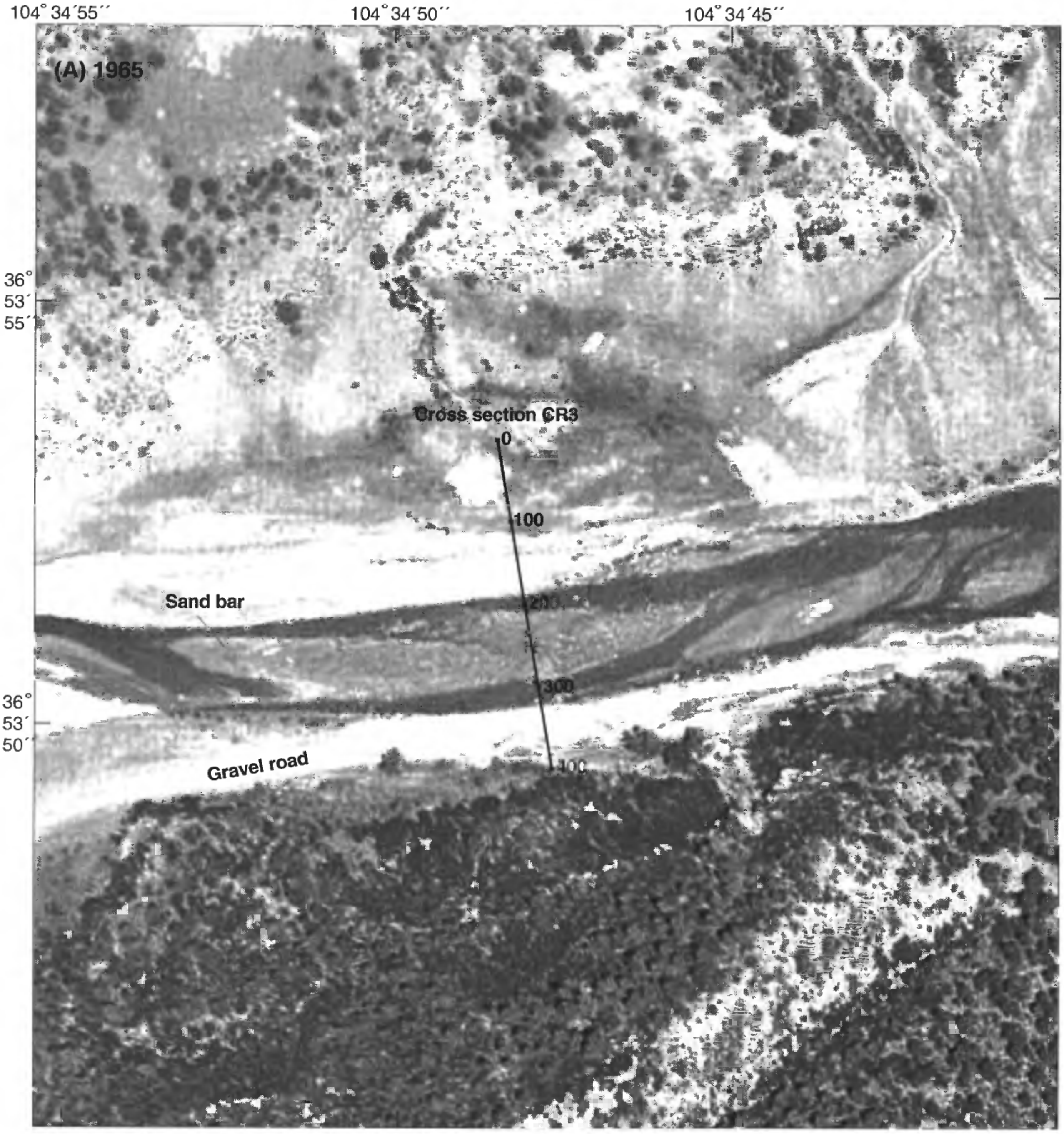


Figure 5B. Channel cross sections and distances along Canadian River Valley centerline superimposed on (A) 1965 and (B) 1999 aerial photographs.



Base from U.S. Geological Survey digital data, 1:100,000
Universal Transverse Mercator projection, zone 13
North American Datum of 1983

0 250 500 FEET
0 62.5 125 METERS

EXPLANATION

0 100 LINE OF SECTION—Number is distance along section, in feet

Figure 6A. Aerial photographs and location of cross section CR3 for (A) 1965 and (B) 1999, and (C) schematic showing 1965 and 1999 channels.

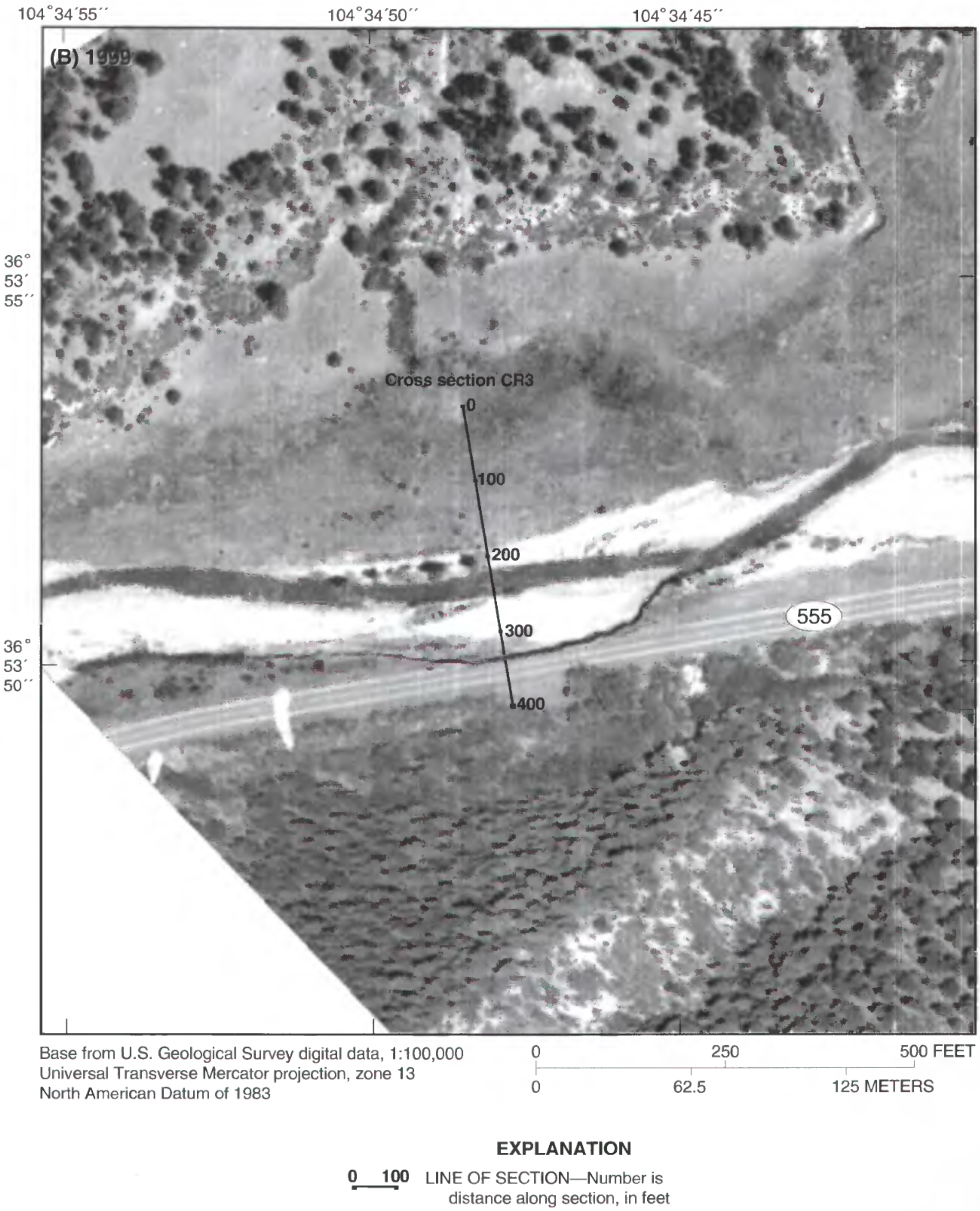


Figure 6B. Aerial photographs and location of cross section CR3 for (A) 1965 and (B) 1999, and (C) schematic showing 1965 and 1999 channels.

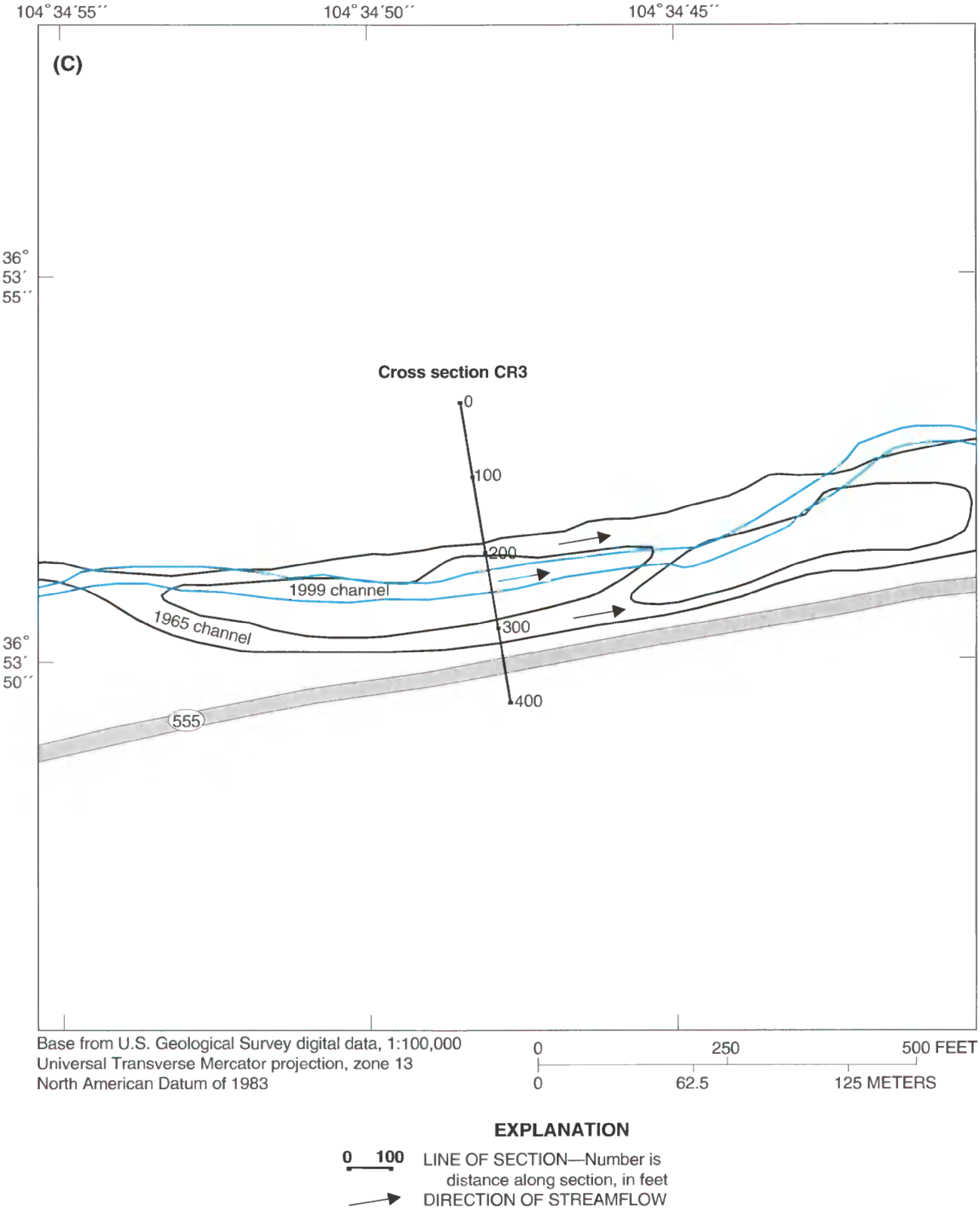


Figure 6C. Aerial photographs and location of cross section CR3 for (A) 1965 and (B) 1999, and (C) schematic showing 1965 and 1999 channels.

Base from U.S. Geological Survey digital data, 1:100,000
Universal Transverse Mercator projection, zone 13
North American Datum of 1983

0 250 500 FEET

0 62.5 125 METERS

EXPLANATION

0 100 LINE OF SECTION—Number is distance along section, in feet

Figure 7A. Aerial photographs and location of cross sections CR4A and CR4B for (A) 1965 and (B) 1999, and (C) schematic showing 1965 and 1999 channels.

Figure 7B. Aerial photographs and location of cross sections CR4A and CR4B for (A) 1965 and (B) 1999, and (C) schematic showing 1965 and 1999 channels.

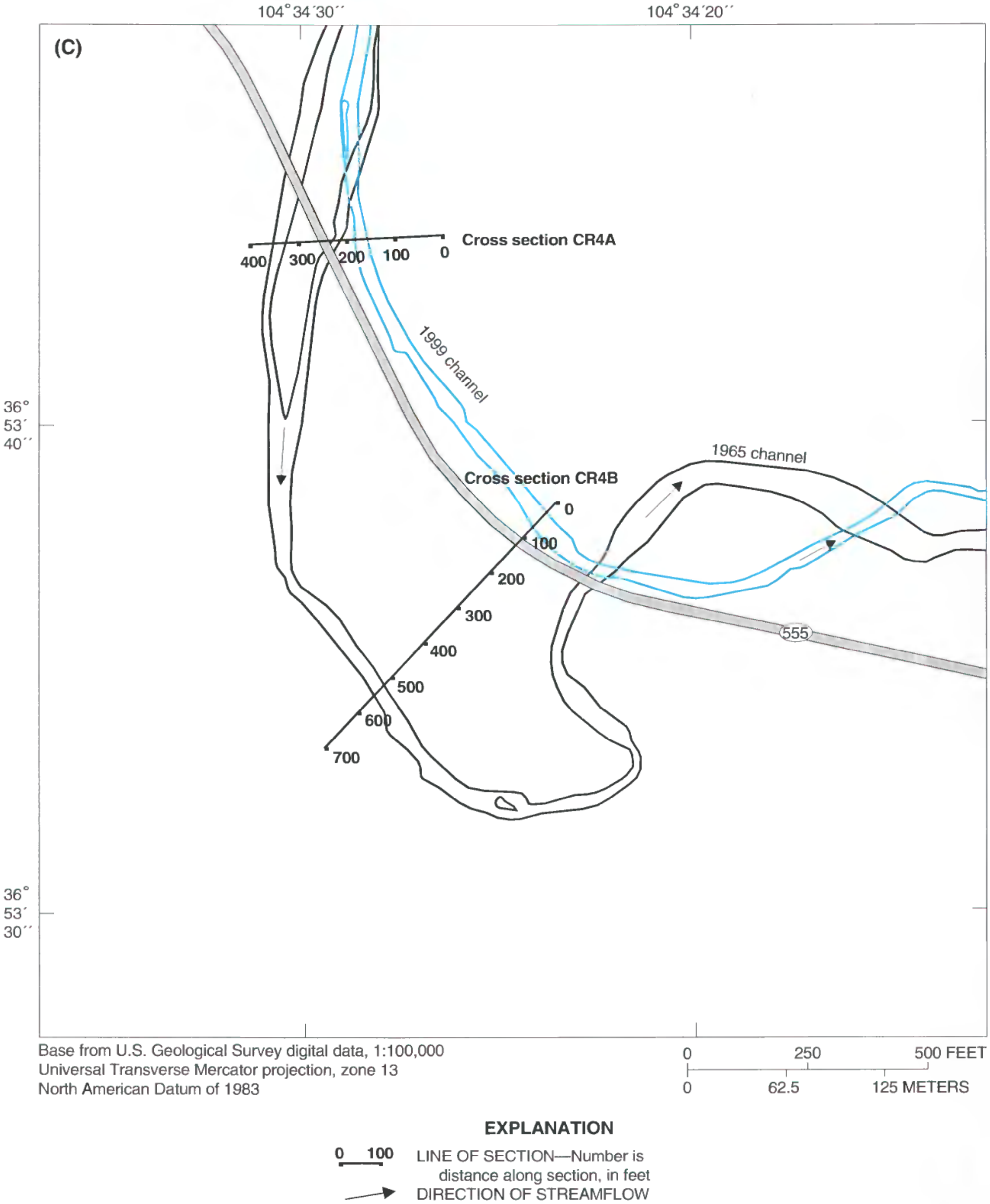
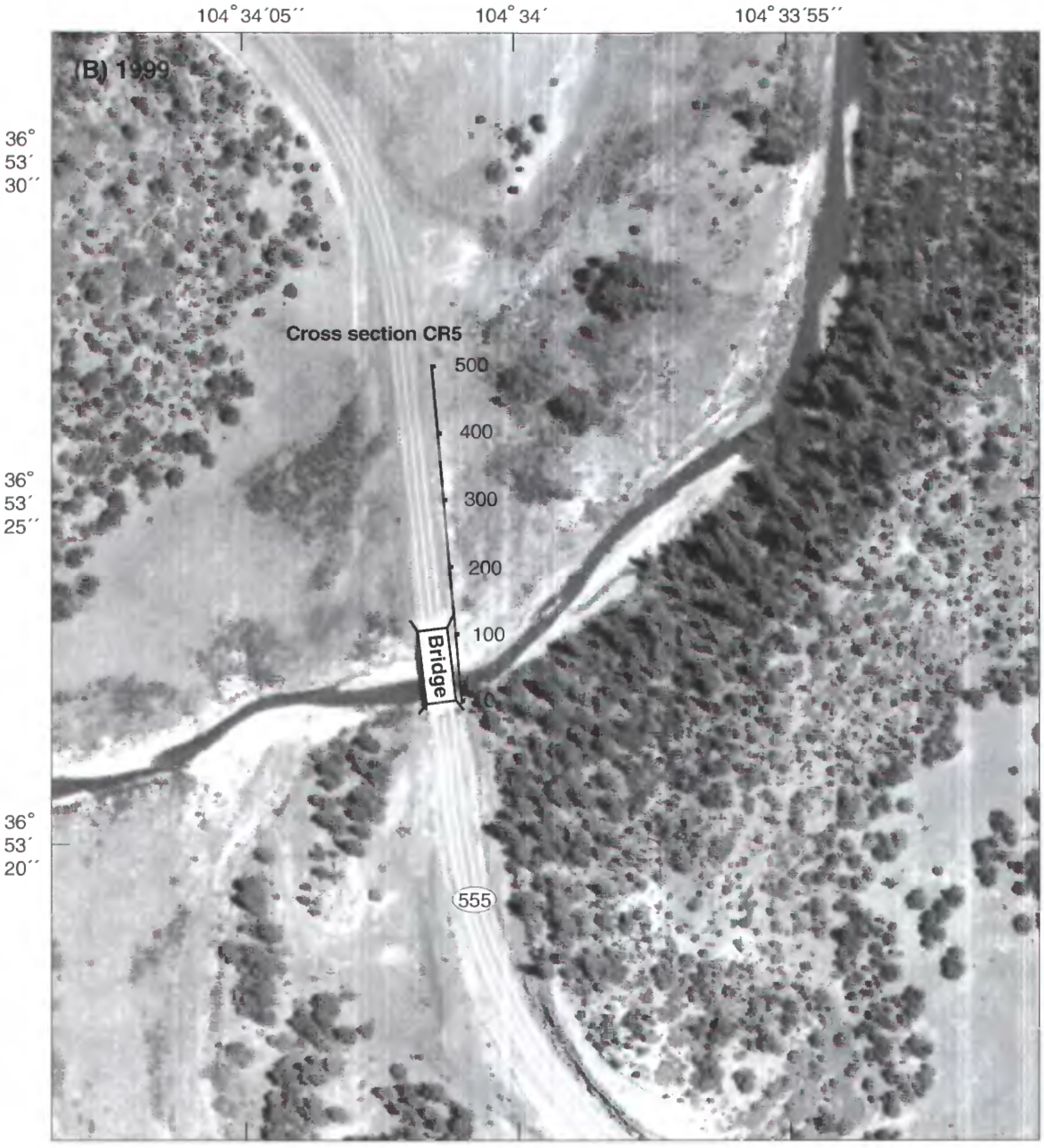


Figure 7C. Aerial photographs and location of cross sections CR4A and CR4B for (A) 1965 and (B) 1999, and (C) schematic showing 1965 and 1999 channels.

Figure 8A. Aerial photographs and location of cross section CR5 for (A) 1965 and (B) 1999, and (C) schematic showing 1965 and 1999 channels.



Base from U.S. Geological Survey digital data, 1:100,000
Universal Transverse Mercator projection, zone 13
North American Datum of 1983

0 250 500 FEET
0 62.5 125 METERS

EXPLANATION

0 100 LINE OF SECTION—Number is distance along section, in feet

Figure 8B. Aerial photographs and location of cross section CR5 for (A) 1965 and (B) 1999, and (C) schematic showing 1965 and 1999 channels.

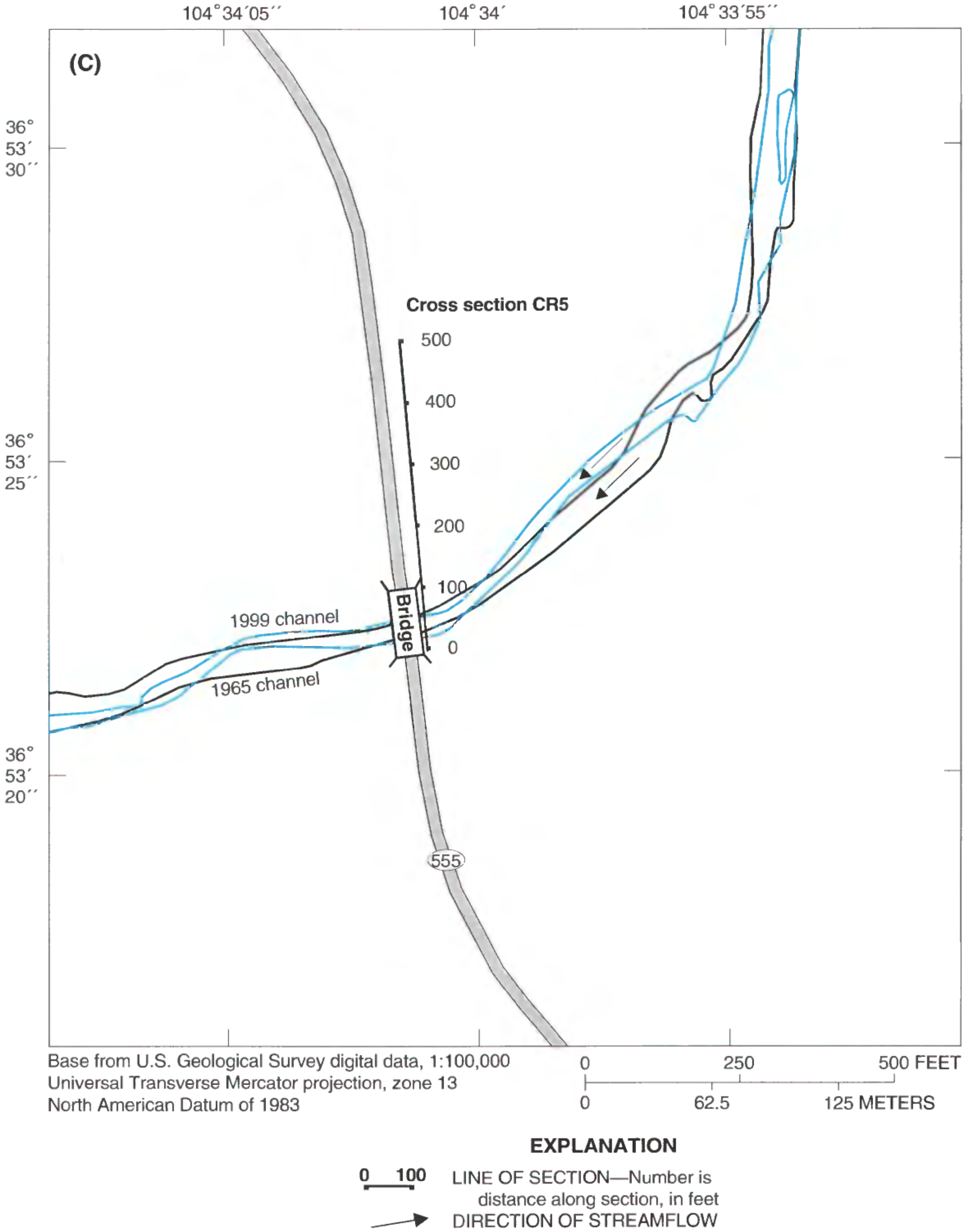
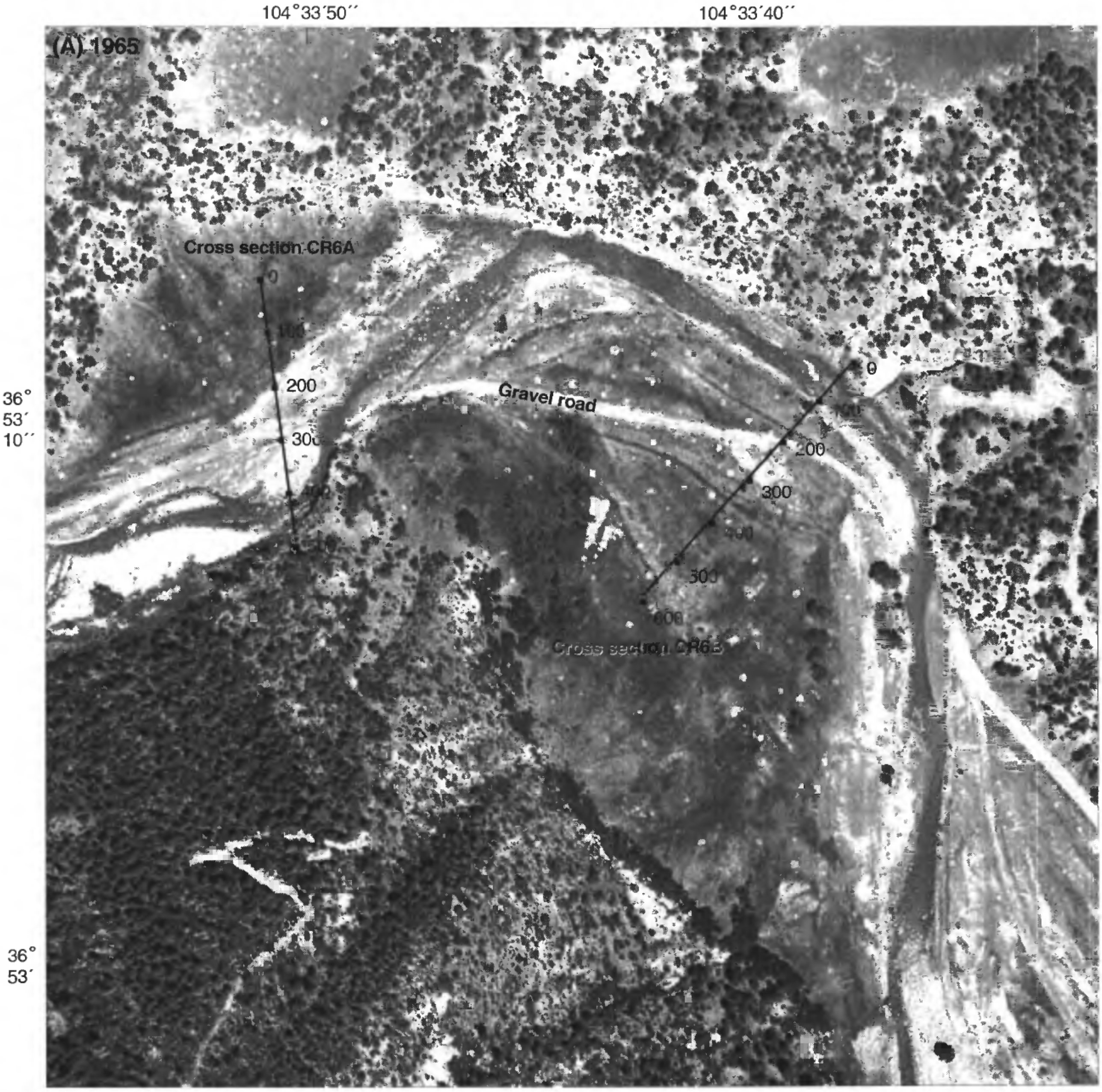


Figure 8C. Aerial photographs and location of cross section CR5 for (A) 1965 and (B) 1999, and (C) schematic showing 1965 and 1999 channels.



Base from U.S. Geological Survey digital data, 1:100,000
Universal Transverse Mercator projection, zone 13
North American Datum of 1983

EXPLANATION

0 100 LINE OF SECTION—Number is distance along section, in feet

Figure 9A. Aerial photographs and location of cross sections CR6A and CR6B for (A) 1965 and (B) 1999, and (C) schematic showing 1965 and 1999 channels.

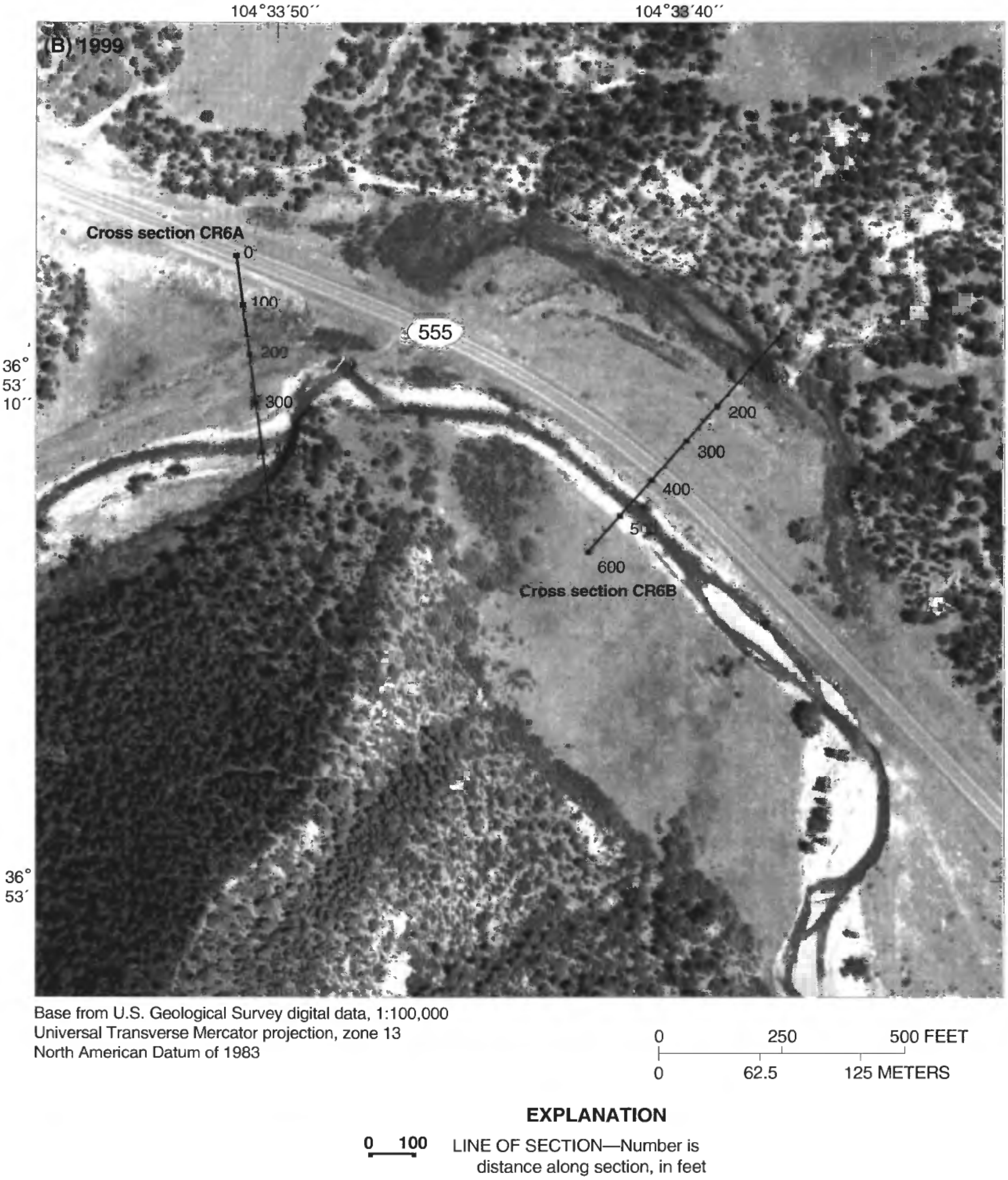
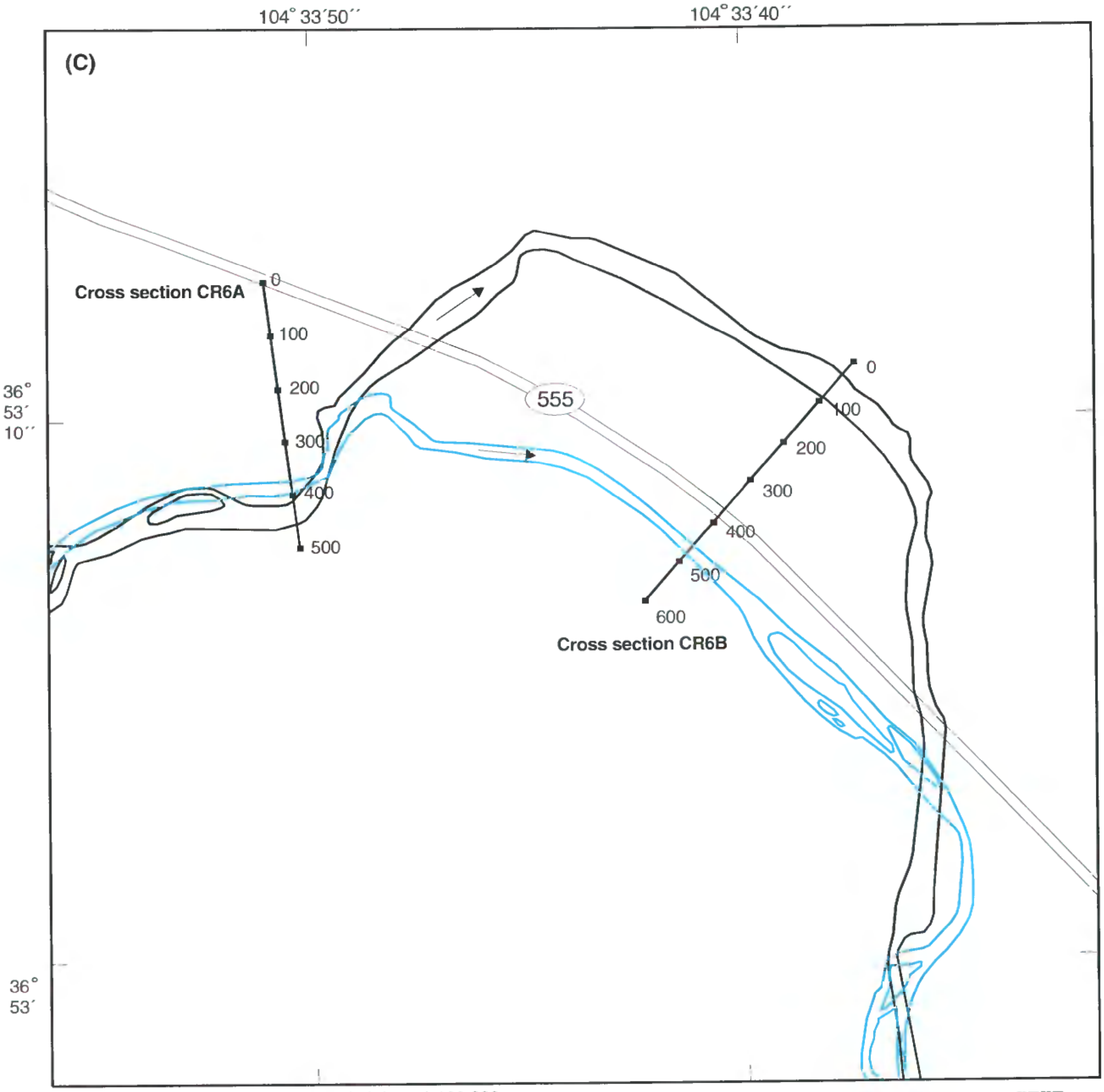


Figure 9B. Aerial photographs and location of cross sections CR6A and CR6B for (A) 1965 and (B) 1999, and (C) schematic showing 1965 and 1999 channels.



Base from U.S. Geological Survey digital data, 1:100,000
Universal Transverse Mercator projection, zone 13
North American Datum of 1983

0 250 500 FEET
0 62.5 125 METERS

EXPLANATION

0 100 LINE OF SECTION—Number is distance along section, in feet

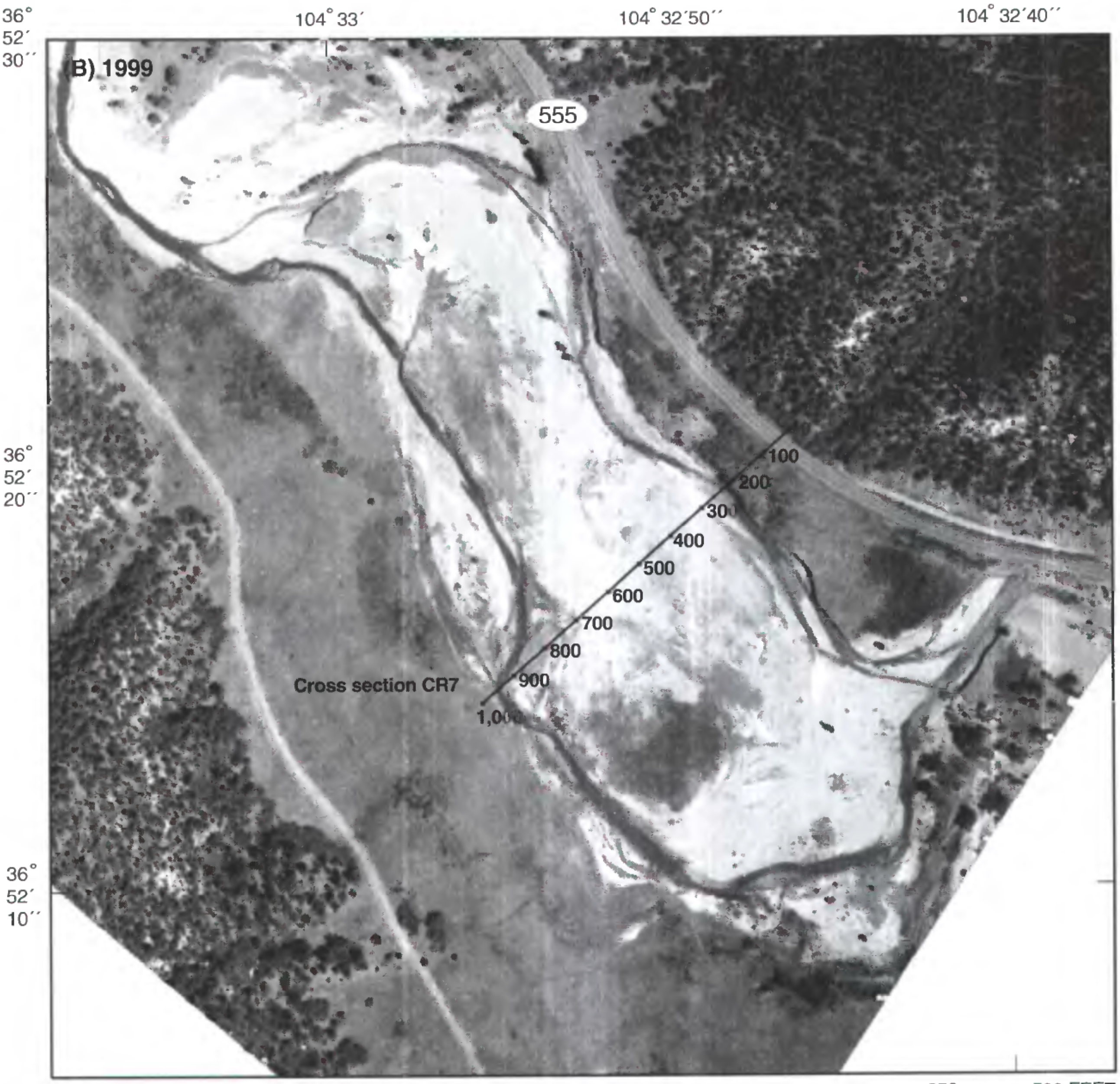
DIRECTION OF STREAMFLOW

Figure 9C. Aerial photographs and location of cross sections CR6A and CR6B for (A) 1965 and (B) 1999, and (C) schematic showing 1965 and 1999 channels.

EXPLANATION

0 100 LINE OF SECTION—Number is distance along section, in feet

Figure 10A. Aerial photographs and location of cross section CR7 for (A) 1965 and (B) 1999, and (C) schematic showing 1965 and 1999 channels.



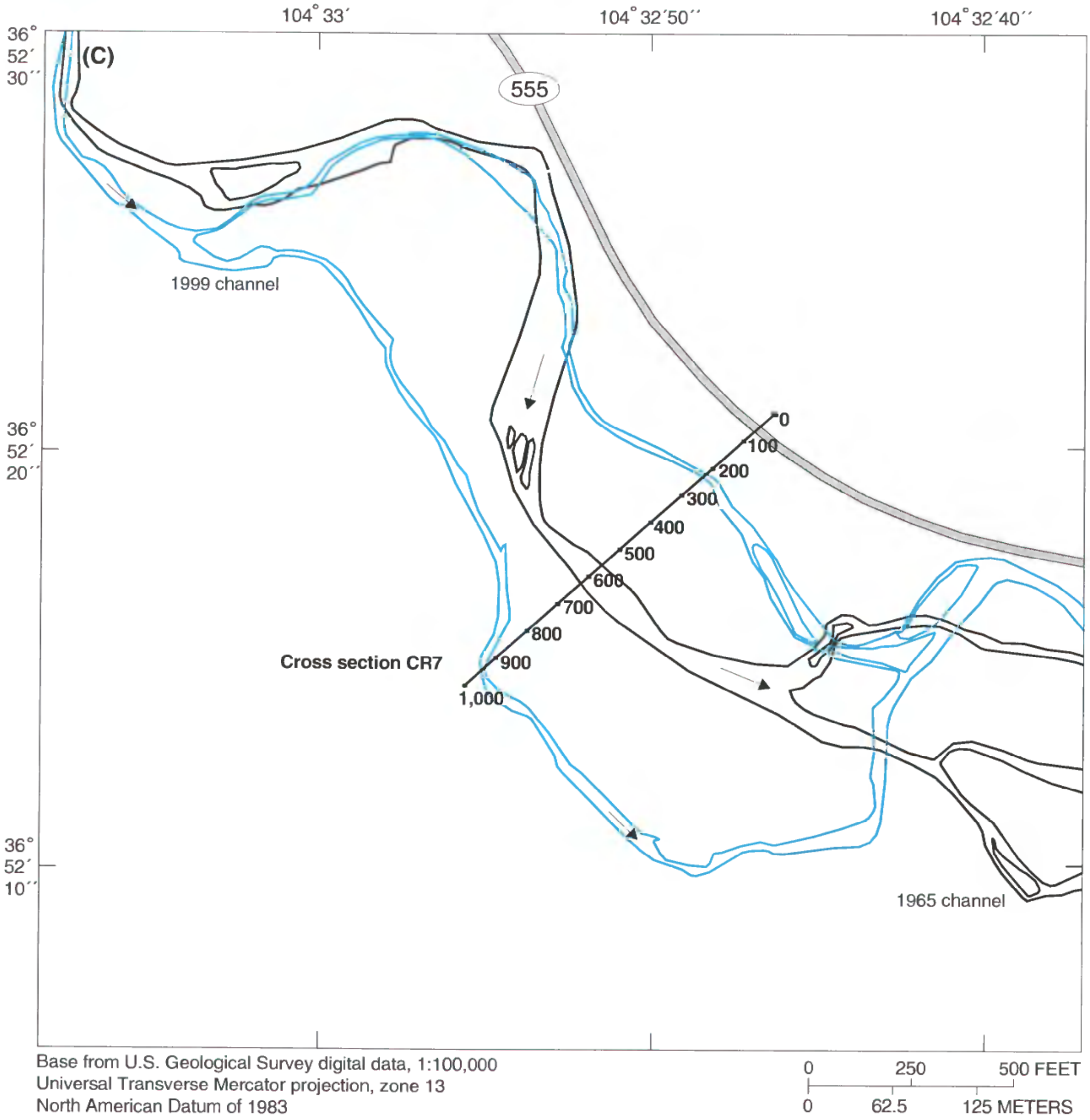
Base from U.S. Geological Survey digital data, 1:100,000
Universal Transverse Mercator projection, zone 13
North American Datum of 1983

0 250 500 FEET
0 62.5 125 METERS

EXPLANATION

0 100 LINE OF SECTION—Number is distance along section, in feet

Figure 10B. Aerial photographs and location of cross section CR7 for (A) 1965 and (B) 1999, and (C) schematic showing 1965 and 1999 channels.



EXPLANATION

0 100 LINE OF SECTION—Number is distance along section, in feet

DIRECTION OF STREAMFLOW

Figure 10C. Aerial photographs and location of cross section CR7 for (A) 1965 and (B) 1999, and (C) schematic showing 1965 and 1999 channels.

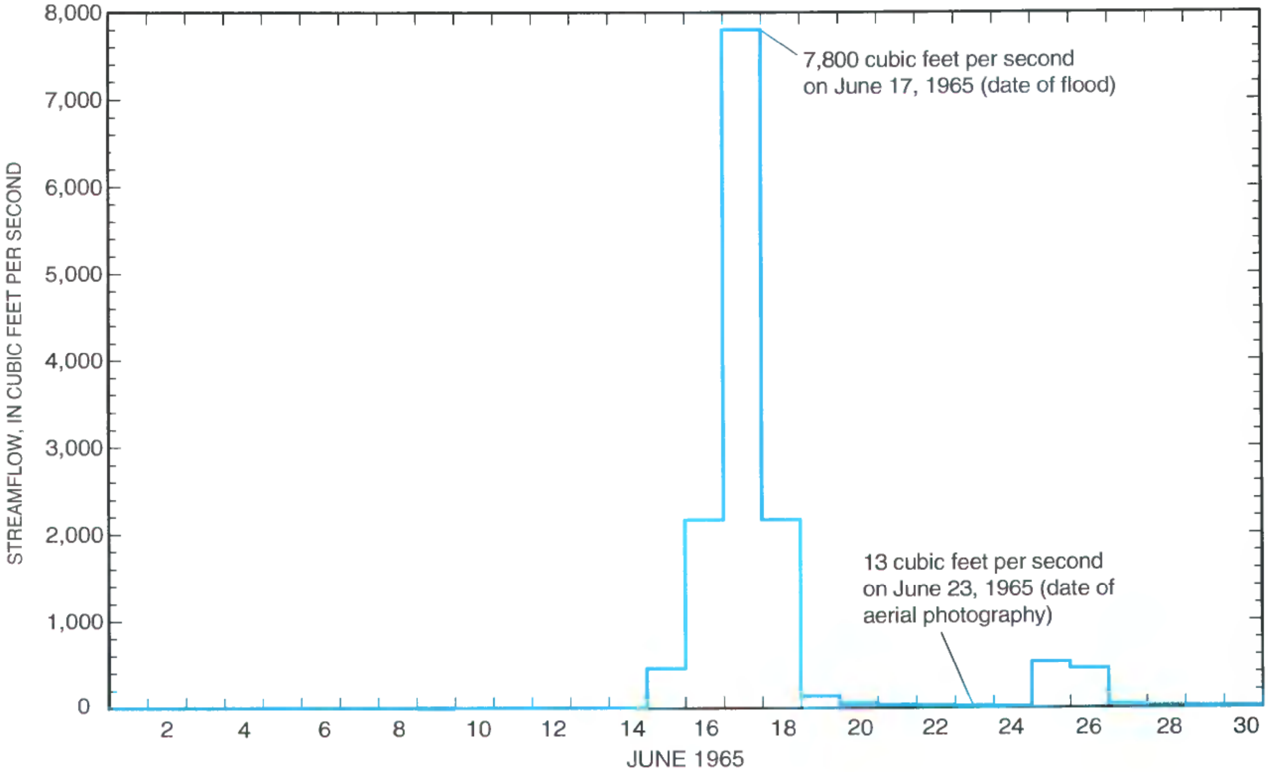


Figure 11. Mean daily streamflow during June 1965 at the Canadian River near Hebron streamflow-gaging station. Streamflow data on file with U.S. Geological Survey, Albuquerque, New Mexico. Location of gaging station in figure 1.

The basal shear stress is directly related to the slope and the hydraulic radius (approximated as mean channel depth) of the channel. In an entrenched confined channel (deep, with steep-sided banks; fig. 12A), the hydraulic radius, and therefore basal shear stress, increases as discharge increases, thus increasing the sediment-transport capacity of the stream. In a not entrenched unconfined channel (shallow, with sloping banks; fig. 12D), as discharge increases above bankfull stage and overbank flooding occurs, the flow is spread over a wide area, and the hydraulic radius increases less than it would for the same increase in discharge in an entrenched confined channel (fig. 12A) of similar bankfull dimensions. Therefore, the basal shear stress in a not entrenched unconfined channel would be smaller than for the same magnitude discharge in a confined channel. Most channel cross-sectional geometries fall in a continuum between the entrenched confined and not entrenched unconfined endpoints. Cross-sectional geometries may change position along this classification continuum with increasing magnitude of discharge, depending on the relative configuration of the channel and flood plain to the broader valley morphology. The cross-sectional channel dimensions at any given river stage (and corresponding discharge) strongly influence basal shear stress and sediment-transport capacity within the stream. To the extent that channelization alters the cross-sectional channel configuration, the impact of a given discharge, in terms of sediment-transport capacity, is also enhanced or decreased.

Although channel slope is the primary measure of energy potential and sediment-transport capacity (Leopold and others, 1964), slope-discharge relations are difficult to determine for an ungaged stream such as the presently ungaged Canadian River. The following analysis therefore will focus primarily on the relation of channel dimensions to the magnitude of flow at cross sections CR3 through CR7. Given channels of constant slope and considering only cross-sectional dimensions, three scales of magnitude and frequency of events can be considered:

(1) Flows at or below bankfull (frequent, small-magnitude flows) – For a given magnitude flow, a channel with a large width-to-depth (W:D) ratio (a wide shallow channel) will have a small basal shear stress. A channel with a small W:D ratio (a narrow deep channel) will have a larger basal shear stress.

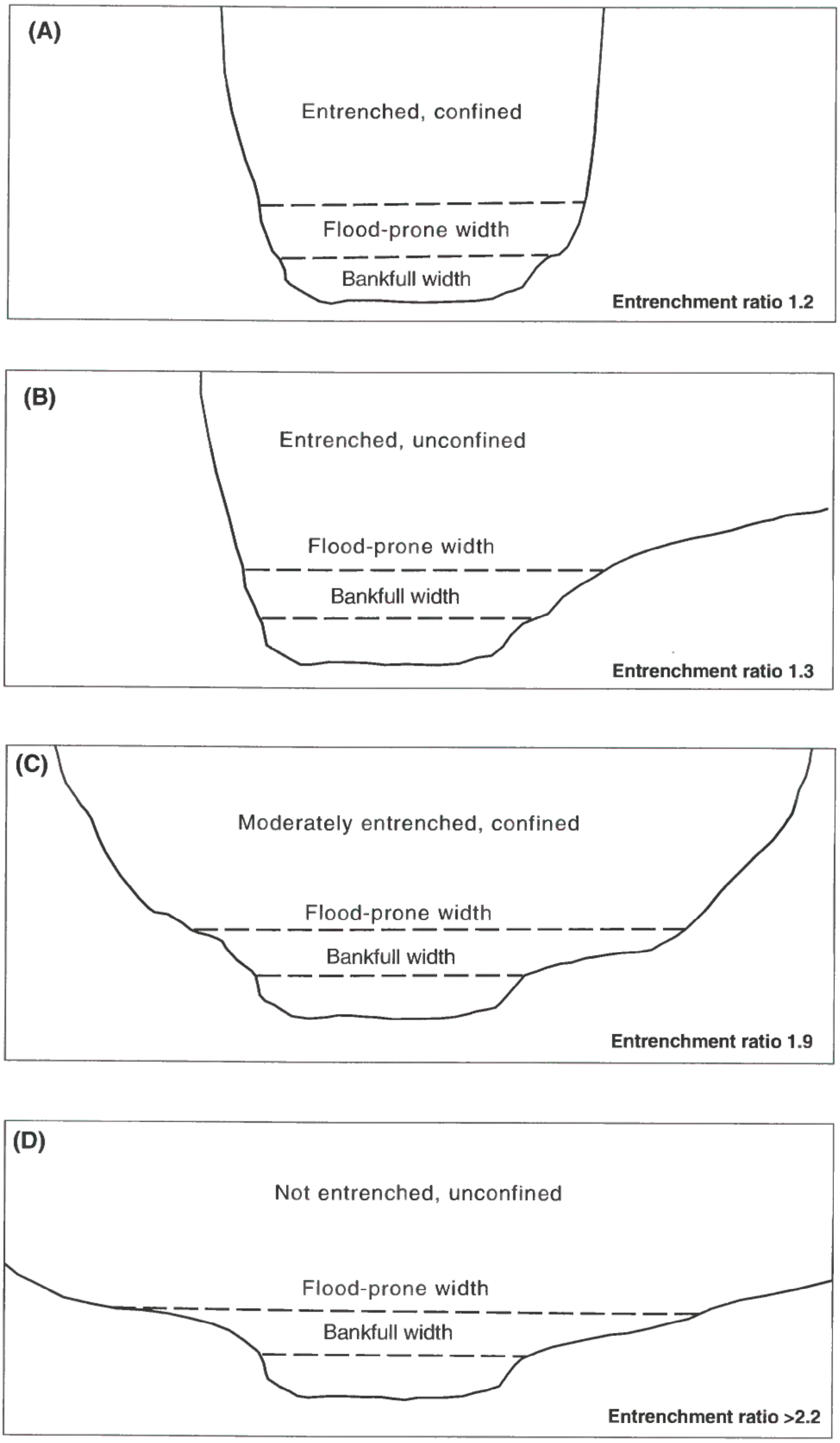


Figure 12. Examples of (A) entrenched and confined, (B) entrenched and unconfined, (C) moderately entrenched and confined, and (D) not entrenched and unconfined channels. The entrenchment ratio is equal to the flood-prone width divided by the bankfull width.

(2) Overbank flows within the flood-prone area (more frequent, smaller magnitude floods) – In an entrenched channel (fig. 12A and B), basal shear stress increases with increasing discharge. If the channel is moderately entrenched or not entrenched (fig. 12C and D), basal shear stress increases with increasing discharge but at a slower rate than in an entrenched channel of similar bankfull dimensions.

(3) Flows greater than the flood-prone width (less frequent, larger magnitude floods) – Here the larger valley configuration becomes important, with smaller basal shear stress in reaches where flood waters can expand over a broader valley (fig. 12; compare 12A and 12C to 12B and 12D).

Geomorphic and Hydraulic Characteristics of the Channel in 2000

The discussion presented in this section is based on data collected during surveys of channel cross sections and reaches conducted in August 2000. Bankfull stage is defined as the stage corresponding to a significant change in the relation of cross-sectional area to top width (Williams, 1986). For channels whose morphology is in equilibrium with flow, the discharge at bankfull stage (bankfull discharge) has a theoretical recurrence interval of 1.2 to 1.5 years (Wolman and Miller, 1960). However, equilibrium channel morphologies are uncommon in rivers in arid regions (Graf, 2002) and unlikely in a river such as the Canadian, which at the time of this study had recently experienced flood discharges. Because the channel morphology of the Canadian River likely was not in equilibrium with discharge when field work was done for this project, bankfull channel dimensions for the various cross sections probably do not correspond to any one recurrence-interval discharge. Therefore, the definition of bankfull discharge as used in this report is based strictly on channel geometry at each individual cross section and is not inherently related to a particular recurrence-interval discharge. Bankfull discharge, as used in this report, defines a discharge that is entirely confined within the primary stream channel and is used to qualitatively compare relatively small discharges with larger overbank (flood-prone and 20-year recurrence-interval) discharges.

Flood-prone width, entrenchment ratio, and the bankfull W:D ratio can be used to characterize the morphology of a channel (table 1). Flood-prone width is defined by Rosgen (1996) as the channel width at a height above the channel bottom that is twice the maximum bankfull depth. The entrenchment ratio is a measure of the degree of lateral containment of a river and is equal to the flood-prone width divided by the bankfull width. A value less than 1.4 is entrenched, 1.4 to 2.2 is moderately entrenched, and greater than 2.2 is not entrenched (Rosgen, 1996). The W:D ratio is a measure of channel shape. The W:D and entrenchment ratios together help characterize a channel's ability to dissipate the energy of higher magnitude discharges as overbank flow. For example, for a given channel slope, a channel with a larger W:D ratio will have smaller basal shear stress and less sediment-transport capacity than a narrower, deeper channel with a smaller W:D ratio. A large entrenchment ratio indicates that a channel, at discharges greater than bankfull but within the flood-prone width, can dissipate some of the sediment-transport capacity of flow by expanding it over the flood plain.

Surveyed channel slope (table 1) was the low-flow water surface at the time of measurement or the channel bottom if there was no flow. Channel-slope measurements were not made for bankfull discharge or flood-prone stages. Surveyed channel slope is used in both the bankfull and flood-prone computations of basal shear stress. Thus, for a cross section, the computed basal shear stresses show changes solely based on changes in cross-sectional dimensions.

Basal shear stress was calculated at each cross section (table 2) on the basis of surveyed channel geometry (fig. 13A-J) using DuBuoy's equation (McCuen, 1998):

$$\tau = \gamma R_h S \quad (1)$$

where

τ = bottom shear stress, in pounds per foot squared;

γ = the specific weight of water, in pounds per foot cubed;

R_h = hydraulic radius, in feet; and

S = channel slope, dimensionless.

Hydraulic radius may be approximated by mean depth for channels in which the width is large with respect to depth (McCuen, 1998).

Table 1. Canadian River channel characteristics for 1965, 1999, and 2000

[DEM, Digital Elevation Model; --, no data; >, greater than]

		Computations based on channel survey done in August 2000								Computations based on 1965 and 1999 DEM's	
Cross section (fig. 2)	Latitude Longitude	Bankfull width, in feet	Mean bankfull depth, in feet	Maximum depth, in feet	Bankfull area, in feet squared	Surveyed channel slope[1], dimensionless	Flood-prone width, in feet	Bankfull width-to-depth ratio, dimensionless	Entrenchment ratio, dimensionless	1965 channel slope[2], dimensionless	1999 channel slope[3], dimensionless
CR1	36°54'27" 104°35'50"	57.0	1.6	2.4	93.1	0.004	85.0	35.6	1.49	--	--
CR2	36°54'05" 104°35'06"	35.8	2.3	3.0	83.4	0.004	58.8	15.6	1.64	--	--
CR3	36°53'51" 104°34'48"	48.0	1.3	2.4	64.0	0.008	133.8	36.9	2.79	0.009	0.008
CR4A	36°53'44" 104°34'28"	41.6	2.0	2.7	82.3	0.008	101.1	20.8	2.43	0.004	0.008
CR4B	36°53'38" 104°34'24"	14.9	1.8	2.4	26.3	0.010	70.3	8.3	4.72	0.011	0.008
CR5	36°53'22" 104°34'01"	24.2	3.5	4.7	84.5	0.008	55.5	6.9	2.29	0.010	0.008
CR6A	36°53'09" 104°33'51"	70.6	1.1	2.0	78.8	0.009	106.8	64.2	1.51	0.009	0.007
CR6B	36°53'08" 104°33'41"	39.5	1.8	2.7	70.8	0.015	77.4	21.9	1.96	0.010	0.010
CR7	36°52'19" 104°32'48"	46.3	1.7	3.8	77.6	0.007	68.0	27.2	1.47	0.007	0.008
CR8	36°51'32" 104°31'18"	47.0	3.4	5.1	161.1	0.004	>191.1	13.8	>4.07	--	--

[1]Slope of water surface. If no flow in channel, then value is slope of channel bottom.

[2]Slope determined from topographic contours derived from 1965 aerial photographs.

[3]Slope determined from topographic contours derived from 1999 aerial photographs.

Table 2. Estimated basal shear stress for bankfull, flood-prone, and 20-year recurrence-interval discharges and width-to-depth ratio at the 20-year recurrence-interval discharge

[--, no data]

	Estimated basal shear stress (τ), in pounds per foot squared					Width-to-depth ratio at 20-year recurrence-interval discharge[1] (dimensionless)	
Cross section (fig. 2)	2000 bankfull discharge[2]	2000 flood-prone discharge[2]	Increase in basal shear stress from bankfull to flood-prone discharge (percent)	1965 20-year recurrence-interval discharge[3]	1999 20-year recurrence-interval discharge[4]	1965	1999
CR1	0.40	0.77	92	--	--	--	--
CR2	0.57	1.07	88	--	--	--	--
CR3	0.65	1.3	100	2.13	2.45	54.4	33.0
CR4A	1.00	1.50	50	[5]0.87/0.75	3.14	[5]64.1/58.8	13.5
CR4B	1.12	1.25	12	1.85	2.70	68.4	22.0
CR5	1.75	2.95	69	3.31	3.10	22.4	14.4
CR6A	0.62	1.29	108	2.64	2.62	42.0	23.9
CR6B	1.68	3.09	84	2.75	2.06	36.2	106.8
CR7	0.74	1.22	65	1.31	2.10	137.3	42.7
CR8	0.85	>1.47	73	--	--	--	--

[1]Width-to-depth ratio computed on the basis of channel dimensions derived from 1965 or 1999 Digital Elevation Model (DEM).

[2]Basal shear stress computed on the basis of channel dimensions derived from the 2000 level survey of channel cross sections.

[3]Basal shear stress computed on the basis of channel dimensions derived from 1965 DEM.

[4]Basal shear stress computed on the basis of channel dimensions derived from 1999 DEM.

[5]First value is for the main 1965 channel and second value is for a secondary 1965 channel.

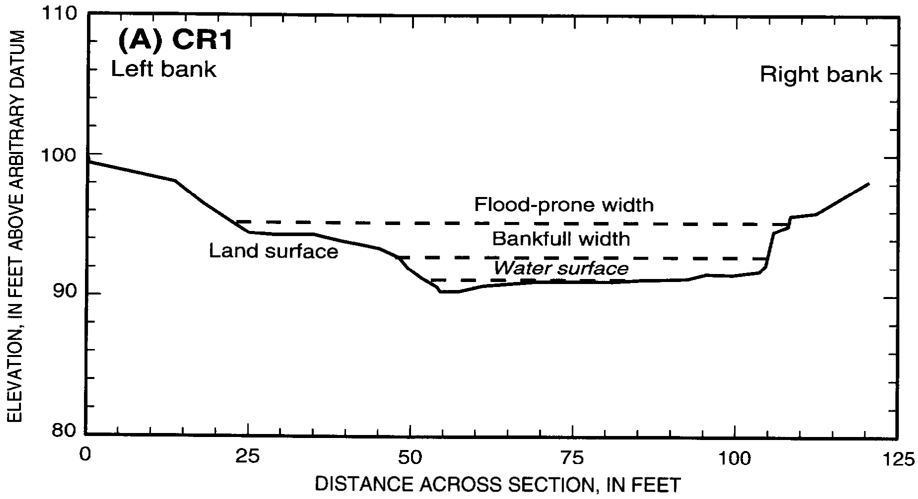


Figure 13A. Surveyed 2000 channel profile and bankfull and flood-prone widths at cross section CR1. View is downstream.

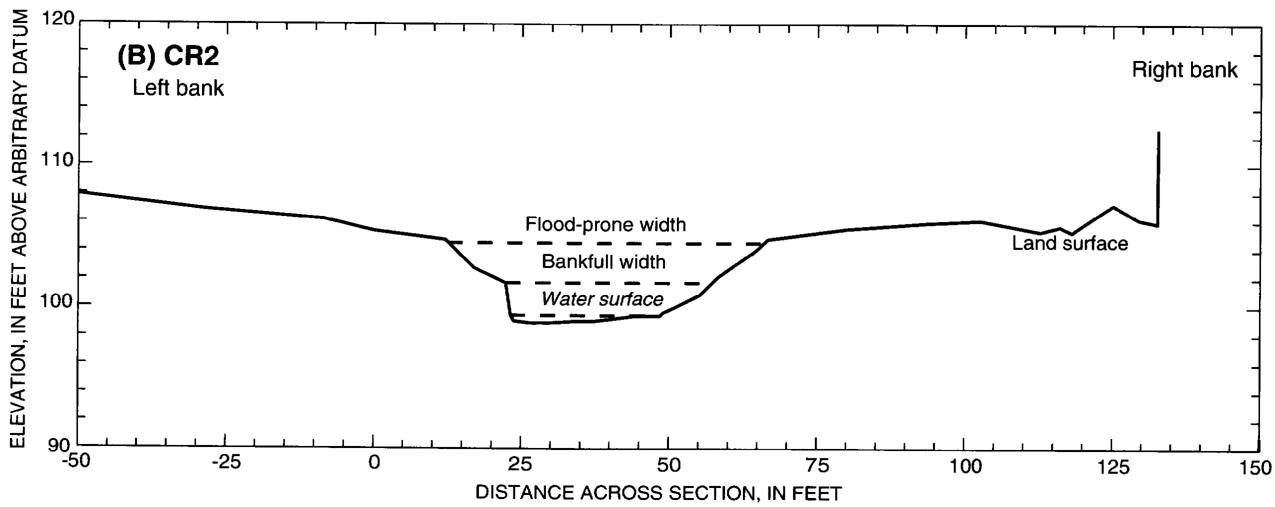


Figure 13B. Surveyed 2000 channel profile and bankfull and flood-prone widths at cross section CR2. View is downstream.

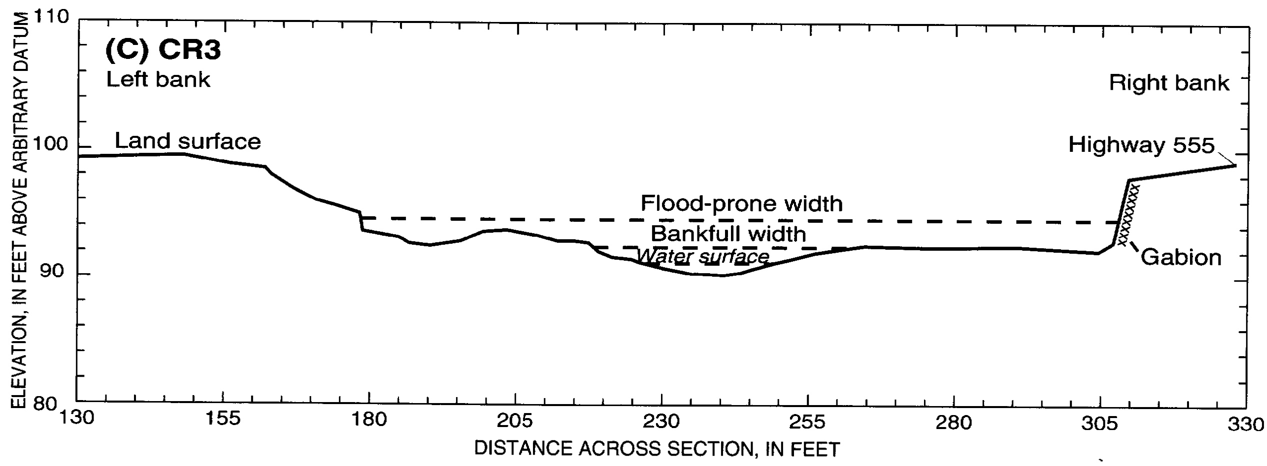


Figure 13C. Surveyed 2000 channel profile and bankfull and flood-prone widths at cross section CR3. View is downstream.

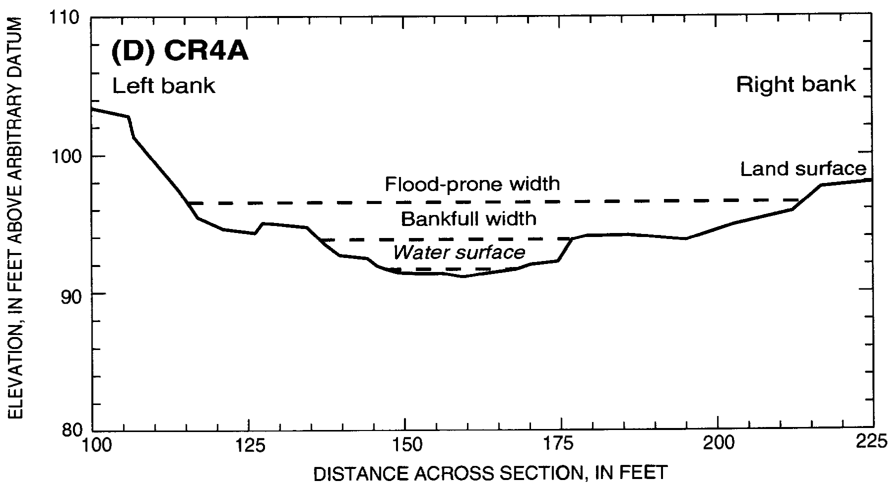


Figure 13D. Surveyed 2000 channel profile and bankfull and flood-prone widths at cross section CR4A. View is downstream.

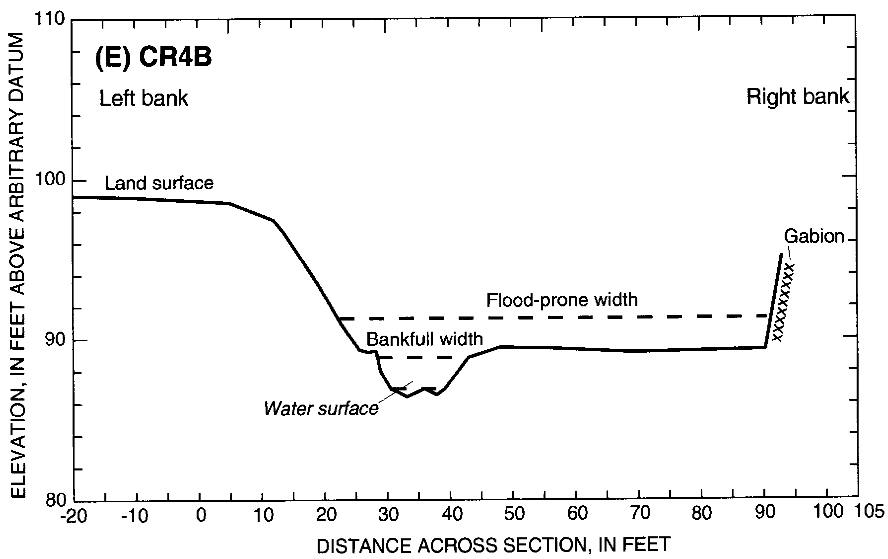


Figure 13E. Surveyed 2000 channel profile and bankfull and flood-prone widths at cross section CR4B. View is downstream.

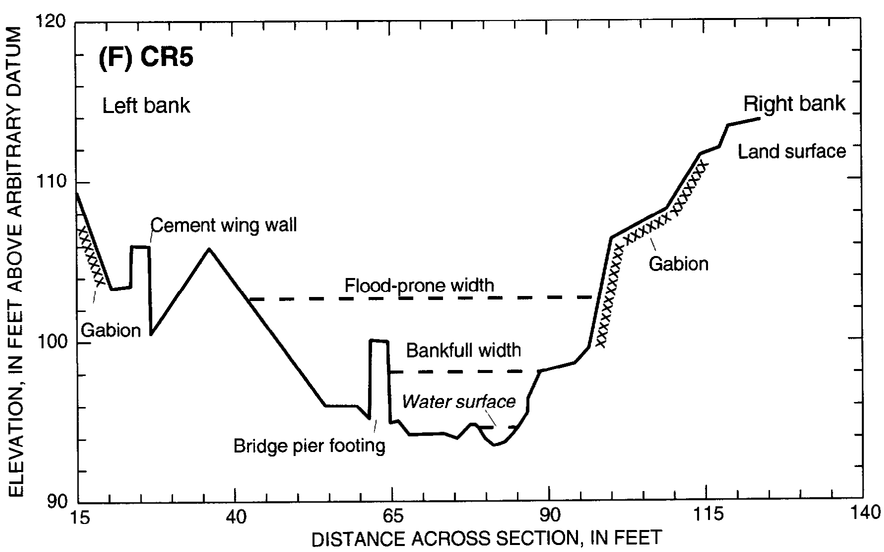


Figure 13F. Surveyed 2000 channel profile and bankfull and flood-prone widths at cross section CR5. View is downstream

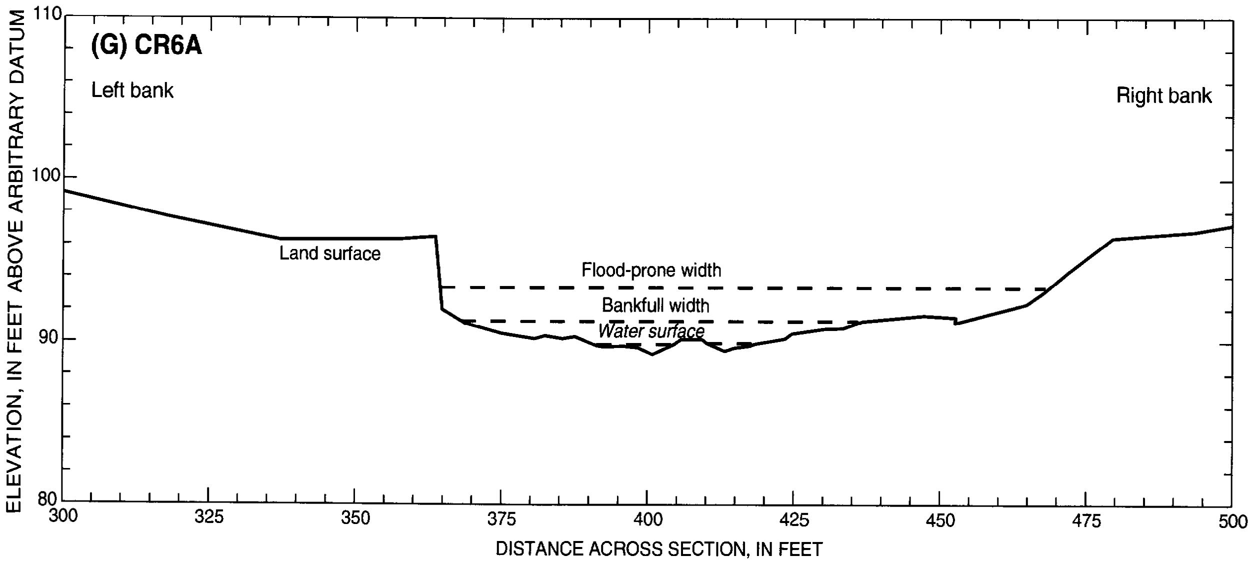


Figure 13G. Surveyed 2000 channel profile and bankfull and flood-prone widths at cross section CR6A. View is downstream.

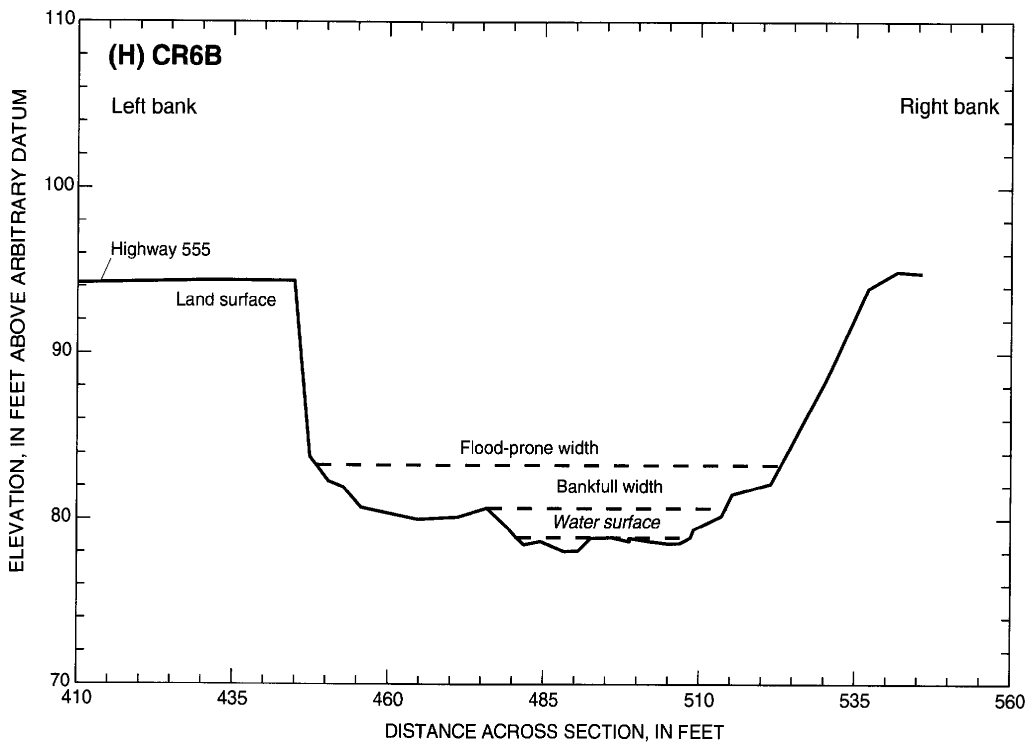


Figure 13H. Surveyed 2000 channel profile and bankfull and flood-prone widths at cross section CR6B. View is downstream.

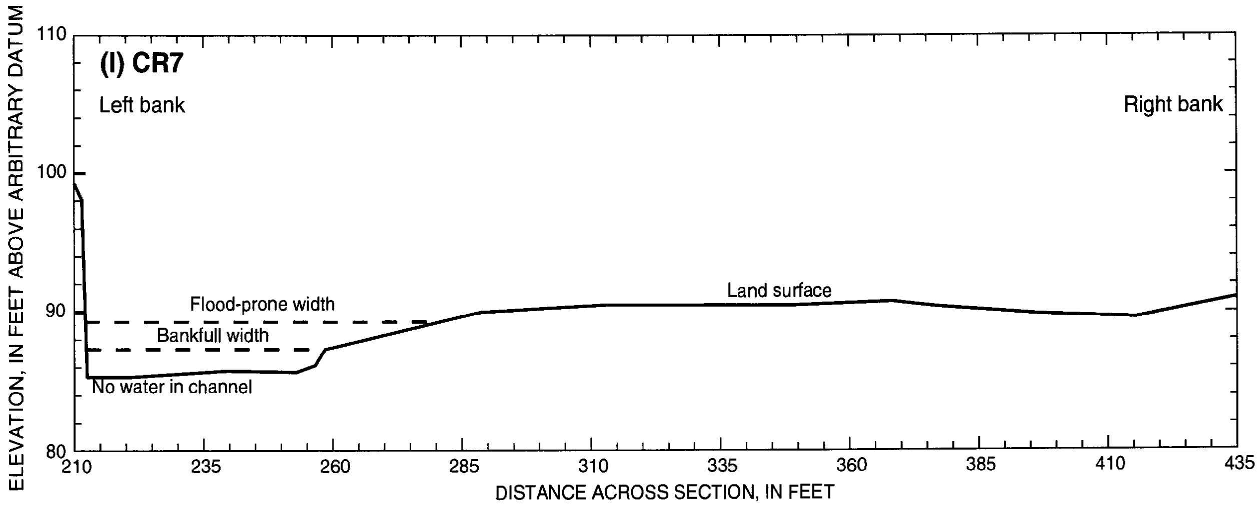


Figure 13I. Surveyed 2000 channel profile and bankfull and flood-prone widths at cross section CR7. View is downstream.

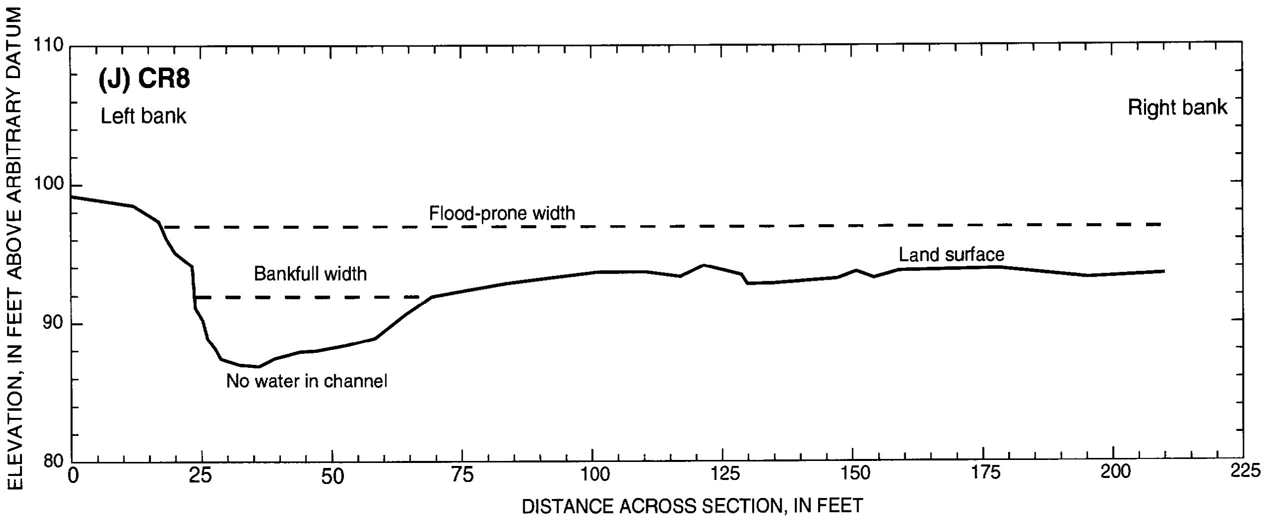


Figure 13J. Surveyed 2000 channel profile and bankfull and flood-prone widths at cross section CR8. View is downstream.

Based on pebble counts at four locations, the streambed material is poorly sorted, with a weak bimodal distribution. D_{35}, the diameter of the 35th-percentile size fraction, averages 10 mm, a medium gravel, and D_{84} averages 92 mm, a medium cobble. D_{50} ranges from 21 to 31 mm; 50 percent of streambed surface material lies in this gravel-size range (coarse gravel). No downstream trend in particle size was observed. The lack of downstream trend is typical of a river such as the Canadian, with lateral inputs from ephemeral tributary canyons that can serve as sources of coarse material.

The unchannelized reaches at cross sections CR1 and CR2 have surveyed channel slopes of 0.004 (table 1). This slope is less than half the average slope (0.0093) of the channelized reaches at cross sections CR3 through CR7. Only CR8, in the wider part of the valley, has an equally small slope. The channel at cross sections CR1 and CR2 is moderately entrenched (table 1; figs. 13A and 13B), with bankfull W:D ratios of 35.6 and 15.6, respectively, in the low to midrange for W:D ratios compared with the channel reaches at cross sections further downstream. The bankfull W:D and entrenchment ratios at cross sections CR1 and CR2 indicate a low to moderate capacity, compared with reaches at downstream cross sections, for accommodating larger discharges by overbank flooding. Based solely on these two parameters, a comparatively higher estimated basal shear stress and sediment-transport capacity might be predicted for this reach. Because of the smaller channel slope, however, estimated bankfull and flood-prone shear stresses are smaller than in any of the downstream reaches (table 2). In this unchannelized reach of the river, the small channel slope and correspondingly smaller basal shear stress result in a smaller sediment-transport capacity compared with downstream reaches.

At cross section CR3, NM 555 and a rock gabion constrain the right-bank side of the river valley but do not confine the bankfull channel (figs. 6B, 6C, and 13C). The surveyed channel slope at CR3 (0.008) is twice that of upstream cross sections CR1 and CR2, but the W:D ratio (36.9) and entrenchment ratio (2.79) indicate that the channel is not entrenched (table 1; fig. 13C). The estimated bankfull basal shear stress at cross section CR3 is similar to those at cross sections CR1 and CR2 in the unchannelized reach, indicating that cross-sectional channel dimensions, instead of channel slope, limit basal shear stress at cross section CR3.

At cross section CR4B, the length of the river channel in 1999 was 60 percent shorter than in 1965 because of the elimination of a channel meander during construction of NM 555 (fig. 7C). The channel is narrowly confined by the road and control structures along this reach (fig. 7B). Although the surveyed channel slope at CR4B is about the same as those at cross sections CR3 and CR4A, the bankfull W:D ratio is much smaller (table 1), indicating a deeper channel at this point. The channel is not entrenched at cross sections CR4A and CR4B. The percentage increase in estimated basal shear stress from bankfull to flood-prone discharge is much smaller at cross section CR4B than that at any other cross section (table 2). This suggests that, within the limit of flood-prone discharges, the river reach at cross section CR4B is effective in limiting the increase in basal shear stress and sediment-transport capacity by utilizing overbank flow.

At cross section CR5, located just upstream from the NM 555 bridge, the river channel is tightly confined in the channelized approach to the bridge (figs. 8B and 13F). The bankfull W:D ratio (6.9) is small compared with those of other cross-section reaches, but the channel is not entrenched (table 1). The estimated basal shear stress at cross section CR5 is the largest of all cross sections for bankfull discharge (1.75 lb/ft^2) and second largest for flood-prone discharge conditions (2.95 lb/ft^2) (table 2).

At cross section CR6B, the length of the river channel also was shortened by the elimination of a meander during construction of NM 555 (fig. 9C). The channel at cross section CR6B is confined on its left bank by the road and on its right bank by a steep bank (fig. 13H). The surveyed channel slope at cross section CR6B was the steepest measured (0.015, table 1). The bankfull W:D ratio of 21.9 was similar to that of CR4A, whereas the estimated bankfull basal shear stress (1.68 lb/ft^2) was the second largest value and the estimated flood-prone basal shear stress (3.09 lb/ft^2) was the largest. The surveyed channel slope at CR6A (fig. 13G) was 0.009, and the bankfull W:D ratio (64.2) was relatively large. The river channel at both cross sections CR6A and CR6B is moderately entrenched; however, a relatively large bankfull W:D ratio limits the estimated bankfull basal shear stress at cross section CR6A. In bankfull cross-sectional dimension, the channel at cross section CR6B is similar to the channel at CR4A, but the steeper channel slope and moderately entrenched channel at cross section CR6B result in estimated bankfull and flood-prone discharge shear stresses similar to the channelized bridge cross section at CR5.

At cross section CR7, located downstream from the point where the valley begins to widen, there were, at the time of this study, two active channels (fig. 10B). At the time of the 1999 aerial photography and during visits to the study area, the southwestern channel appeared to be the primary channel and the northeastern channel a secondary channel (fig. 10B). Even though the northeastern channel appears to be secondary, it is the channel of concern because of its proximity to NM 555 and, therefore, was the channel surveyed for this study. The left-bank side of the secondary channel has been stabilized by gabions where the channel impinges on the NM 555 roadway. The secondary channel at cross section CR7 is in the midrange for all channel characteristics (tables 1 and 2).

Cross section CR8, located about 2 mi downstream from CR7, has a small channel slope (0.004) equal to those of cross sections CR1 and CR2 and a comparatively small bankfull W:D ratio (13.8). The channel survey did not include the right-bank end of the flood-prone width, which is in excess of 200 ft at this location (fig. 13J). The small channel slope and lack of entrenchment result in a small estimated basal shear stress at both bankfull and flood-prone discharges at this cross section.

Based on the surveyed channel cross sections, for in-channel flows and low magnitude, more frequent floods, slope is the primary determinant of basal shear stress and sediment-transport capacity in a channel reach. For reaches with similar slopes, W:D ratio and degree of entrenchment determine the ability of the channel to effectively accommodate more frequent, lower magnitude overbank flooding without a large increase in basal shear stress.

Comparison of Geomorphic and Hydraulic Characteristics of the Channel in 1965 and 1999

The discussion in this section is based primarily on data and DEM's derived from the 1965 and 1999 aerial photographs.

Within the study area, the river channel along NM 555 is laterally confined within a narrow, steep-sided valley from Potato Canyon to a point about 0.5 mi downstream from cross section CR6B, where the valley widens (fig. 2). Prior to construction of NM 555, the zone of active-channel migration encompassed the entire width of this narrow upper valley. Streamflow-control structures designed to protect the road from erosion and deep, narrow stream channels built during construction of NM 555 now constrain the channel and, compared to pre-road-construction conditions, have reduced the amplitude and frequency of channel meanders (figs. 7C and 9C). Major channel modifications associated with construction of NM 555 include channel straightening and elimination of meanders at cross sections CR4B (fig. 7C) and CR6B (fig. 9C), gabion construction at cross sections CR3 (fig. 6) and CR7 (fig. 10), and construction of a bridge at cross section CR5 (fig. 8B,C). (Gabions were constructed after the 1999 photographs were taken.)

The 1999 stream channel overall had deepened since 1965 (fig. 14). This deepening was most pronounced upstream from the channelization at cross section CR4B (fig. 14).

The channel slope, as computed from 1965 and 1999 DEM's between cross sections CR3 and CR7, is significantly steeper in 1999 (0.0085) than in 1965 (0.0078) (fig. 14). Because of DEM error (plus or minus 1.5 ft for the 1965 DEM), the error in slope over the approximately 20,000 ft of overall channel reach is about 0.000075. Therefore, the slope difference between the 1965 and 1999 channels (0.0007) is significant.

Although channel slopes for each cross section were determined by level survey in 1999, channel slopes also were determined from the 1965 and 1999 DEM's at cross sections CR3 through CR7 for consistency in comparison of geomorphic and hydraulic characteristics. Channel slopes determined from the DEM's were calculated for a channel distance of about 800 ft centered on each cross section. However, the vertical DEM error (plus or minus 1.5 ft for the 1965 DEM) resulted in an error of about plus or minus 0.002 in the channel-slope measurements over the 800-ft-long reaches. Thus, only the channel-slope values at cross sections CR4A and CR4B are significantly different in 1999 compared with 1965 (table 1). In 1965, the slope at CR4A was small, and then steepened at CR4B, whereas in 1999 both cross sections had an equal intermediate slope.

Channel sinuosity between cross sections CR3 and CR7, calculated as the longitudinal channel distance of the channel reach divided by the corresponding longitudinal distance down the valley axis, was 1.5 in 1965 and 1.3 in 1999 (table 3). A channel with sinuosity greater than 1.5 is considered to be highly meandering, a channel with sinuosity of 1.5 to 1.2 is considered to be moderately meandering, and a channel with sinuosity less than 1.2 is considered to be not meandering (Langbein and Leopold, 1966). Most of the decrease in channel sinuosity occurred in

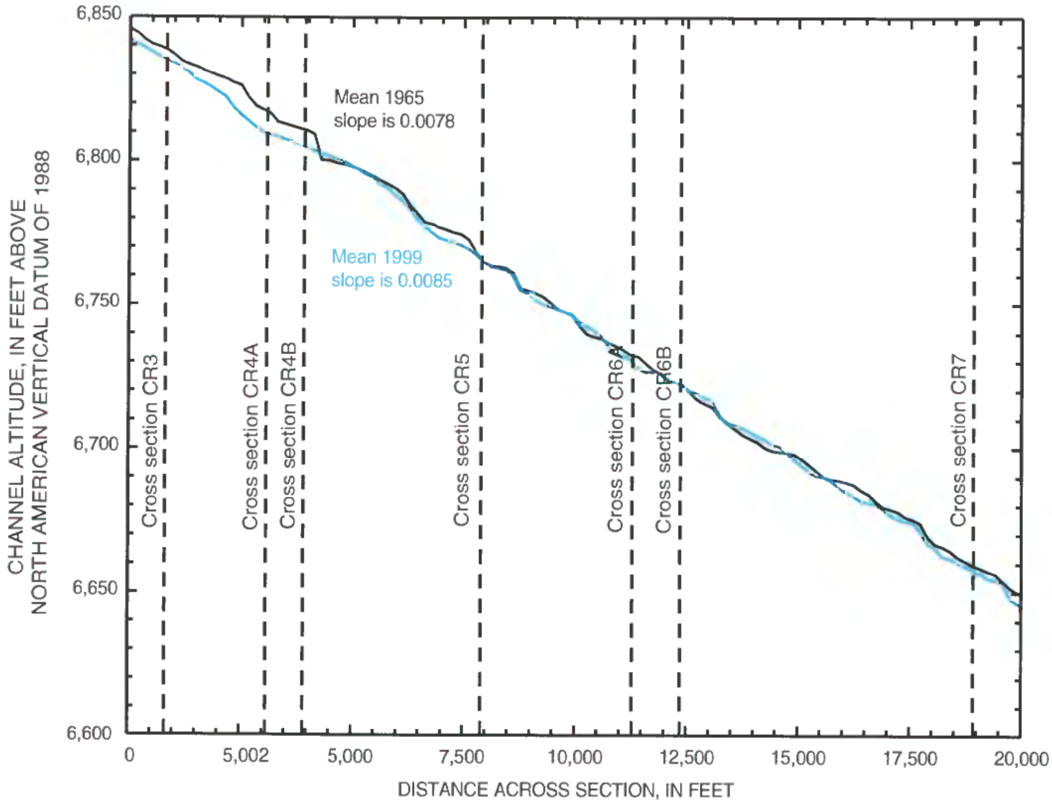


Figure 14. Down-valley altitude for 1965 and 1999 channels. Location of cross sections in figures 2 and 5A–10C.

Table 3. Channel sinuosity in 1965 and 1999

Channel reach location	Channel sinuosity (1965)	Degree of meander (Langbein and Leopold, 1966) (1965)	Channel sinuosity (1999)	Degree of meander (Langbein and Leopold, 1966) (1999)
CR4B[1]	1.5	Moderate	0.9	None
CR6B[1]	1.3	Moderate	1.1	Moderate
CR7[1]	1.4	Moderate	1.2	Moderate
CR3 through CR7	1.5	Moderate	1.3	Moderate

[1]2,500-foot channel reach centered at cross section.

three 2,500-ft channel reaches centered on cross sections CR4B, CR6B, and CR7. Between 1965 and 1999 the channel sinuosity of the reach centered on cross section CR4B decreased from 1.5 to 0.9 (moderately to not meandering); channel sinuosity of the reach centered on cross section CR6B decreased from 1.3 to 1.1 (both moderately meandering); and channel sinuosity of the reach centered on cross section CR7 decreased from 1.4 to 1.2 (both moderately meandering; table 3).

The changes in sinuosity are consistent with the degree of channelization of these reaches. Channel length decreased because of channelization in the three 2,500-ft reaches corresponding to cross sections CR4B, CR6B, and CR7. Between 1965 and 1999 the channel length of the reaches centered on cross sections CR4B and CR6B decreased by 60 and 30 percent, respectively, because of the elimination of meanders. The channel length of the reach centered on cross section CR7 decreased by 10 percent.

Valleywide channel cross-sectional profiles were derived from the 1965 and 1999 DEM's at cross sections CR3, CR4A, CR4B, CR5, CR6A, CR6B, and CR7 (fig. 15A-G). Valleywide cross-sectional profiles were not derived at cross sections CR1, CR2, and CR8 because these cross sections are not within the area of aerial photography. Cross-sectional channel dimensions corresponding to the 20-yr peak discharge were determined for the valleywide cross sections for the 1965 and the 1999 channels using Manning's equation and a Manning's constant (n) of 0.032. The value for n was selected on the basis of field observations and with reference to Barnes (1967). The n-value is consistent with the value used in the indirect discharge determination (Scott Waltemeyer, U.S. Geological Survey, oral commun., 1999). The valleywide cross-sectional channel geometry derived from both the 1965 and the 1999 DEM's was used as a basis for computation of the estimated basal shear stress and W:D ratio at each cross section for the 20-year recurrence-interval discharge. However, the vertical and horizontal resolution of the DEM's was too coarse to allow determination of channel dimensions corresponding to bankfull and flood-prone discharges. Although derived from different topographic data, the basal shear stress values derived from the 2000 level survey for bankfull and flood-prone discharges and the basal shear stress values derived from the DEM's for the 1965 and 1999 20-year recurrence-interval discharge are used here for a qualitative comparison of pre- and post-channelization basal shear stresses at various discharges.

For the recent (1999 and 2000) channel, basal shear stress generally increases as discharge increases from bankfull to the 20-year recurrence-interval discharge (table 2). At cross section CR5, basal shear stress increases only slightly between the flood-prone and 20-year recurrence-interval discharge and is nearly the same for 1965 and 1999 at the 20-year recurrence-interval discharge. This suggests that bridge construction resulted in a channel that is hydraulically similar to the uncontrolled pre-bridge channel in its ability to accommodate floods as large as a 20-year recurrence-interval discharge. Likewise, basal shear stress estimates at CR3 and CR6A are similar for a 20-year flood in both the 1965 and 1999 channels.

Following the 1999 flood, the NMDOT reported road damage near cross sections CR4A and CR4B but did not report damage near cross sections CR6A and CR6B. The 1999 W:D ratio computed for the 20-year recurrence-interval discharge is about one-third the ratio at CR4B and about one-fourth to one-fifth the ratio at CR4A (table 2) than in 1965. The channel in 1999 was confined between the hillslope and the roadbed compared to the 1965 configuration (figs. 15B and 15C). These changes in channel geometry at cross sections CR4A and CR4B resulted in 20-year recurrence-interval discharge basal shear stresses that were larger in 1999 than in 1965. This indicates that for the 20-year flood, the channel at cross section CR4A and CR4B cannot limit basal shear stress by expanding over a broader flood plain and that basal shear stress estimates are greater for the channelized than for the pre-construction configuration.

The 20-year recurrence-interval basal shear stress at cross section CR6B is smaller for the 1999 channel than for the 1965 channel because the 20-year recurrence-interval W:D ratio in 1999 is about three times that of the ratio in 1965. In contrast to the channel at cross section CR4B, the channel at cross section CR6B, although much straighter, is not confined and has access to a flood plain to the southwest that can accommodate the larger magnitude discharges. Basal shear stresses associated with the larger magnitude flows are therefore limited, explaining, in part, why the 1999 flood resulted in road damage at cross sections CR4A and CR4B but not at cross sections CR6A and CR6B.

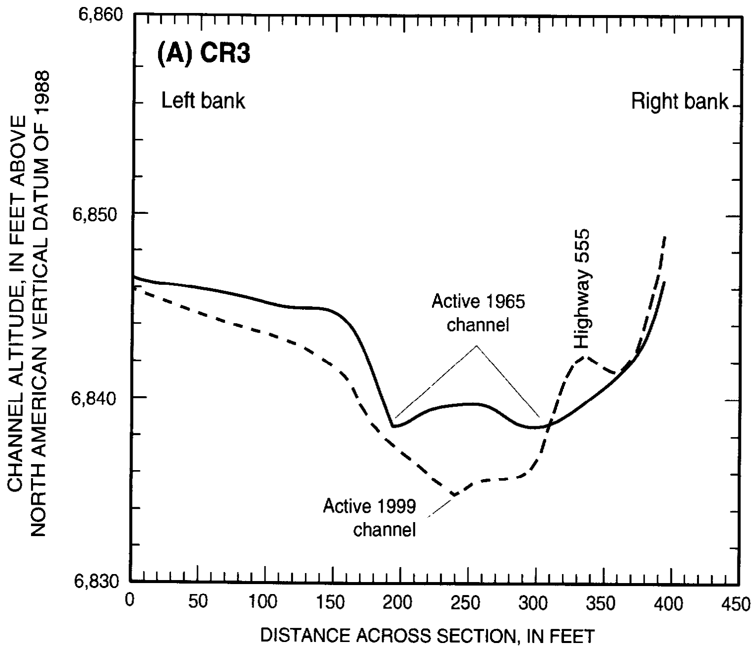


Figure 15A. Profiles of 1965 and 1999 channels at cross section CR3. See figures 5 and 6 for section locations. View is downstream.

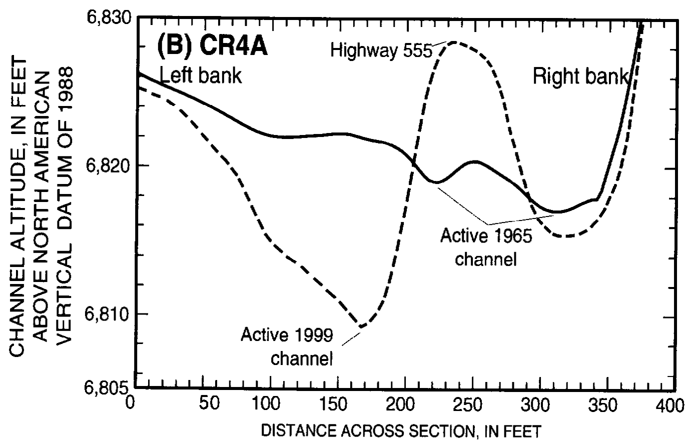


Figure 15B. Profiles of 1965 and 1999 channels at cross section CR4A. See figures 5 and 7 for section locations. View is downstream.

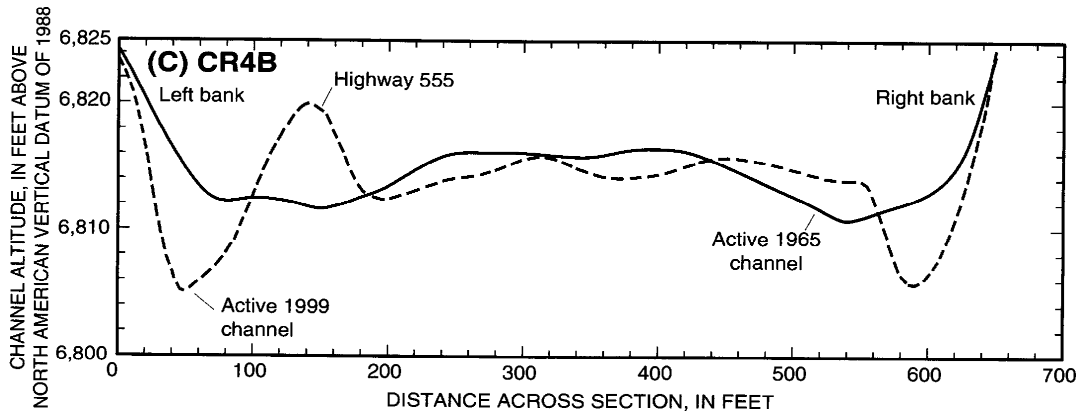


Figure 15C. Profiles of 1965 and 1999 channels at cross section CR4B. See figures 5 and 7 for section locations. View is downstream.

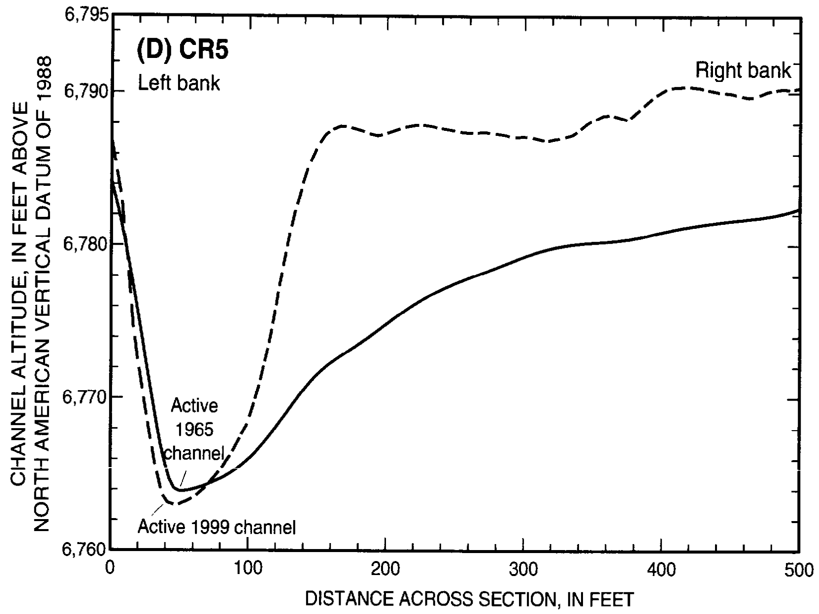


Figure 15D. Profiles of 1965 and 1999 channels at cross section CR5. See figures 5 and 8 for section locations. View is downstream.

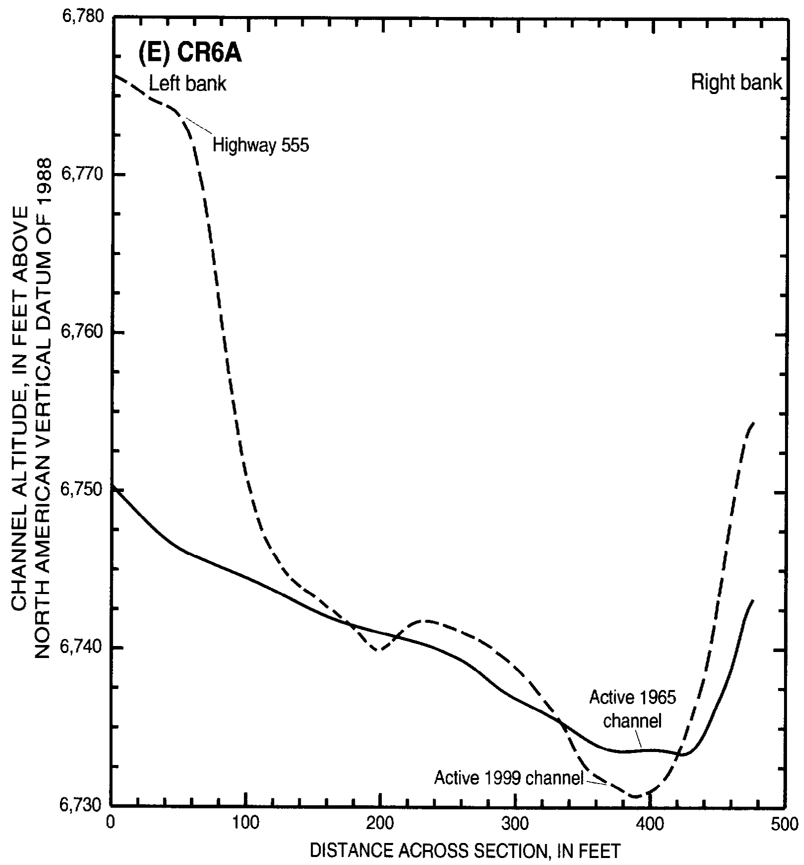


Figure15E. Profiles of 1965 and 1999 channels at cross section CR6A. See figures 5 and 9 for section locations. View is downstream.

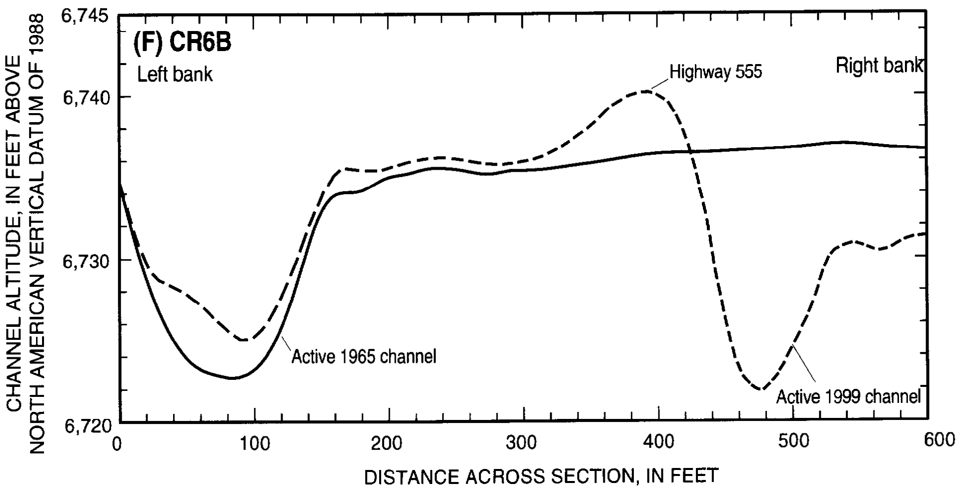


Figure 15F. Profiles of 1965 and 1999 channels at cross section CR6B. See figures 5 and 9 for section locations. View is downstream.

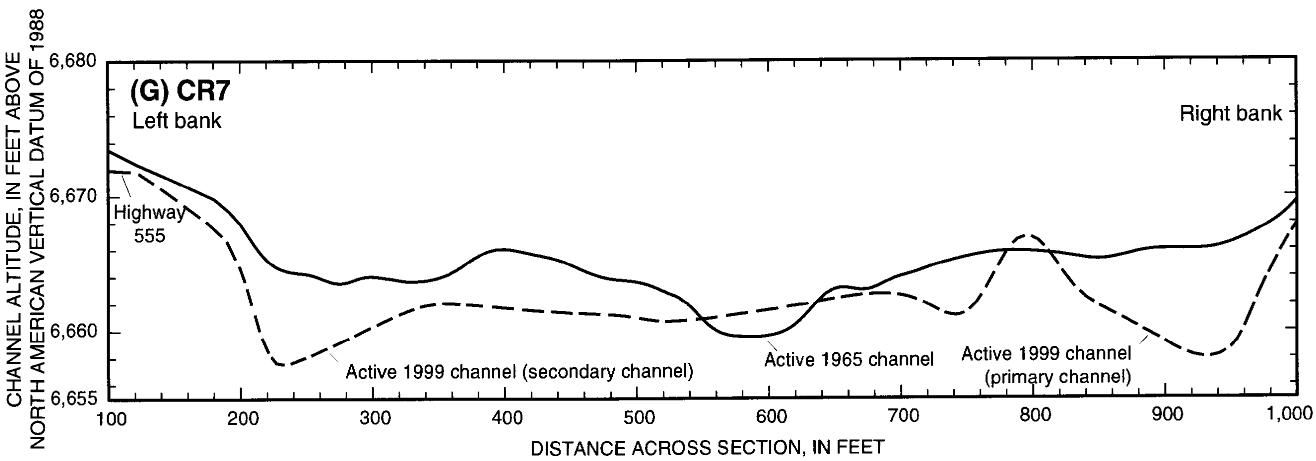


Figure 15G. Profiles of 1965 and 1999 channels at cross section CR7. See figures 5 and 10 for section locations. View is downstream.

The channel at cross section CR7 has a larger 20-year recurrence-interval-discharge basal shear stress for 1999 than for 1965, if all flow is assumed to follow the primary channel. However, the two basal shear stresses are similar if flow in 1999 is apportioned between the two channels, which the aerial photography indicates is a likely scenario. Thus, the 1999 basal shear stress estimate for the channel at cross section CR7 is an upper limit for the 20-year recurrence-interval discharge at that cross section.

Natural Channelization

NM 555 opposite the mouth of Coal Canyon (fig. 2) is an area where the roadway was damaged during the 1999 floods. Coal Canyon discharges into the Canadian River Valley downstream from cross section CR7. By using Waltemeyer's (1996) equation for ungaged streams and the flood-frequency record for the Canadian River at Hebron streamflow-gaging station, peak discharge at the mouth of Coal Canyon for the 1999 flood was estimated to be about 1,800 ft /s. A channel exiting from the mouth of Coal Canyon continues north across the Canadian River Valley and splits into several smaller channels in a debris-fan deposit adjacent to the Canadian River channel where the river parallels NM 555. The debris-fan deposit confines the active river to a channel adjacent to the roadway. Downstream from Coal Canyon, the Canadian River moves toward the center of the valley and becomes more broadly meandering. The Coal Canyon debris-fan deposit appears to effectively channelize the Canadian River along this reach, much like the artificially confined channel at cross section CR4, with similar consequences in terms of increased potential sediment-transport capacity at large discharges.

SUMMARY AND CONCLUSIONS

Following a 500-year flood in 1965, NM Highway 555 was built in its present (2000) configuration through the Canadian River Valley. During road construction, the river was channelized over several reaches. A 20-year recurrence-interval flood in 1999 damaged the NM 555 roadway.

Many factors can and do contribute to flood damage at a particular section of roadway, including details of control structures, bridges, and road construction. Analysis for this report did not consider any of those factors but did include examination of the way in which variations in cross-sectional dimensions contribute to the expected effect of larger magnitude discharges. In channelized streams, channel configurations effective in accommodating small-magnitude floods may be ineffective at accommodating larger magnitude floods. Road damage opposite the mouth of Coal Canyon indicates that channel constriction due to natural phenomena can have effects similar to those from artificial channelization.

In August 2000, 10 channel cross sections and 10 channel slopes were surveyed on the Canadian River. Cross sections were selected to represent channelized and unchannelized conditions.

Streamflow data were obtained for the Canadian River near Hebron streamflow-gaging station for October 1, 1946, to September 30, 1986, and by an indirect-discharge measurement just downstream from Potato Canyon in September 1999. In addition, discharges for the peak 1999 flood in the Canadian River and for Coal Canyon were estimated using the Canadian River peak-frequency record and regional equations for discharge on an ungaged stream. Precipitation data were obtained from the National Climatic Data Center for the Filter Plant at Raton, New Mexico, weather station.

DEM's of the Canadian River Valley within the study area were photogrammetrically generated using aerial photographs taken on June 23, 1965, and June 1, 1999. Both sets of photographs show abundant evidence of flooding in the form of large sand bars and unvegetated areas throughout the valley bottom.

A large flood in the Canadian River (62,400 ft /s at the Canadian River near Hebron gaging station) on June 17, 1965, was associated with above-average precipitation during the month of June 1965. The peak 1999 flood discharge was estimated to be about 7,000 ft /s, based on an indirect-discharge measurement on September 10, 1999. Based on the peak-frequency record for the gaging station near Hebron, the June 1965 flood was estimated to have a recurrence interval of 500 years, whereas the peak 1999 flood was estimated to have a recurrence interval of about 20 years.

Flood-prone width, entrenchment ratio, and the bankfull W:D ratio were computed on the basis of data collected during channel surveys in August 2000. Basal shear stress was calculated at each cross section on the basis of surveyed channel geometry using DuBuoy's equation.

For bankfull and floodprone stages measured at these cross sections, the relative magnitudes of slope, W:D ratio, and entrenchment ratio determine the magnitude of basal shear stress at a given discharge. The unchannelized reaches at CR1 and CR2 are moderately entrenched, but low slopes result in a low basal shear stress at both bankfull and floodprone discharges. CR3 and CR6A have slopes about twice the unchannelized cross sections. CR3 has a similar W:D ratio and is not entrenched, and CR6A is moderately entrenched, but has a large W:D ratio. Bankfull basal shear stresses are similar to the unchannelized reach.

The channelized cross section at CR6B is moderately entrenched with a moderate W:D ratio but has the steepest slope measured. Bankfull and floodprone basal shear stress are among the highest calculated, similar to the bridge cross section at CR5. In contrast, CR4B, in the most channelized reach, is not entrenched with a small W:D ratio, and has a moderate slope and a moderate bankfull and floodprone basal shear stress. At CR4B, channel geometry within the limits of the floodprone width can accommodate overbank floods with little increase in basal shear stress.

A comparison of data derived from the 1965 and 1999 aerial photographs indicates that prior to construction of NM 555 the zone of active-channel migration encompassed the entire width of the valley in the upper part of the study area. Streamflow-control structures designed to protect the road from erosion and deep, narrow stream channels built during construction of NM 555 now constrain the channel and have reduced the amplitude and frequency of channel meanders. Major channel modifications include channel straightening and elimination of meanders at cross sections CR4B and CR6B, gabion construction at cross sections CR3 and CR7, and construction of a bridge at cross section CR5. In 1999 the stream channel was shorter, deeper, steeper, and less sinuous than in 1965. The deepening is most pronounced upstream from cross section CR4B. Channel slopes determined from the 1965 and 1999 DEM's at cross sections CR3 through CR7 were significantly different only at cross sections CR4A and CR4B.

The basal shear stress for the 20-year recurrence-interval discharge was computed for cross sections CR3, CR4A, CR4B, CR5, CR6A, CR6B, and CR7 using the valleywide channel cross-sectional profiles derived from 1965 and 1999 DEM's. The results show that at cross section CR5 the basal shear stress increases only slightly between the flood-prone and the 20-year recurrence-interval discharges and is nearly the same for the 1965 and 1999 20-year recurrence-interval discharges, indicating that the bridge construction resulted in a channel that is hydraulically similar to the pre-bridge channel. Likewise, CR3 and CR6A are hydraulically similar in terms of estimated basal shear stress for a 20-year recurrence-interval flood in 1965 and 1999.

Flood damage to NM 555 in the area of cross sections CR4A and CR4B at an estimated 20-year recurrence-interval discharge may be attributed to W:D ratios that were smaller in 1999 than in 1965, indicating that the channel in this reach cannot limit basal shear stress by expanding over a broader flood plain. Basal shear stress estimates are greater for the channelized than for the pre-construction configuration.

In the channel at cross section CR6B, the basal shear stress is smaller for the 1999 channel. The W:D ratio for the channel at cross section CR6B is about three times the ratio for 1999 for the 20-year recurrence-interval discharge than for 1965. In contrast to the channel at cross section CR4B, the channel at cross section CR6B, although much straighter, is not confined and has access to a flood plain to the south that can accommodate larger magnitude flood flows. Basal shear stresses associated with the larger magnitude flows are therefore limited, explaining, in part, why the 1999 flood resulted in road damage at cross sections CR4A and CR4B but not at cross sections CR6A and CR6B.

The channel at cross section CR7 has a larger 20-year recurrence-interval discharge basal shear stress for 1999 than for 1965, if all flow is assumed to follow the primary channel. However, the two basal shear stresses are similar if flow in 1999 is apportioned between the two channels. Thus, the 1999 basal shear stress estimate for the channel at cross section CR7 is an upper limit for the 20-year recurrence-interval discharge at that cross section.

In conclusion, channelized portions of the river appear to be able to accommodate the more frequent, smaller magnitude discharges (discharges at or below the flood-prone width). At the larger 20-year recurrence-interval discharge, however, the ability of flood flows to limit basal shear stress by expanding over a larger flood plain is limited in confined reaches, causing a larger erosional and sediment-transport capacity compared to unconfined portions of the channel.

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GLOSSARY

Bankfull depth. The average distance from the water surface to the channel bottom when the stream is at **bankfull stage**.

Bankfull stage. The stage that corresponds to the **bankfull discharge**.

Bankfull width. The top width of a stream at **bankfull discharge**.

Bankfull width-to-depth ratio. A quantity equal to the **bankfull width** divided by the **bankfull depth**.

Basal shear stress. The amount of drag exerted by flowing water on a unit area of a stream-channel bed. This is the force that moves streambed material.

Confined channel. A channel confined to a relatively narrow course by the river valley.

Entrenched channel. A channel that is constrained within banks sufficiently high to contain flows that would cause overbank flooding in a similar-sized, unentrenched channel. Gullies, ravines, and bedrock gorges are typical landforms where **entrenched channels** occur.

Entrenchment ratio. A quantity equal to the **flood-prone width** divided by the **bankfull width**.

Flood-prone width. The top width of a stream at a stage that is twice the maximum depth at the **bankfull discharge**.

Gabion. Generally a rock structure built along riverbanks to prevent erosion of the banks.

Left bank. The streambank on the left side, when facing downstream.

Overbank flow. Flow that overtops the banks of the stream channel.

Right bank. The streambank on the right side, when facing downstream.

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