Channel Change on the Santa Cruz River, Pima County, Arizona, 1936–86

United States Geological Survey Water-Supply Paper 2429

Prepared in cooperation with the Pima County Department of Transportation and Flood Control District

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Channel Change on the Santa Cruz River, Pima County, Arizona, 1936–86

By JOHN T.C. PARKER

Prepared in cooperation with the
Pima County Department of
Transportation and
Flood Control District

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CONTENTS

FIGURES

TABLES

CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
cubic foot per second (ft^3/s)	0.02832	cubic meter per second

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Channel Change on the Santa Cruz River, Pima County, Arizona, 1936–86

By John T.C. Parker

Abstract

The Santa Cruz River, an ephemeral river that drains 8,581 square miles in southeastern Arizona, has a long history of channel instability. Since the late 19th century, lateral channel erosion has caused extensive property damage, particularly in Pima County. During the flood of 1983, about $100 million of damage was caused in the Tucson area alone; most damage resulted from bank erosion on the Santa Cruz River and its tributaries.

Aerial photographs, interpretations of field observations, and published and unpublished geomorphic, topographic, geotechnical, and historical data were used to investigate channel change from 1936 through 1986 along a 70-mile reach of the Santa Cruz River in Pima County, Arizona. The nature, magnitude, location, and frequency of channel change on the Santa Cruz River have been highly variable in time and space.

Three mechanisms of lateral channel change—meander migration, avulsion and meander cutoff, and channel widening—were identified on the Santa Cruz River. The dominant mechanism in a reach depends on channel morphology and flood magnitude. The dominant vertical change has been degradation, although alternating periods of aggradation and degradation have occurred at some sites. Vertical and lateral channel-change mechanisms operate in concert with bank-retreat mechanisms to produce widening of entrenched channel systems known as arroyos.

The timing and magnitude of channel change at a particular location are controlled primarily by hydrologic and climatic factors such as magnitude, duration, intensity, and frequency of precipitation and floods. The location of channel change and its magnitude in response to a given discharge are controlled largely by topographic, geologic, hydraulic, and artificial factors. Although much of the present morphology of the Santa Cruz River is the result of recent large floods, a direct link between hydroclimatic conditions and channel change is not always evident because of the complicating effects of other controls.

Although an appropriate model for predicting channel change on the Santa Cruz River has not been identified, the stability of reaches relative to one another and to time can be evaluated by recognition of the major channel-changing mechanisms operating in a reach and of the local controls on channel change. Much of the channel change that occurred during the study period has been artificial.

INTRODUCTION

The Santa Cruz River, which at its confluence with the Gila River drains about 8,581 mi^2 in southeastern Arizona and northern Sonora, Mexico, is typical of large, ephemeral rivers in the western United States (fig. 1). Before the late 19th century, the Santa Cruz River upstream from Tucson was a shallow, narrow channel in an active flood plain marked by gentle swales and ridges. In the late 19th and early 20th century, the river incised its flood plain to form an arroyo—an entrenched channel system—that is now locally as much as 30 ft below its historical flood plain and more than 1,900 ft wide (Betancourt and Turner, 1988). In the process of changing, the Santa

Cruz River has destroyed bridges and buildings and washed away acres of agricultural and commercial land. Major floods in 1977 and 1983 were particularly destructive. During the flood of record in 1983, bank erosion in the Tucson area alone caused about $100 million of property damage (Saarinen and others,

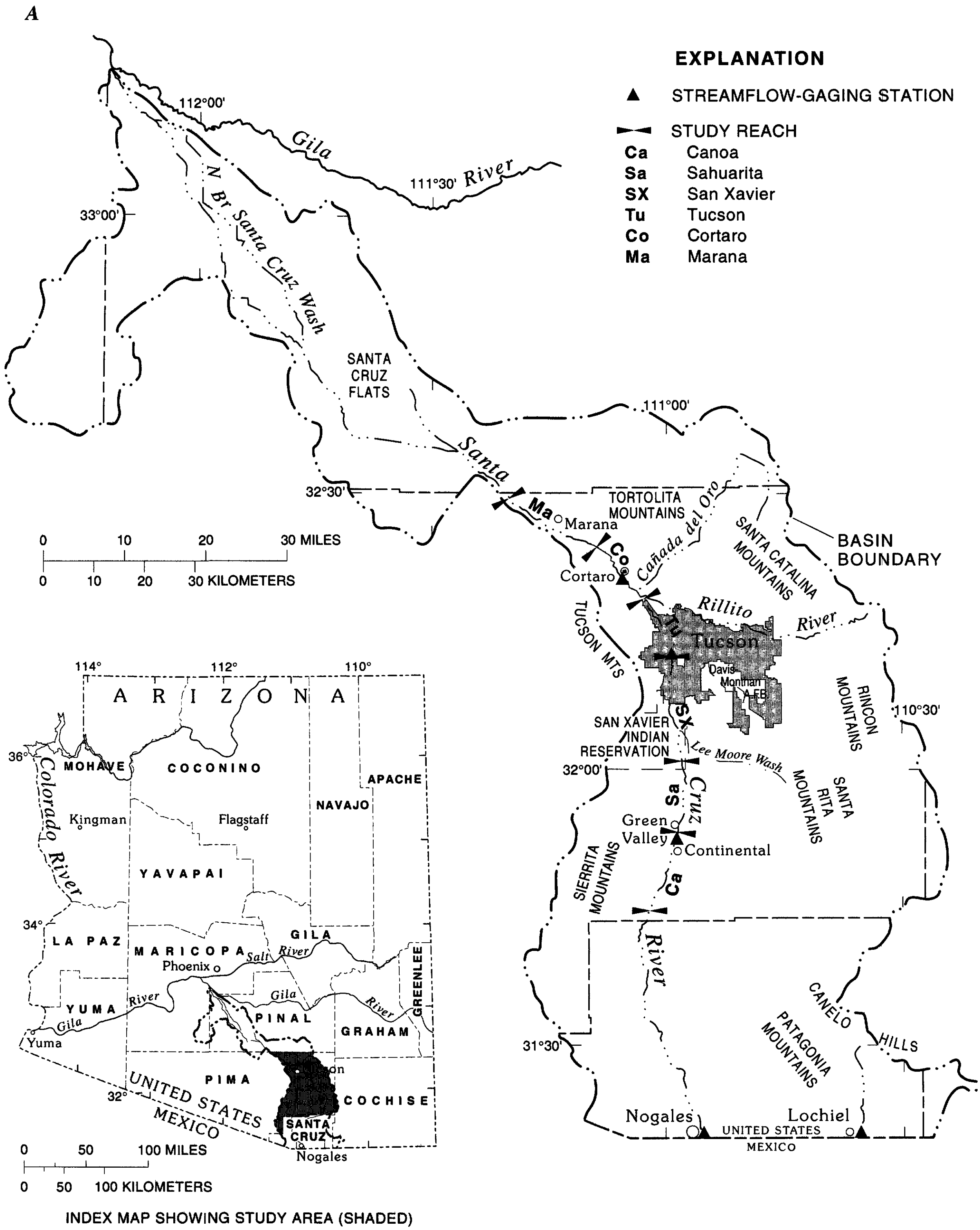

Figure 1. Santa Cruz basin, Arizona.

1984; Kresan, 1988). Channel change on the Santa Cruz River has been highly variable in time and space because of climatic fluctuations and variation in physical controls such as bank resistance and sediment sources. Human activities such as irrigation-canal construction, landfill operations, and sewage-effluent discharge have changed channel morphology and hydraulic properties and affected the location and

B

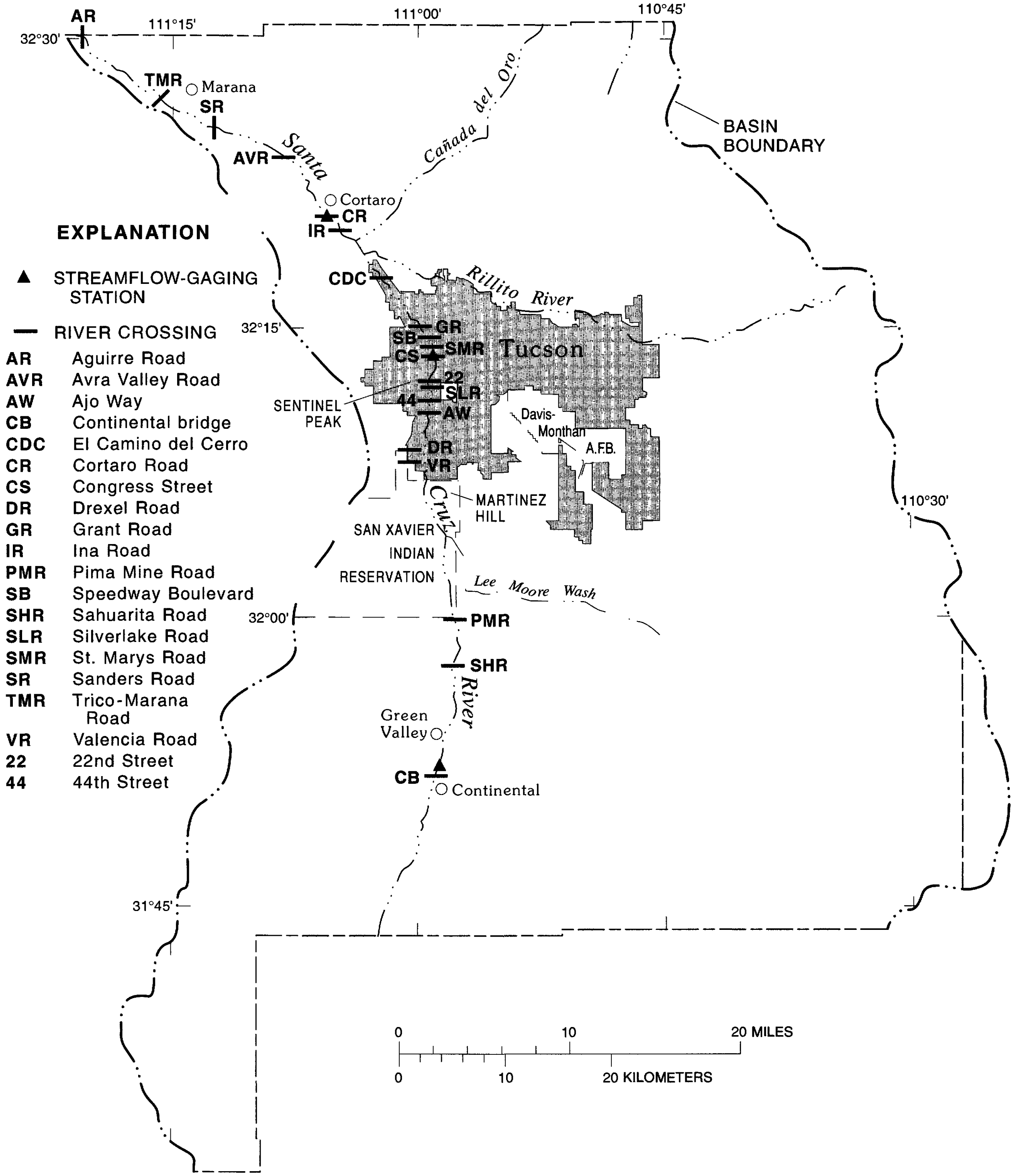

Figure 1. Continued.

magnitude of channel change occurring during flows (Baker, 1984b; Saarinen and others, 1984; Betancourt and Turner, 1988; Parker, 1990a).

The instability of desert channels, particularly ephemeral ones, is well known (Graf, 1988b). Rapid changes in channel morphology reflect extreme variation in flow magnitude and frequency that prevents long-term maintenance of equilibrium conditions (Stevens and others, 1975; Thornes, 1980). The rate, magnitude, and mechanism of change on desert channels are highly variable. Spatial variability results from changes in physical properties, such as bank material and vegetation density (Schumm and others, 1984), and changes in flow conditions such as caused by transmission losses into the channel bed and banks (Burkham, 1970, 1981) and local generation of runoff from convectional storms (Hirschboeck, 1985). Temporal variability results from the occurrence of rare, extreme flows (Baker, 1977; Webb, 1985; Webb and Baker, 1987; Graf and others, 1991), the climatic fluctuations that change the frequency of storms that produce high-magnitude, erosive flows (Webb and Betancourt, 1992), the sequence of events that shape channel morphology (Graf, 1983b), and the time-dependent changes in channel resistance such as increased vegetation growth (Parker, 1990b).

Because of extensive urbanization of some arid regions, channel change in desert rivers has become a matter of increased concern to flood-plain managers. The problems posed by channel change in dry regions—flood-plain destruction by bank erosion and alteration of the hydrologic regimen resulting from changes in hydraulic conditions—generally are not the same as in more humid environments where overbank inundation is the dominant hazard (Federal Emergency Management Agency, 1986). Most research on fluvial processes involves humid regions where geomorphic conditions are essentially different from those of drier environments (Graf, 1988a). Consequently, an increased understanding of channel-changing processes on desert rivers is needed to (1) assess spatial and temporal stability of natural channels; (2) establish location and magnitude of channel change in response to a given level of flow; (3) evaluate the topographic, climatic, geologic, and hydraulic controls that produce channel change; (4) determine the nature of the flood hazard associated with unstable channels; and (5) assess the effect of human activity on channel instability. Such an understanding would contribute to more effective utilization of traditional structural methods for bank-erosion control and would provide a rationale for alternative approaches, such as flood-plain zoning or condemnation.

This report is the second of two reports on channel change and flood frequency of the Santa Cruz River undertaken in 1988 by the U.S. Geological Survey in cooperation with the Pima County Department of Transportation and Flood Control District. The first report (Webb and Betancourt, 1992) evaluated the link between low-frequency climatic variability and changes in flood frequency of the Santa Cruz River.

Purpose and Scope

This report describes the history of channel change on the Santa Cruz River in Pima County from 1936 through 1986 and evaluates the hydrologic, climatic, topographic, geologic, hydraulic, and artificial controls that have affected the location, magnitude, and timing of such change. The scope of the report includes the following:

1. Documentation of channel change. A time series of channel change on the river was developed to document the location and timing of such change by extensive use of aerial photographs supplemented by geomorphic and topographic data. In addition, the nature of lateral-channel instability and the mechanisms of bank failure were identified.

2. Evaluation of controls on channel change. The time series was used to investigate the spatial and temporal variability of channel change. In particular, the links between spatial variability and topographic, geologic, and hydraulic controls and between temporal variability and hydroclimatic controls were evaluated.

3. Evaluation of the flood hazard associated with channel change. A synthesis of channel history and conditions associated with channel change was developed to assess the risk posed by channel instability. The potential for modeling channel change was evaluated.

4. Effects of human activity on channel change. Artificial modifications, such as bank armoring, irrigation-canal construction, and sewage-effluent discharge to the channel, were examined to determine the effects on channel morphology and hydraulic properties.

Description of the Study Area

The Santa Cruz River heads in the San Rafael Valley between the Canelo Hills and the Patagonia Mountains in southeastern Arizona, flows southward into Sonora, Mexico, turns back to the north, and reenters the United States east of Nogales. From the international boundary, the river flows about 85 mi to the northern city limits of Tucson in Pima County, then turns northwestward, and eventually empties into the Santa Cruz Flats, a broad plain of indistinct and discontinuous channels in Pinal County (fig. 1) that has been described as an inland delta (Waters, 1988). Continuous flow across the Santa Cruz Flats to the Gila River rarely occurs; however, a distinct channel of the Santa Cruz River reappears a short distance upstream from its confluence with the Gila River. The study area is the 70-mi reach through Pima County. At the downstream end of the study area, the Santa Cruz River basin has an area of 3,641 mi^2. The Santa Cruz River is ephemeral from the upstream end of the study area to the sewage-treatment plant at Ina Road in northwest Tucson (fig. 1). Sewage-effluent discharge results in a base flow of 5 to 50 ft^3/s downstream from Ina Road.

The study area is characterized by a semiarid climate with hot summers and mild winters. Mean annual precipitation at Tucson is 11 in. Adjacent mountain ranges receive three times as much precipitation, and the average precipitation for the Tucson basin is about 19 in./yr. Summers are characterized by widely scattered, convectional thunderstorms, and winters are characterized by regional frontal systems (Sellers and others, 1985). Dissipating tropical cyclones, a third storm type, occur primarily in September and October (Hirschboeck, 1985; Webb and Betancourt, 1992). Although less frequent than other types of storms, dissipating tropical cyclones have caused record floods of regional extent (Aldridge and Eychaner, 1984; Saarinen and others, 1984; Roeske and others, 1989).

The Santa Cruz River basin is in the Basin and Range physiographic province, which is characterized by deep alluvial basins flanked by fault-bounded mountain ranges. In southern Arizona, the mountains include volcanic, plutonic, and metamorphic rocks that range from Mesozoic to Cenozoic age; some sedimentary rocks that range from Paleozoic to Cenozoic age; and mainly crystalline rocks of Precambrian age (Wilson and others, 1969). Within the study area, the Santa Cruz River flows through the Tucson basin, which is underlain by more than 20,000 ft of sediments of middle to late Cenozoic age. The Fort Lowell Formation, which ranges in age from 2.5–2.0 m.y. to 1.3 m.y., underlies most of the Tucson basin beneath a veneer of surficial deposits (Davidson, 1973; Anderson, 1987). Surficial deposits include terrace gravels of late Pleistocene age (Haynes and Huckell, 1986) and alluvium of Holocene age that is associated with modern fluvial systems.

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Personnel of the Pima County Department of Transportation and Flood Control District provided historical and technical data. The tribal council of the San Xavier District of the Tohono O'Odham Nation granted access to the Santa Cruz River where it crosses the San Xavier Indian Reservation. Professor V.R. Baker, University of Arizona, and Richard Hereford, U.S. Geological Survey, reviewed earlier versions of this report and provided suggestions that resulted in improvement of the text. Robert H. Webb, U.S. Geological Survey, assisted in major revisions of earlier drafts and prepared most of the section in this report on modeling of channel change.

Methods

The primary methods used in this study were interpretation and analysis of aerial photographs supplemented by interpretation of field observations and published and unpublished geomorphic, topographic, geotechnical, and historical data. Six study reaches along the 70-mi-long main stem of the Santa Cruz River in Pima County were defined on the basis of morphology, historical stability, and dominant channel-forming processes (fig. 1, table 1).

The coverage and quality of aerial photographs used in this study varied from one location to another. Complete photographic coverage that was adequate for interpretation and mapping of channel changes generally was not available for the entire study area for any single year. Consequently, different time intervals were analyzed for the different reaches. Quality of the photographs depends on resolution, scale, distortion, and amount of overlapping coverage for stereoscopic viewing. More aerial photographs were used for qualitatively evaluating channel change than were used for mapping channel change (table 2).

Table 1. Physical characteristics of reaches, Santa Cruz River

Reach (see fig. 1)	Number of cross sections	Axial length, in feet[1,2]	Stream distance, in feet[2] 1936	Stream distance, in feet[2] 1986	Channel gradient, in foot per foot[3]	Mean width, in feet[4] 1936	Mean width, in feet[4] 1986	Median width, in feet 1936	Median width, in feet 1986	Width range, in feet 1936	Width range, in feet 1986	Standard deviation, in feet 1936	Standard deviation, in feet 1986	Maximum width increase[5] 1936–86	Maximum width decrease[5] 1936–86
Canoa	85	40,500	49,000	43,500	0.0034	250	500	200	400	50–800	100–1,750	160	360	1,250	400
Sahuarita	130	61,500	72,500	67,500	.0032	100	200	100	150	<50–450	<50–650	80	140	450	100
San Xavier	132	62,000	69,000	67,500	.0035	200	500	150	450	50–850	50–1,950	170	320	1,200	150
Tucson	91	43,000	48,500	48,000	.0029	200	250	200	250	50–450	100–650	100	90	300	200
Cortaro	95	43,000	50,000	46,500	.0027	300	200	250	200	50–950	50–1,100	160	190	900	800
Marana	152	82,000	88,500	88,500	.0029	500	200	350	200	50–1,450	<50–700	430	130	250	1,200

[1]See "Methods" section for explanation of axial length.
[2]Reported to nearest 500 feet.
[3]Federal Emergency Management Agency (1982, 1987, 1990).
[4]Widths reported to nearest 50 feet. See "Methods" section for definition of channel or arroyo width.
[5]Maximum change in width measured at any single cross section during interval.

A base map to document lateral channel change was developed from aerial photographs taken in 1936, which is the earliest coverage available for all reaches. Channel maps were made after projecting the photographs to a uniform scale of about 1:16,000 on the base map. The two reference systems for longitudinal river position used in this study were axial distance—the distance along a straight line through the axis of a river reach—and river distance—the distance along the meandering thalweg of the channel. Use of axial distance provides a fixed reference for measuring changes in channel width or position, whereas river distance changes over time as channels lengthen or shorten. Channel widths were measured at grid points, generally at 500-ft intervals, along the channel axis (fig. 2*A*). The position of the channel center line was referenced to the channel axis by measuring the distance along a line perpendicular to the axis that connects a grid point to the nearest point in the center of the channel (fig. 2*A*). Channel-position change with time was represented by showing the initial channel position as a horizontal line and the subsequent position as a line connecting the new location of each channel center point relative to the channel axis (fig. 2*B*). Although plots such as figure 2*B* indicate lateral channel stability, the magnitude of shift in channel position is not a measure of bank retreat or meander migration, which is a vector quantity. Large shifts in position of the channel center line but minor amounts of channel movement can be caused by a change in channel orientation such as shown at grid point 502 in figure 2*A* and in the boxed area of figure 2*B*.

HISTORY OF CHANNEL CHANGE

Channel Change Prior to 1936

The history of channel change on the Santa Cruz River near Tucson, particularly in the late 19th and early 20th century, has been extensively studied (Cooke and Reeves, 1976; Hendrickson and Minckley, 1984; Betancourt and Turner, 1988; Betancourt, 1990). Before the 1870's, the river occupied a shallow swale interrupted by discontinuous gullies. Floodwaters were spread over a wide, active flood plain. Cienegas, which are marshes fed by perennial flow, were within the present-day city limits of Tucson at the base of Sentinel Peak (known locally as "A" Mountain) and near the San Xavier Mission, which is 9 mi upstream from Tucson. Most of the channel downstream from the cienegas was a dry, sandy riverbed.

Headcuts signaling the onset of arroyo formation were first described in 1871 in the San Xavier area (fig. 3; Betancourt and Turner, 1988). In the late 1880's, extensive headcutting began through Tucson as a result of poorly engineered waterworks and high flows, particularly a series of summer floods in 1890. By 1910, the arroyo extended from Martinez Hill to Tucson. Winter floods in 1914–15 caused major

Table 2. Aerial photographs, Santa Cruz River

[Ca, Canoa; Co, Cortaro; Ma, Marana; Sa, Sahuarita; SX, San Xavier; Tu, Tucson; (p), partial coverage]

Date	Scale	Reaches	Sources
02-22-36 02-26-36 03-07-36	1:30,000	All	U.S. Soil Conservation Service
1941[1]	1:21,000	Co(p), Tu, SX(p)	Pima County Department of Transportation and Flood Control
06-13-53 06-14-53 06-15-53 06-24-53 08-20-53 10-07-53	1:10,000	Co(p), Tu, SX(p)	Cooper Aerial Survey, Tucson, Arizona
02-25-56	1:50,000	SX(p), Sa, Ca	U.S. Geological Survey, Eros Data Center
02-18-60 02-22-60 02-23-60 03-02-60 03-03-60 03-21-60 04-04-60	1:10,000	Co(p), Tu, SX(p)	Cooper Aerial Survey, Tucson, Arizona
05-04-66 05-05-66 05-06-66	1:24,000	Ma(p), Co, Tu(p)	U.S. Geological Survey, Eros Data Center
08-19-67	1:10,000	Co(p), Tu, SX(p)	Cooper Aerial Survey, Tucson, Arizona
01-07-71	1:12,000	Ma(p), Co, Tu, SX	Cooper Aerial Survey, Tucson, Arizona
04-08-72	1:32,000	SX(p), Sa(p)	Cooper Aerial Survey, Tucson, Arizona
11-08-74 11-23-74	1:20,000	Ma, Co, Tu, SX, Sa, Ca(p)	Cooper Aerial Survey, Tucson, Arizona
10-03-76	1:14,000	All	Kucera and Associates, Denver, Colorado
09-06-78 09-07-78 09-08-78	1:20,000	All	Cooper Aerial Survey, Tucson, Arizona
12-07-79	1:12,000	SX	Cooper Aerial Survey, Tucson, Arizona
05-04-84	1:15,000	Co, Tu, SX(p)	Cooper Aerial Survey, Tucson, Arizona
10-20-86 12-18-86 12-22-86 01-13-87	1:24,000	All	Cooper Aerial Survey, Tucson, Arizona

[1]Dates of aerial photographs unknown.

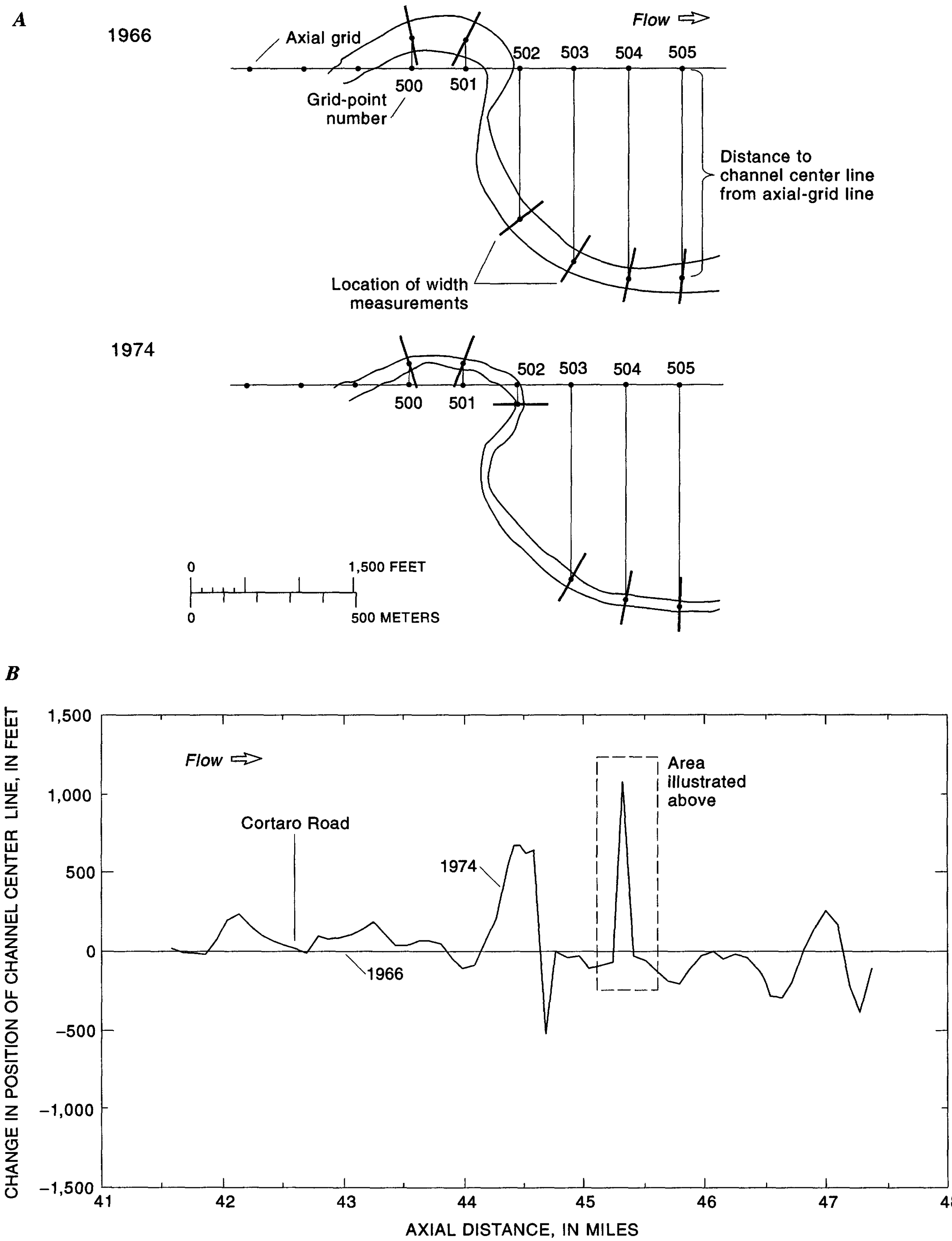


Figure 2. Method of relating channel change to axial reference system. *A*, Measurement of changes in width and channel position from 1966 and 1974. Note large shift in position relative to grid point 502 caused by rotation of meander axis. *B*, Change in position of channel center line with time. Positive values indicate shift in position toward left side of channel; negative values indicate shift toward right side.

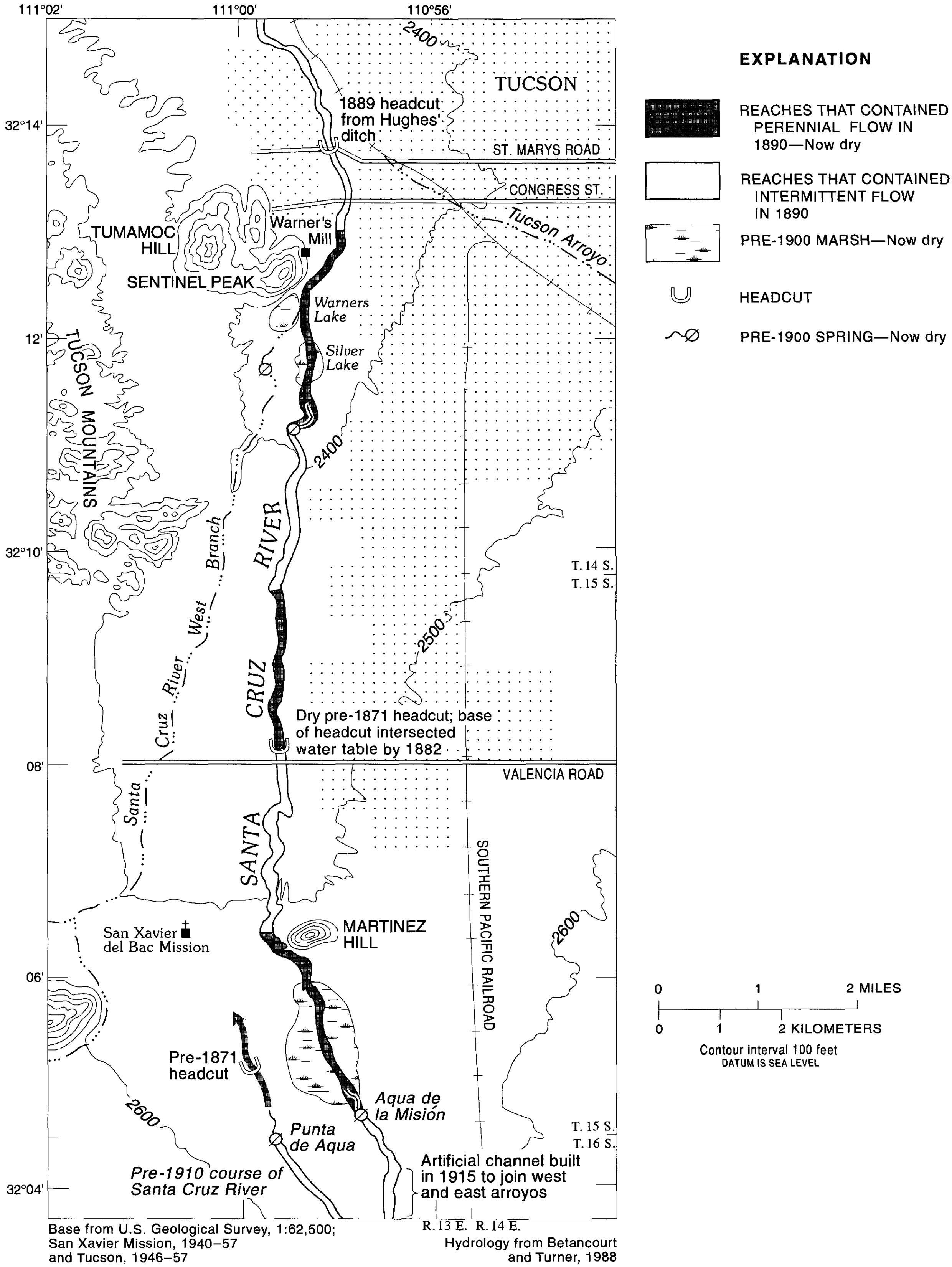


Figure 3. Santa Cruz River in 1988, perennial and intermittent reaches in 1890, and location of headcuts in relation to marshes in the late 19th century.

channel widening and destroyed the bridge at Congress Street in Tucson. These floods also extended the headcutting through the San Xavier Indian Reservation upstream from Martinez Hill along the course of an artificial channel that joined arroyos from the west to the east sides of the valley. Entrenchment of the Santa Cruz River coincided with arroyo formation throughout the southwestern United States (Cooke and Reeves, 1976). Further downcutting of the Santa Cruz arroyo has continued well into this century (Aldridge and Eychaner, 1984). Aerial photographs indicate that headcut extension of the Santa Cruz arroyo has occurred at the southern edge of the San Xavier Reservation as recently as the 1940's.

Channel Change from 1936 through 1986

From 1936 through 1986, channel change on the Santa Cruz River was characterized by an increase in width and a decrease in length throughout most of the study area (table 1, fig. 4). Most of the reduction in length was the result of channelization. The increase in mean width would have been greater except for human intervention such as bank armoring, which inhibited channel widening, and landfill operations or channel maintenance, which narrowed channels artificially. Net vertical change in the same period was primarily degradational (fig. 5).

The Canoa reach is characterized by a generally unentrenched, sandy channel that occupies a 5,000-ft-wide active flood plain. The reach has undergone major channel widening (fig. 4*A*); however, little natural change occurred before the floods of 1977 and 1983. Much of the change in channel position and stream length (fig. 4*B*, table 1) resulted from artificial channelization that has been in place since at least the 1950's; 70 percent of channel widening during the study interval was caused by the 1983 flood.

The Sahuarita reach, which is characterized by a discontinuous arroyo, has undergone little or moderate lateral channel change during the study period except at its downstream end below Pima Mine Road (fig. 4*B*), where a shallow, meandering channel segment was cut off by headward extension of the Santa Cruz arroyo after the 1930's. About 20 ft of incision in the Sahuarita reach cut off several other meanders, and this incision combined with channelization shortened the reach by about 1 mi (table 1).

The San Xavier reach was the most continuously unstable reach of the Santa Cruz River during the study period (fig. 4*C*). The channel is entrenched 20 to 30 ft into weakly indurated alluvium of Holocene age that fails readily when undercut during flows. The arroyo has widened continuously along most of the reach throughout the study period. Mean width increased 2.3 times, and median width increased by almost three times between 1936 and 1986. Downstream from Martinez Hill, sand and gravel operations and other activities, such as landfill operations, have altered the arroyo; however, upstream from that point, disturbance from human activity has been slight.

The Tucson reach has shown the least lateral instability during the study period (fig. 4*D*). Much of the apparent stability is artificial—either as a result of bank armoring, which has prevented channel change, or of artificial filling, which has obscured the record of change occurring between 1936 and 1986. Parts of the reach underwent about 15 ft of degradation between the 1950's and 1976 (fig. 5*I*).

The Cortaro and Marana reaches have had the most complex record of channel change since 1936 (fig. 4*E, F*). The Marana reach has changed from a wide, braided channel to a compound channel that is less than half the width of the channel in 1936. Both reaches were unstable before 1966 when they had sparsely vegetated ephemeral channels and would undergo large, frequent shifts in channel position. In 1970, when flow from sewage effluent began, channel morphology became controlled by the low, steady base flows, and the channel became generally narrower and more sinuous than previously. The channel also was stabilized by vegetation growth, undergoing little change during the then-record 1977 flood, although the much larger flood of 1983 produced substantial channel shifts.

MECHANISMS OF CHANNEL AND ARROYO CHANGE

The Santa Cruz River changes laterally by meander migration, channel avulsion or meander cutoff, and channel widening (table 3). In addition to the lateral channel-changing processes, vertical changes—aggradation or degradation of the channel bed—have been significant at some locations during the study period (table 3, fig. 5). Where the channel is entrenched into an arroyo, a combination of fluvial processes and bank-retreat mechanisms leads to arroyo change. The type of process operating at any location depends on channel

Table 3. Channel-changing processes that occur along reaches of the Santa Cruz River

Reach	Meander migration	Avulsion and meander cutoff	Channel widening	Arroyo widening	Degradation and aggradation	Artificial changes
Canoa	During high flows.	Under natural conditions, probably frequent.	Major during large floods.	No arroyo.	Degradation from channelization in 1950's. Aggradation from 1977 flood.	Considerable channelization, armoring, and channel maintenance, especially in upper reach.
Sahuarita	Within arroyo.	At downstream end in San Xavier Indian Reservation. Suspected elsewhere.	Minor to moderate where not entrenched.	Minor to moderate; locally major from floods.	Major period of degradation after 1940.	Extensive channelization, armoring, channel maintenance, and levee construction upstream from Pima Mine Road.
San Xavier	Within arroyo.	Within arroyo.	Within arroyo.	Major widening throughout study period.	Considerable degradation in lower reach during 1950's and 1960's. Suspected in upper reach during that interval.	Sand-gravel mining at Valencia Road. Some armoring, highway fill, and landfill in lower reach. Little disturbance above Martinez Hill.
Tucson	Within arroyo.	One incomplete avulsion downstream from El Camino del Cerro.	Within arroyo.	Generally minor to moderate but with considerable property damage. Locally major widening of unprotected arroyo walls.	Considerable degradation in 1950's and 1960's.	Extensive channelization and armoring; landfill operations.
Cortaro	During low to moderate flow through most of reach.	During overbank flows.	During large floods.	Above confluence with Cañada del Oro.	Aggradation of flood plain; alternating degradation and aggradation of channels.	Perennial flow sustained by sewage effluent since 1970; sand-gravel mining at Cortaro Road.
Marana	Local migration during low to moderate flows.	During overbank flows; similar history as Cortaro reach. May occur from flows near lower end of reach.	During large floods.	No arroyo.	Aggradation of flood plain; alternating degradation and aggradation of channels.	Perennial flow from sewage effluent; discontinuous channelization and armoring, and levee construction; sand-gravel mining at Avra Valley Road.

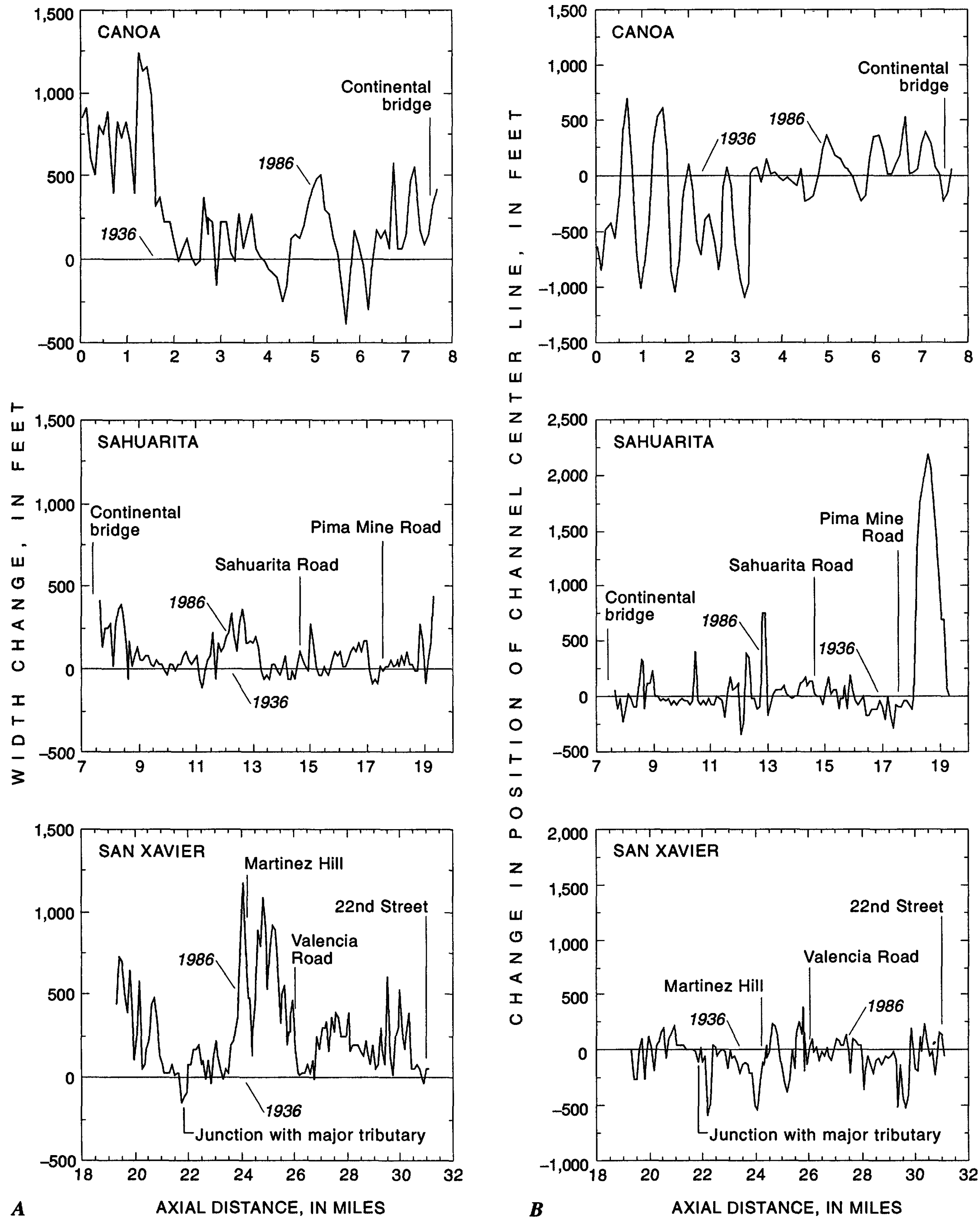
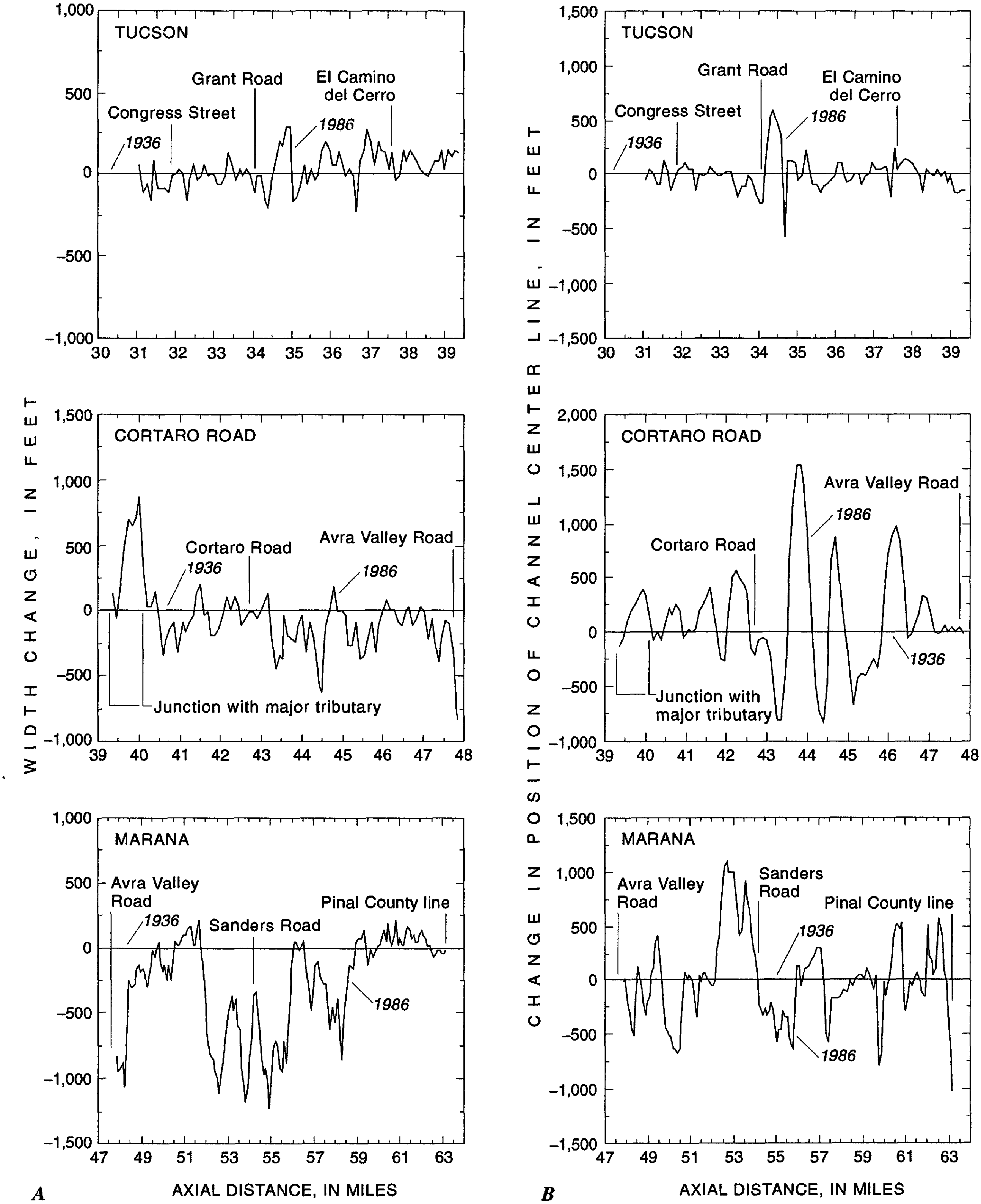


Figure 4. Channel changes on the Canoa, Sahuarita, San Xavier, Tucson, Cortaro, and Marana reaches, 1936–86. *A*, Width change. *B*, Change in position of channel center line. Positive values indicate shift in position toward left side of channel; negative values indicate shift toward right side.



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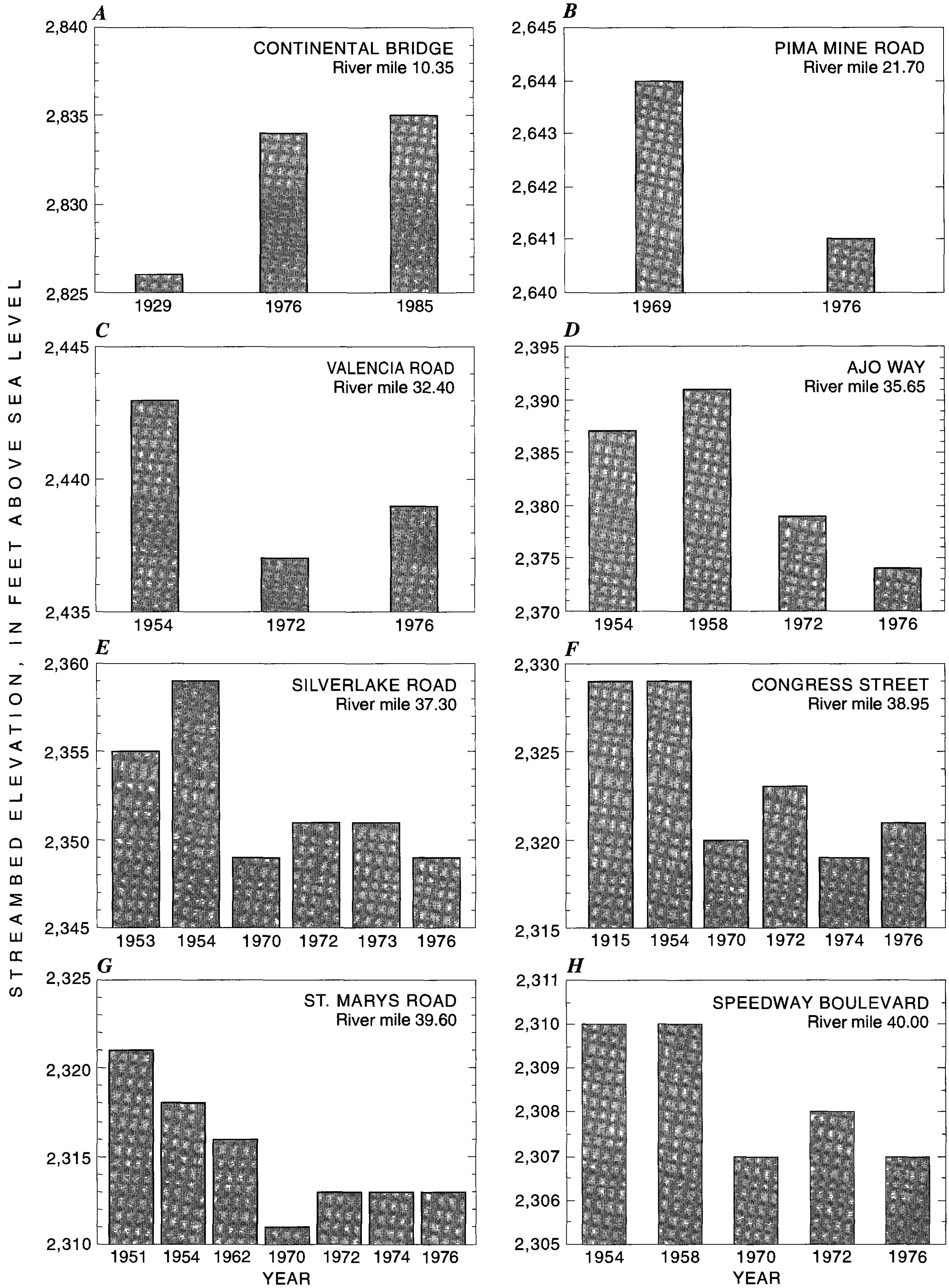


Figure 5. Changes in streambed elevations, Santa Cruz River. Note the vertical scale changes among various graphs. (Source: Data from Federal Emergency Management Agency, 1982, 1987, 1990; Pima County Department of Transportation and Flood Control District.)

morphology, channel sediment, bank resistance, and magnitude of flow. Identification of the type of channel-changing processes is important because each process has its own spatial and temporal variability and each process represents a distinct kind of erosional hazard. In this section, mechanisms that primarily change channel position and pattern—meander migration and avulsion and meander cutoff—are discussed first. Mechanisms that change channel geometry—channel widening, related bank retreat and stability mechanisms, and vertical change mechanisms—are then discussed. This is followed by a description of arroyo change, which is caused by all the channel-change mechanisms operating within the confines of an entrenched channel system. Examples of channel- and arroyo-change mechanisms as they occur on the Santa Cruz River are presented throughout this section.

Meander Migration

Meander migration refers to lateral shifts of centerline position associated with the inception of meanders and their subsequent downstream translation, lateral

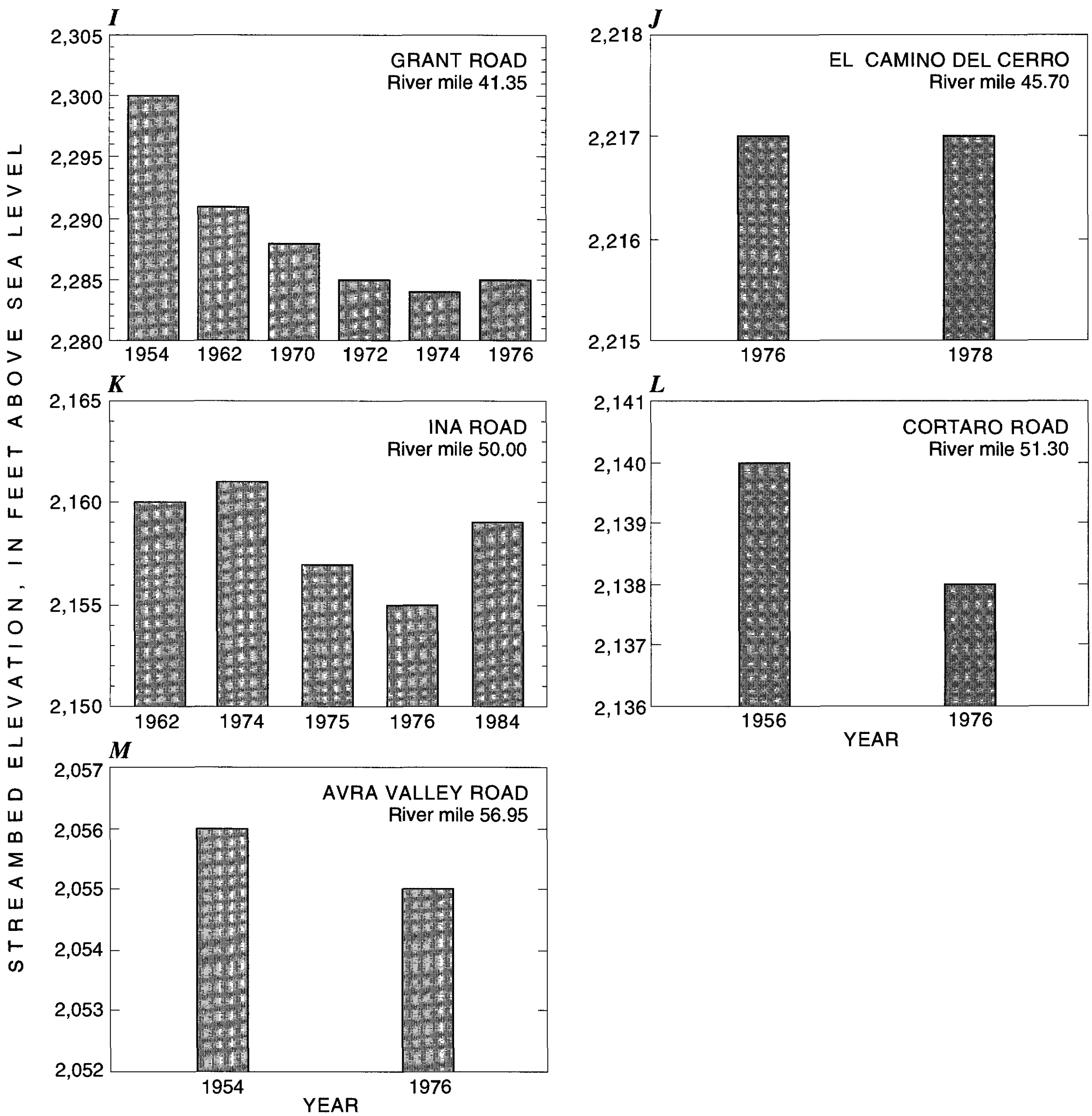


Figure 5. Continued.

extension, or rotation of meander axis (fig. 6; Knighton, 1984). Meander migration involves the spatially continuous movement of channel position across a flood plain rather than a discrete, abrupt channel shift caused by avulsion or meander cutoff. Generally, meander migration increases sinuosity and lowers gradients. Where the channel is not confined within an arroyo, meander migration may be the dominant expression of lateral instability. Where the channel is confined within an arroyo, meander migration is a major component of arroyo widening. Meander migration on the Cortaro and Marana reaches is primarily a result of low to moderate flows that generally produce low rates of lateral channel movement. Moderate but prolonged flows having a peak discharge with a recurrence interval of 2 years or less, however, have caused hundreds of feet of erosion by meander migration on the lower Santa Cruz River (Hays, 1984). Along other reaches, especially the San Xavier reach, meanders have formed and migrated as a result of large floods, probably during recessional flows when sediment was deposited on growing point bars and flow was forced against opposite banks (Meyer, 1989).

Avulsion and Meander Cutoff

Avulsion is an abrupt shift in channel position that occurs when overbank flow incises new channels as other channels aggrade and are abandoned. Channel cutoff occurs at meanders and may or may not involve concurrent aggradation of the abandoned channel segment. On the Santa Cruz River, these processes occur mainly when overbank flows are confined by existing flood-plain topography. The flows strip vegetation and erode underlying sediment (fig. 7). Incision of the new channel apparently occurs either as a result of vertical scour into the flood plain or by headcutting across the flood plain from the point at which overbank flow reenters the main channel. Meander cutoff reduces sinuosity and increases channel gradients, reflecting its association with high flows. Avulsion on the Santa Cruz River generally seems to be a high-flow phenomenon, but some shifting has occurred near the Pinal County line during periods of low to moderate flows, probably because of heavy sedimentation that causes channel plugging as described by Graf (1981) on the Gila River.

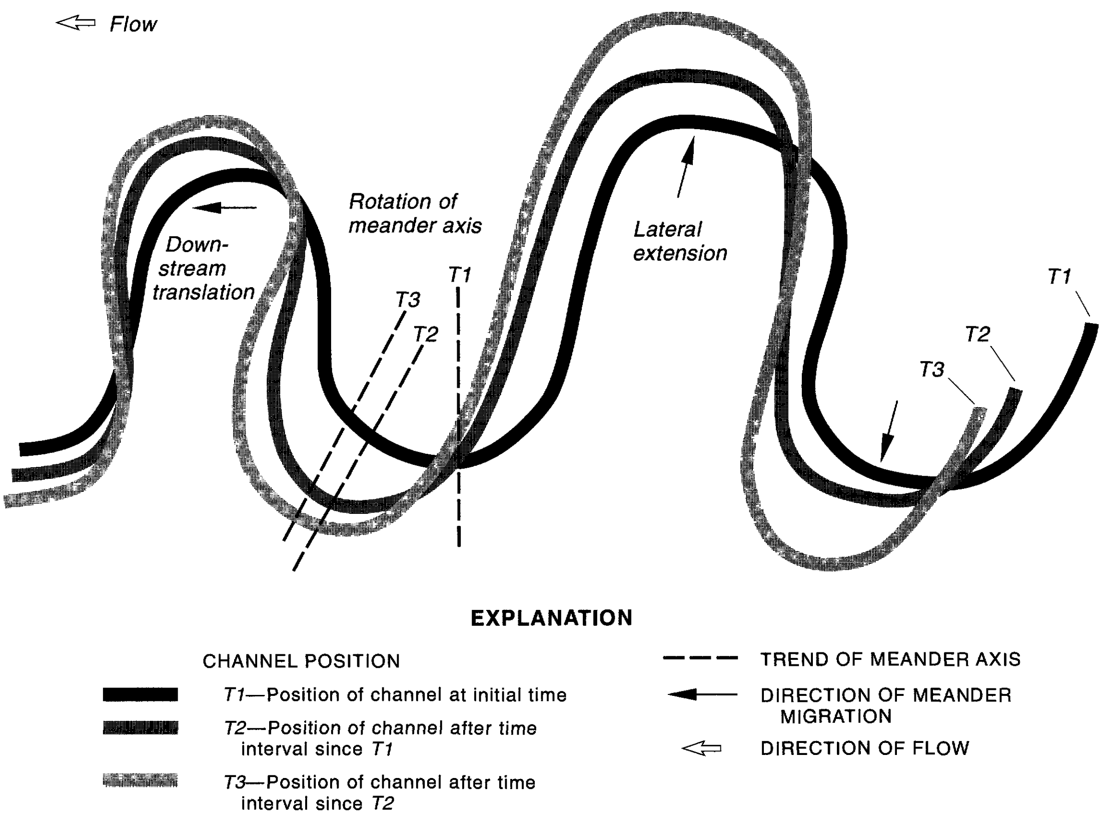


Figure 6. Channel migration caused by downstream translation of meander, rotation of meander axis, and lateral extension of meander.

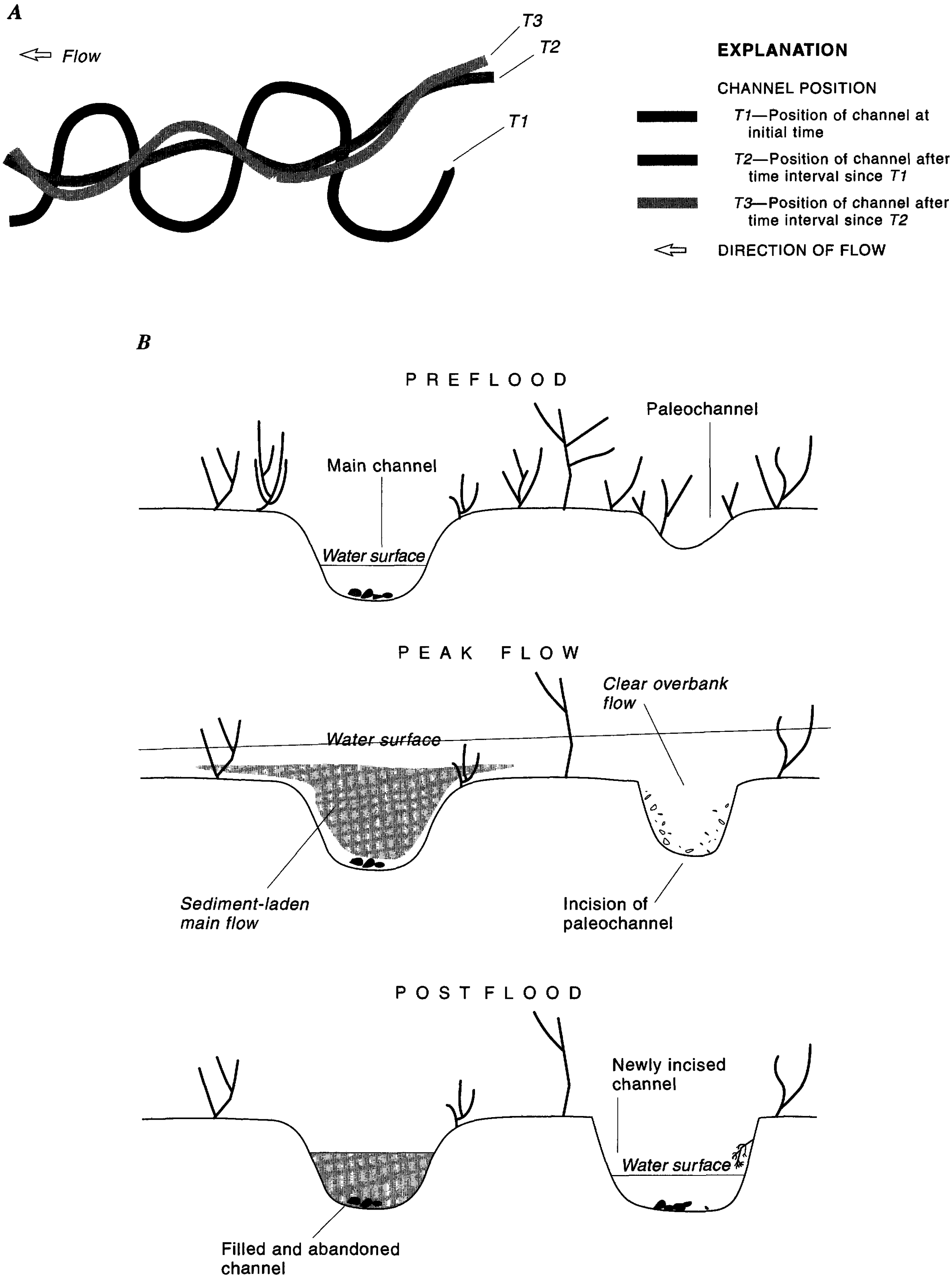


Figure 7. Avulsion and meander cutoff. *A*, Plan view of an initially sinuous channel at time 1 (*T1*) that changes course as a result of a flood (*T2*) and then is modified by subsequent meander migration during low flows (*T3*). *B*, Processes that produce a lateral shift in channel position by avulsion or meander cutoff.

Table 4. Meander dimensions and channel movement,[1] Santa Cruz River at Cortaro, 1936–86

[AV, avulsion; CO, meander cutoff; DT, downstream translation; LE, lateral extension; NC, no change; RA, rotation of meander axis; RM, reformation of cutoff meander]

	1936	1966	1978	1986
Stream length, in feet[2]	29,800	28,700	30,100	27,100
Sinuosity[3]	1.18	1.14	1.19	1.07
Number of meanders	6	5	5	2
Dominant type(s) of channel movement:				
A	([4])	CO	NC	AV
B	([4])	DT	NC	CO
C	([4])	CO	RM,DT	CO
D	([4])	DT,RA	DT	CO
E	([4])	LE	LE,DT	CO
F	([4])	LE,RA	LE	NC
Meander wavelength, in feet[5]:				
A–B	3,550	([6])	([6])	
B–C	3,150	1,950	3,350	([6])
C–D	1,950	2,650	1,200	([6])
D–E	3,100	1,900	2,150	([6])
E–F	2,300	1,650	1,500	1,250
Mean	2,800	2,050	2,050	([6])
Radius of curvature, in feet:				
A	1,200	([6])	([6])	([6])
B	1,800	1,500	950	([6])
C	1,050	2,050	1,800	([6])
D	1,350	850	750	([6])
E	800	700	700	1,050
F	4,600	1,800	1,350	1,700
Mean	1,800	1,400	1,100	1,350

[1]See figure 8 for location of reach and for identification of meanders labeled A through F in table.
[2]Reported to nearest 100 feet.
[3]Sinuosity equals stream length divided by axial length.
[4]Initial year of study period.
[5]Meander dimensions reported to nearest 50 feet.
[6]Meanders were eliminated by meander cutoff.

Avulsion and meander cutoff are observed mainly where the channel is shallowly incised, the flood plain is active, and aggradation rates generally are high. Low relief between the flood plain and the channel bottom allows overbank flow to cut a new channel. Rapid deposition enhances avulsion by aggrading the channel and adjacent flood plain, thus forcing flow into a more direct, steeper course across lower flood-plain surfaces. Furthermore, as sediment is deposited in the main channel, it is depleted in the overbank flow, making the overbank flow more erosive and more capable of forming a new channel (Baker, 1988).

Meander Migration and Avulsion and Meander Cutoff on the Cortaro and Marana Reaches

Meander migration and avulsion and meander cutoff have been the most significant lateral channel-changing processes on the Cortaro and Marana reaches during the study period. The Cortaro reach is the only one in the study area with a series of unconfined meanders that have been undisturbed by channelization throughout the study period. Unconfined meanders also occur on the Marana reach; however, they tend to be isolated bends in an otherwise straight channel. Characteristics of channel change on the Cortaro reach from 1936 through 1986 include the absence of systematic change in meander dimensions, considerable variation in the extent and direction of meander migration, and obliteration of the meanders between 1976 and 1986 because of the flood of 1983 (table 4, fig. 8). At the downstream end of the reach, the channel was artificially straightened between 1936 and 1966.

Between 1936 and 1966, the lower Cortaro reach showed a high degree of channel instability (fig. 9) caused by meander migration (meanders *B*, *D*, *E*, and *F*, fig. 8) and meander cutoff (meanders *A* and *C*).

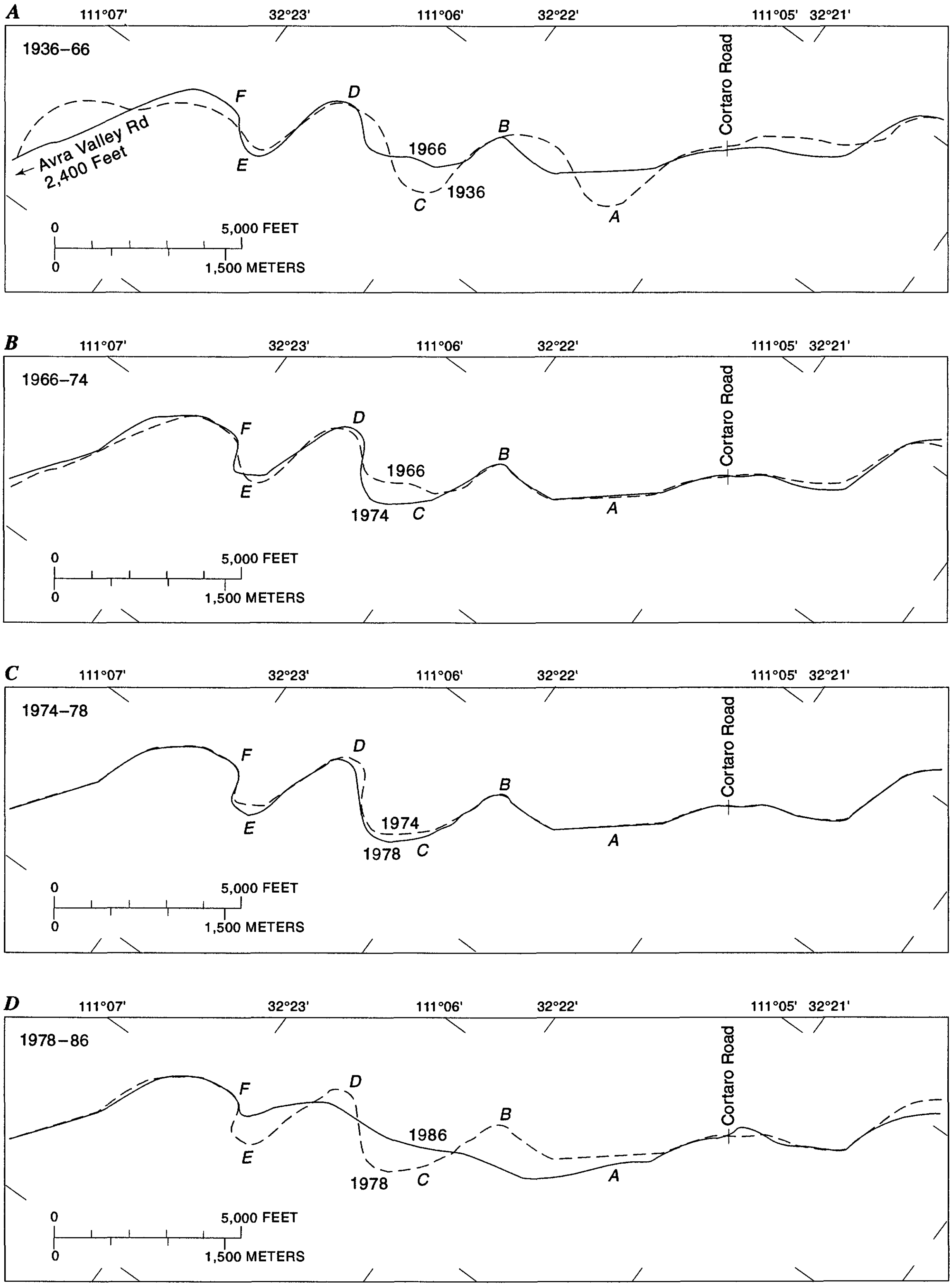


Figure 8. Meander development on lower Cortaro reach. Lines show location of channel center line.

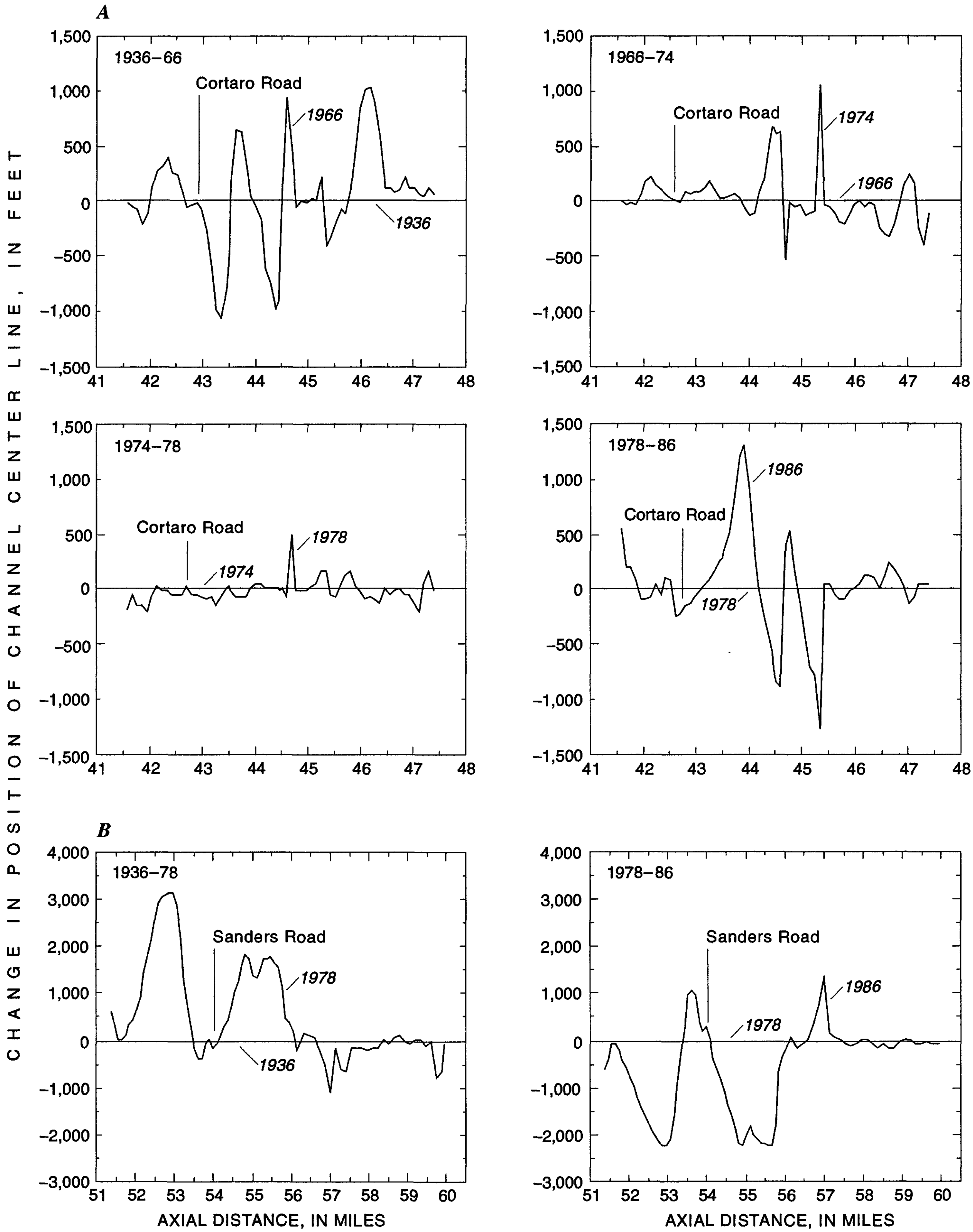


Figure 9. Changes in position of channel center line. *A*, Lower Cortaro reach. *B*, Upper Marana reach. Positive values indicate shift in position toward left side of channel; negative values indicate shift toward right side.

The position of the channel center line shifted laterally as much as 900 ft because of cutoff at meander *A*. Downstream translation of the upper limb of meander *B* produced more than 600 ft of lateral channel movement by meander migration. During this interval, flow in the Cortaro reach was ephemeral and flood-plain and channel vegetation was sparse.

Between 1966 and 1978, the channel through most of Cortaro reach was more stable, but meander *C*, which had been cut off during the previous interval, reformed and produced almost 700 ft of lateral channel movement from meander migration. No channel change occurred as a result of avulsion and meander cutoff between 1966 and 1978, in spite of the record 1977 flood that had a peak discharge through the Cortaro reach of about 23,000 ft^3/s. During this period, vegetation density increased after sewage effluent caused perennial flow in the reach.

Between 1978 and 1986, all meanders between Cortaro and Avra Valley Roads except one were destroyed during the flood of 1983, which had a peak discharge of 65,000 ft^3/s through the reach. On the Cortaro and Marana reaches, almost 23,000 ft of channel was abandoned 6 ft above the new channel bed, and channel position shifted laterally as much as 2,000 ft (fig. 9).

Channel Widening

Channel widening results primarily from high flows that erode weakly cohesive banks. Channel widening is distinct from arroyo widening because arroyo boundaries may delineate not only a channel but also a flood plain at the bottom of the arroyo (Schumm and others, 1984). Widening is a product of corrasion by fluvial erosion during rising flow (Hooke, 1979) or mass wasting of banks following the flow peak (fig. 10; Baker, 1988; Simon, 1989).

Asymmetric channel widening occurs on the outside of meander bends as a result of lateral meander extension or downstream translation during high flows. During low to moderate flows, deposition within a meandering reach is approximately in balance with erosion of the outside bank. The point bar on the inside of the meander is not scoured and grows laterally as the outer bank retreats (fig. 11*A*). Lateral migration of the channel occurs with little change in channel dimensions. During high flows, the point bar is eroded; during recession of the flood, deposition of coarse material on the point bar deflects flow against the outside bank causing accelerated erosion and lateral extension of the meander. Meander migration results in channel widening when the volume of material deposited on the point bar is significantly less than the volume of material removed from the reach (fig. 11*B*). Symmetric widening (simultaneous retreat of both banks) occurs along short sections of straight or curved channel as a result of lateral corrasion from high flows that submerge channel topography and travel straight downchannel rather than along the course of the meandering thalweg (Bathurst and others, 1979; Slezak-Pearthree and Baker, 1987). On

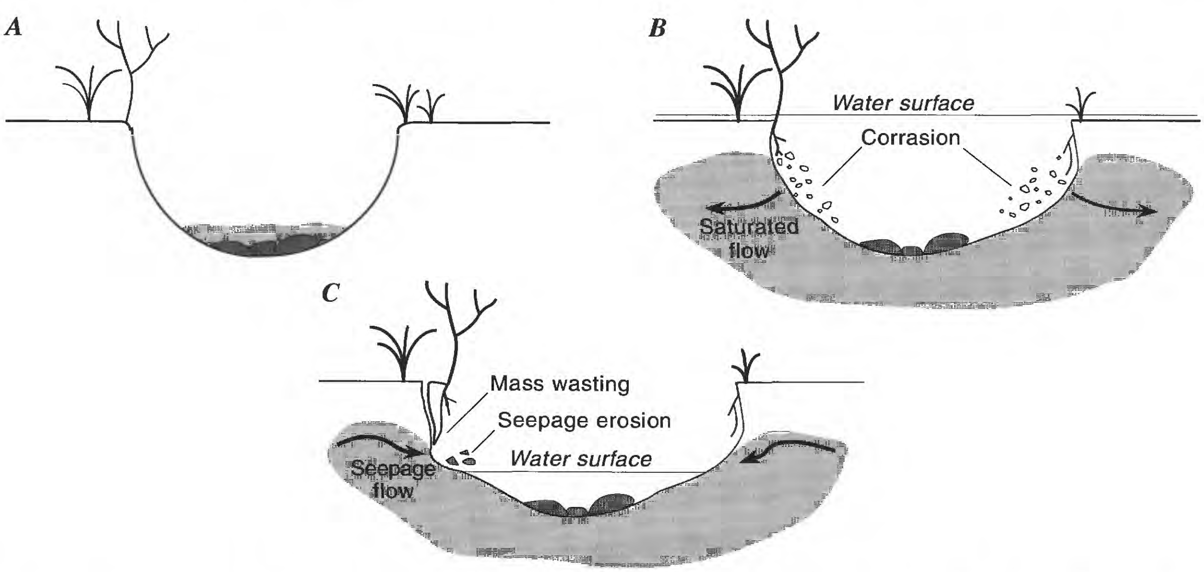


Figure 10. Process of channel widening. *A*, Initial channel. *B*, Corrasion and saturation of banks during rising flow. *C*, Seepage erosion and mass wasting following hydrograph fall.

the Santa Cruz River, symmetric widening appears to occur only in response to extreme flows.

Bank-Retreat and Stability Mechanisms

Retreat of channel banks or arroyo walls along the Santa Cruz River and attendant channel widening or position change are caused by a complex interplay of fluvial erosion, corrasion of lower banks, and mass wasting of upper banks or walls (Thorne and Tovey, 1981). Cohesionless banks erode whenever boundary shear stresses exerted by the flow exceed the resistance of the bank material. Bank materials, however, seldom are initially cohesionless; therefore, there is rarely a direct relation between magnitude of stream discharge and magnitude of bank erosion (Knighton, 1984).

Vegetation of river banks can increase resistance to erosion by several orders of magnitude (Smith, 1976). On the Santa Cruz River, most banks are too steep to be well vegetated, but terrace and point-bar surfaces and the channel bottom, even along ephemeral reaches, become vegetated in the absence of erosive flows. Vegetated surfaces at the base of channel banks or arroyo walls protect against erosion from low to moderate flows. After 1970, the Cortaro and Marana reaches became more stable when sewage-effluent discharge began and vegetation density increased.

Electrochemical forces provide another source of cohesion of bank materials and resistance to erosion. Particle interactions produce greater cohesion of bank materials composed of silt- and clay-sized particles than of bank materials composed largely of sand (Terzaghi, 1950; Schumm, 1960). Chemical cementation of bank materials is particularly significant in semiarid areas where flow-transported carbonate precipitates in drying channel banks (Haynes and Huckell, 1986; Baker, 1988). Almost all banks on the Santa Cruz River, except those that are continuously saturated by perennial flow, are cemented to some degree. Rapid cementation of Santa Cruz River sediments is indicated by induration of fresh channel deposits.

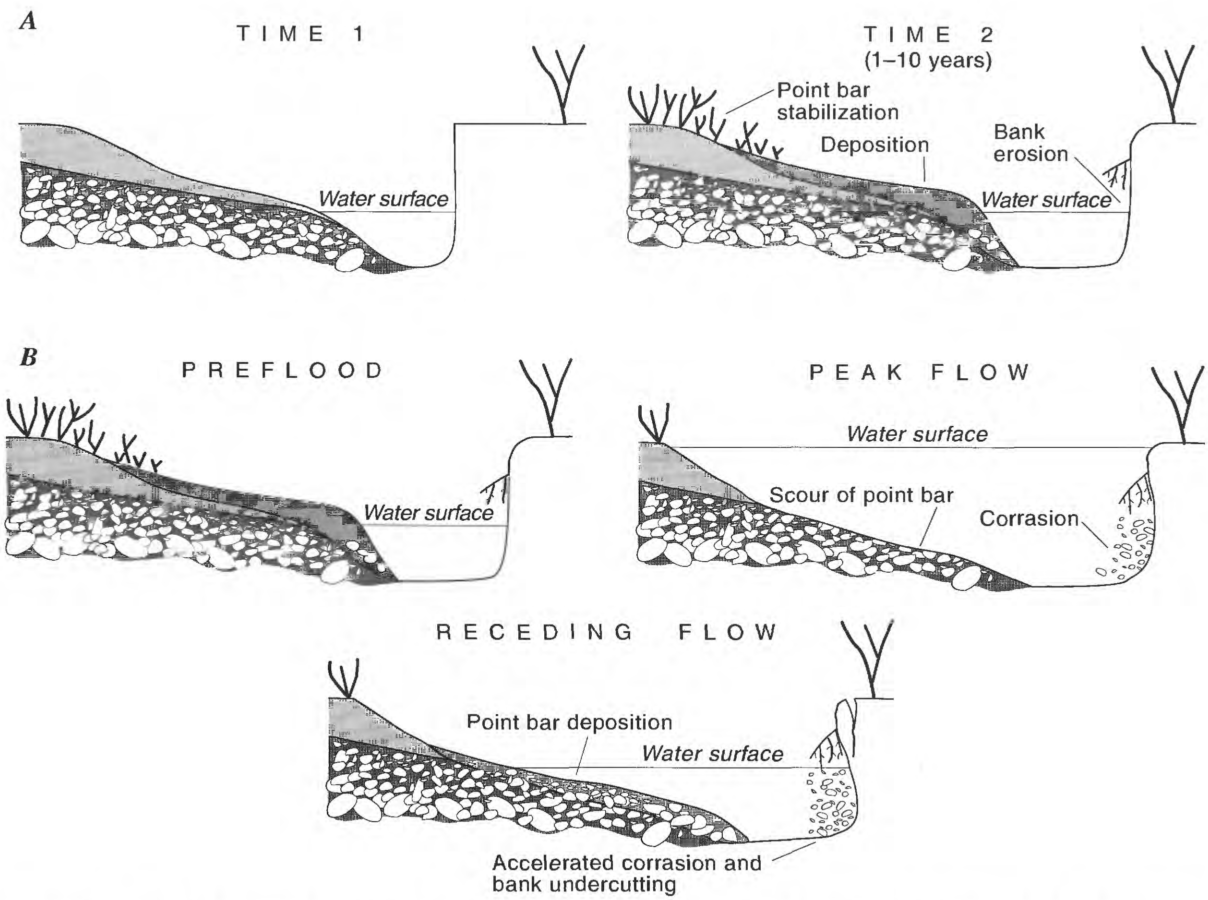


Figure 11. Role of channel migration in channel or arroyo widening. *A*, Migration in response to low to moderate flows producing no significant change in width. *B*, Migration in response to high flows producing channel widening.

The cohesiveness of channel banks produces a lag between application of shear stress and bank erosion (Hooke, 1979; Thorne and Tovey, 1981) because the banks must be wet enough to break down cohesive forces by dissolution before corrasion can occur (Wolman, 1959). Duration of flow, antecedent moisture conditions, and permeability of bank materials influence soil-moisture conditions and thus the spatial and temporal variability of resistance to bank erosion. Field evidence of corrasion on the Santa Cruz River includes undercut banks, especially where a coarse basal layer underlies fine-grained bank materials. Such apparent undercutting, however, also can result from erosion of the coarse layer by seepage from the banks to the channel (Thorne and Tovey, 1981).

Mass wasting, which includes planar and rotational sliding and slumping, is a major component of bank retreat in a variety of settings (Twidale, 1964; Stanley and others, 1966; Klimek, 1974; Thorne and Tovey, 1981; Simon, 1989). Abundant evidence of mass wasting, such as failure blocks in the channel and debris aprons at the base of banks and arroyo walls, is seen along much of the Santa Cruz River.

Failure material in the channel indicates that mass wasting occurs during low to moderate flows or receding floodwaters that are incapable of transporting the material out of the reach. Significant bank retreat has occurred along some reaches of the Santa Cruz River during periods of generally low discharges. Rapid drawdown of floodwaters produces a steep hydraulic gradient in the banks adjacent to the channel, causing water to percolate through sediment at the base of the bank. Associated seepage pressure removes material from the base, which undercuts the bank and leads to failure (Terzaghi, 1950; Keller and Kondolf, 1990).

Banks or arroyo walls on the Santa Cruz River that fail easily tend to be in alluvium of Holocene age that consists of fine-grained sand and silt cohesive enough to maintain an oversteepened face in the absence of disturbance but not so cohesive as to resist corrasion by streamflow. Even slight undercutting by corrasion can then produce large bank failures because of discontinuities in the alluvium produced by tension cracks, fissuring, and piping erosion (fig. 12). At the few locations in the study area where the

A

B

Figure 12. Structural weakening of arroyo walls, Santa Cruz River. *A*, Tension cracking leads to block failure of cohesive alluvium. *B*, Pipes enlarge and may produce cavernous discontinuities in alluvium.

Santa Cruz River channel is incised into alluvium of Pleistocene age, bank retreat generally is slight despite abundant tension cracks and pipes in 15- to 20-ft-high vertical walls. Apparently, the more highly indurated older alluvium resists corrasion and undercutting by streamflow.

Failure material that is left at the base of banks may protect the banks from further retreat until the material is removed by subsequent flows (Knighton, 1984; Meyer, 1989). During high flows, the combination of rapid undercutting and repeated failure of bank material can cause large amounts of bank retreat because flows are more than adequate to transport the eroded material from the area. Arroyo-wall failure on the Santa Cruz River that was observed during the flood of December 1978 occurred by rapid sloughing of thin slabs of alluvium that were easily disaggregated and transported in the flow (D.F. Meyer, U.S. Geological Survey, oral commun., 1990).

Channel Widening on the Canoa Reach

Between 1976 and 1986, about 1,200 ft of widening occurred on the upper Canoa reach, which is characterized by low banks composed of weakly cohesive sand and gravel (fig. 13*A*). The channel was stable from the 1950's, when much of the reach was channelized and banks were armored, until the flood of 1977 during which widening generally was confined to unchannelized sections. The 1983 flood produced a fivefold to sixfold increase in channel width along channelized and unchannelized sections. Widening upstream from axial distance 0.7 mi (fig. 13*A*) was the result of lateral corrasion by high flow; widening in the unchannelized part of the reach between 0.65 and 1.4 mi was caused by channel widening on the outside of a meander as it migrated downstream. Migration of the meander on the Canoa reach was accompanied by almost complete point-bar removal, and only a coarse lag was left in its place.

Vegetational Resistance to Channel Widening on the Cortaro and Marana Reaches

The high resistance to channel widening provided by vegetation is illustrated on the Cortaro and Marana reaches. The channel narrowed after 1966 as a result of vegetation growth in response to perennial flow (fig. 13*B*; Hays, 1984), and in most of the reach the 1977 flood caused little widening. The 1983 flood stripped vegetation and eroded the generally sandy, gravelly banks. Hays (1984) reported an increase in mean width from 250 to about 450 ft on the Marana reach between Avra Valley Road and Trico-Marana Road after the 1983 flood. Aerial photographs taken in 1984 indicate that mean width on the Cortaro reach between Cortaro Road and Avra Valley Road increased from 150 to 270 ft as a result of the 1983 flood. By 1986, however, mean width of the Cortaro reach had declined to 170 ft as a result of subsequent low-flow incision, in-channel deposition, and revegetation.

Vertical Channel Change

Entrenchment of the channel into the previously unincised flood plain during the late 19th and early 20th centuries caused the greatest channel change on the Santa Cruz River in historical times. During the study period, vertical channel change has continued in entrenched and unentrenched reaches of the river (fig. 5). In some places, such as along much of the Sahuarita reach, channel degradation has been the only significant channel change through most of the study period; in other reaches, such as the Cortaro and Marana reaches, vertical changes have resulted from and contributed to lateral channel instability.

Vertical channel changes result from changes in stream power, sediment concentration, or resistance that occur as a result of variation in flood magnitude, sediment availability, channel morphology, or local channel gradient. Scour and fill are transient changes in bed elevation that occur during floods. As much as 25 ft of scour occurred on the Santa Cruz River near Nogales during the 1977 flood; however, the scour hole was completely filled during recession of the flood (Aldridge and Eychaner, 1984). Degradation and aggradation occur over years to decades and may reflect climatic change, adjustments to channel widening or narrowing, sediment storage and episodic transport, and natural or artificial changes in channel-hydraulic properties. Degradation and aggradation can alternate in time and space. On desert streams in particular, spatial alternation of these processes can be expected because of high sediment availability and flow reductions caused by high downstream transmission losses. Although the Santa Cruz River generally has been erosional during the study period, data on bed elevations suggest that much of the river is subject to periods of both aggradation and degradation (fig. 5).

Vertical and lateral channel changes are linked in several ways. High rates of aggradation can plug

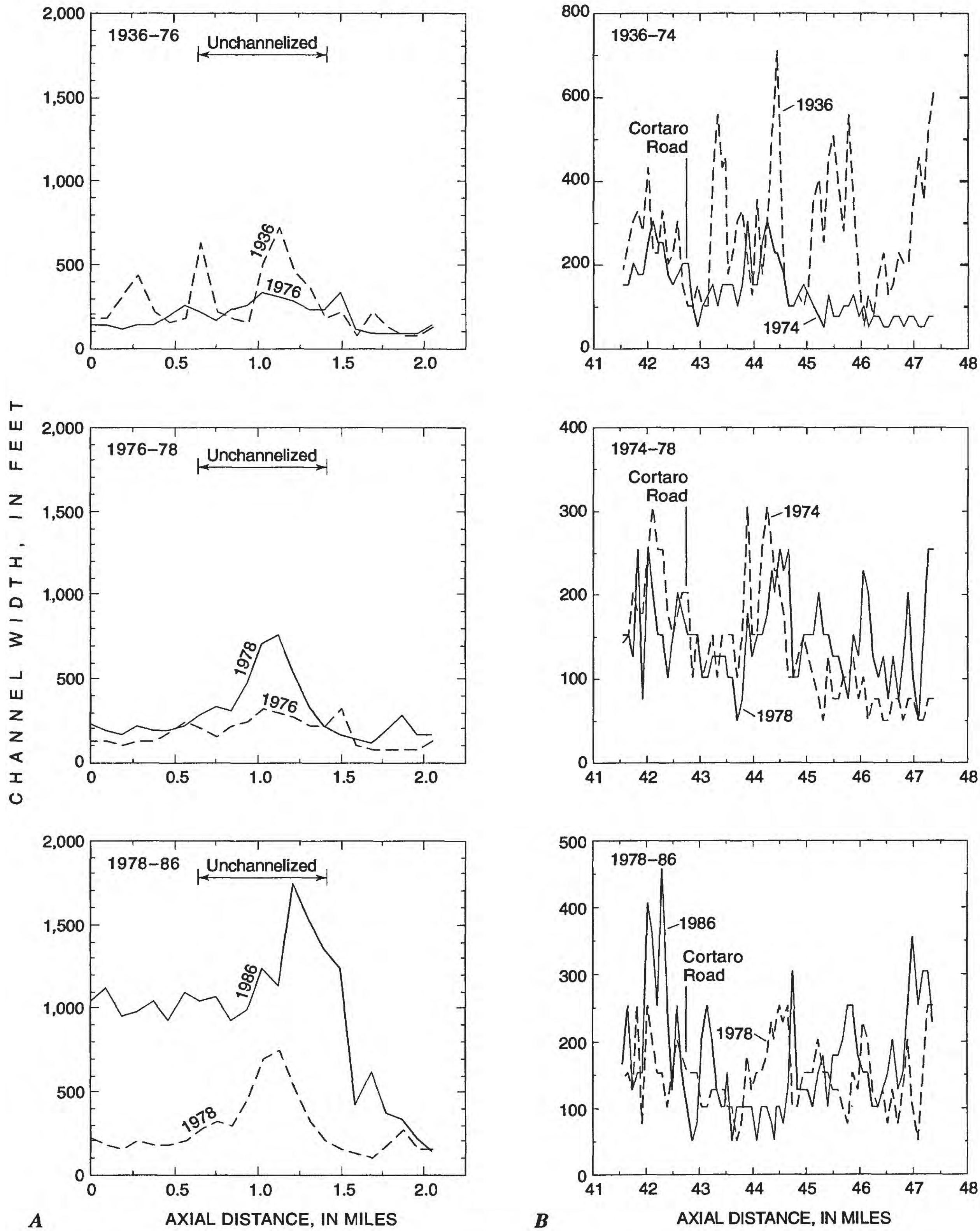


Figure 13. Channel-width changes on the Santa Cruz River. *A*, Upper Canoa reach. *B*, Lower Cortaro reach.

channels and result in lateral shifts of channel position by avulsion or meander cutoff (Graf, 1981; James, 1991). Degradation can cause oversteepening of banks, making them more susceptible to failure when undercut by stream erosion. Subsequent deposition within entrenched channel systems can cause further bank erosion and arroyo-wall retreat by forcing lateral movement of confined meanders.

Most vertical channel change on the Santa Cruz River near Tucson has been degradational since the late 1950's. The most pronounced channel incision has been from Ajo Way in the lower San Xavier reach to Grant Road in the middle of the Tucson reach where 10 to 15 ft of streambed lowering has occurred (fig. 5*D–I*). The general pattern suggests stable or aggrading conditions through the mid-1950's, and limited evidence suggests that this period of vertical stability may have spanned the preceding 40 years (fig. 5*F*). The link between vertical and lateral channel change is illustrated by an episode of aggradation above Tucson in the mid-1950's. The streambed at Ajo Way and 1.6 mi downstream at Silverlake Road in the lower San Xavier reach rose 4 ft in that period (fig. 5*D–E*). As seen in an aerial photograph taken in 1960, the main channel within the arroyo downstream from 44th Street, between Ajo Way and Silverlake Road, underwent an abrupt shift in position of more than 800 ft after 1953 (fig. 14).

Incision was apparently underway by 1962 (fig. 5*G* and *I*), and maximum degradation had occurred at most sites between Valencia and Grant Roads by 1970–74. Following maximum incision,

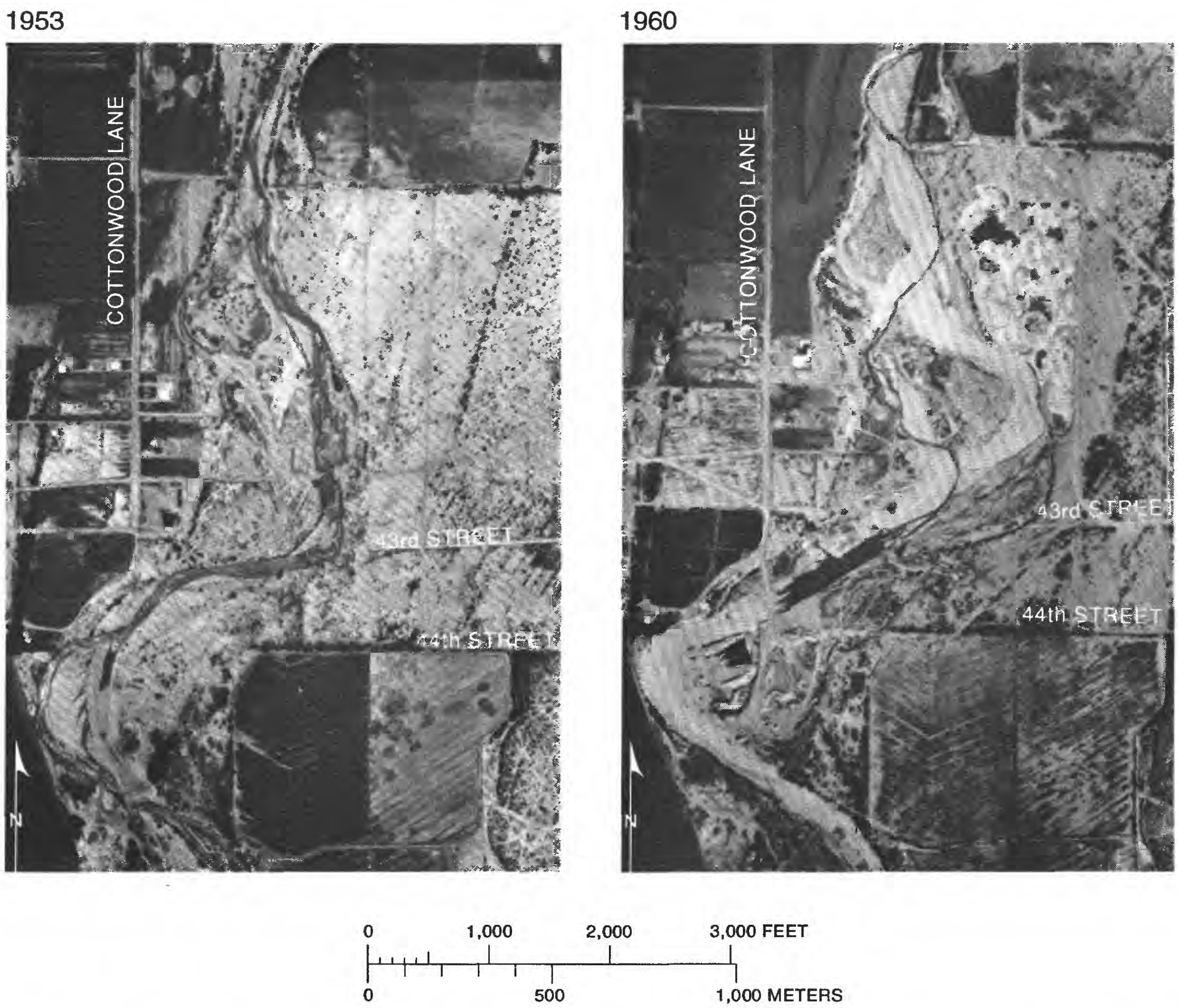


Figure 14. Avulsion within the arroyo in the lower San Xavier reach north of 44th Street, 1953–60. About 4 feet of aggradation occurred in the reach during that interval. (Aerial photographs by Cooper Aerial Survey, 1953 and 1960.)

minor fluctuations in streambed elevation occurred throughout the 1970's.

Downstream from Grant Road, the record of vertical change is sparse and equivocal. Some change occurred at Cortaro and Avra Valley Roads between the 1950's and 1976; however, a more complete record at Ina Road (fig. *5K*) suggests that this interval was characterized by fluctuating streambed elevations. The period of maximum degradation in the mid-1970's lagged slightly behind upstream degradation. Aggradation of 4 ft at Ina Road during the flood of 1983 (fig. *5K*) occurred in conjunction with extensive lateral shifts in channel position by avulsion and meander cutoff.

Upstream from Valencia Road, data on vertical changes are few for most locations. The best record is at Pima Mine Road (fig. *5B*) in the lower Sahuarita reach, which is at the southern boundary of the San Xavier Indian Reservation. In aerial photographs from 1936, the channel is barely visible at the present (1993) crossing of Pima Mine Road, which indicates that little or no incision of the flood plain occurred before 1936. Between 1936 and 1953, the channel incised a maximum of 11 ft and probably much less. Survey data indicate that by 1969 the channel thalweg was 22 ft below the former flood plain and had incised at least 11 ft and possibly more than 20 ft since 1953. In 1976, the channel bed was 24 ft below the flood plain of 1936.

Few data are available on channel degradation upstream from Pima Mine Road. Bridge specifications prepared from data for 1928 show a channel elevation of 2,826 ft at Continental, suggesting that 8 ft of aggradation occurred at that location between 1928 and 1976 (fig. *5A*). These data, however, are not consistent with aerial photographic evidence, which indicates that the main channel at Continental was incised after 1936 and that the channel elevation in 1976 was lower than the channel elevation in 1936. Channel-bed elevation probably changed little between 1928 and 1936. Therefore, the elevation of 1928 must be referenced to a different datum than the elevations of 1976 and 1985. The floods of 1977 and 1983 apparently had little effect on channel elevation at Continental. On the basis of aerial photographs, degradation of the upper Santa Cruz River after 1936 extended through the Canoa reach, although the degree of incision may have decreased upstream.

Arroyo Change

Mechanisms of channel change and bank retreat operating within the confines of an entrenched channel system cause the expansion of arroyo boundaries. An arroyo is created when a stream undergoes such extreme degradation that its flood plain is left standing above the level of most flooding. On the Santa Cruz River, even the largest floods do not overflow the arroyo walls in the San Xavier and Tucson reaches. In the Sahuarita reach, however, some recent large floods have overflowed arroyo walls.

Arroyo widening on the Santa Cruz River occurs when flows undercut weakly indurated, oversteepened arroyo walls or when return flow of bank storage to the channel causes seepage erosion at the base of the walls. Lateral arroyo expansion generally occurs after channels have been entrenched below a critical depth at which arroyo walls become highly unstable (Schumm and others, 1984; Simon, 1989). Arroyo walls can undergo rapid, extensive retreat during lateral extension or downstream translation of entrenched meanders or by inception of a meander within a constricted reach.

Unlike channel widening, the process of arroyo widening is not readily reversed on large systems such as the Santa Cruz River. Because of cementation, arroyo walls can maintain steep faces for decades; degradation of the walls with a decline in bank angle is a slow process that can be interrupted repeatedly by renewed episodes of stream undercutting and mass wasting. As the arroyo widens, the walls can become isolated from streamflow and less frequently undercut. At some locations on the San Xavier reach, arroyo walls, which probably have not been undercut since at least 1936, still maintain a distinct, steep scarp. The alluvial stratigraphic record of the past 8,000 years in the Southwest contains many examples of filled arroyos (Haynes, 1968). Such paleoarroyos typically show distinct vertical walls, indicating that lowering of the slope angle proceeds slowly. Thus, the lateral boundaries of arroyos, delineated by the vertical walls, tend to persist or expand until the arroyos are completely refilled with sediment. The amount of time for arroyo filling varies; however, Waters (1988) found that a paleoarroyo on the Santa Cruz River—comparable in cross-sectional dimensions to the present arroyo—became entrenched and then filled in less than 200 years.

Chronology of Arroyo Expansion on the San Xavier Reach

The San Xavier reach, especially the lower reach above Martinez Hill to Valencia Road, has undergone the most extensive and continuous arroyo widening on the Santa Cruz River (fig. 15). The channel was incised as much as 30 ft in silt and sand of Holocene age, and about 1,200 ft of widening occurred at some places between 1936 and 1986. Mean arroyo width of the entire San Xavier reach increased from 200 ft in 1936 to 500 ft in 1986.

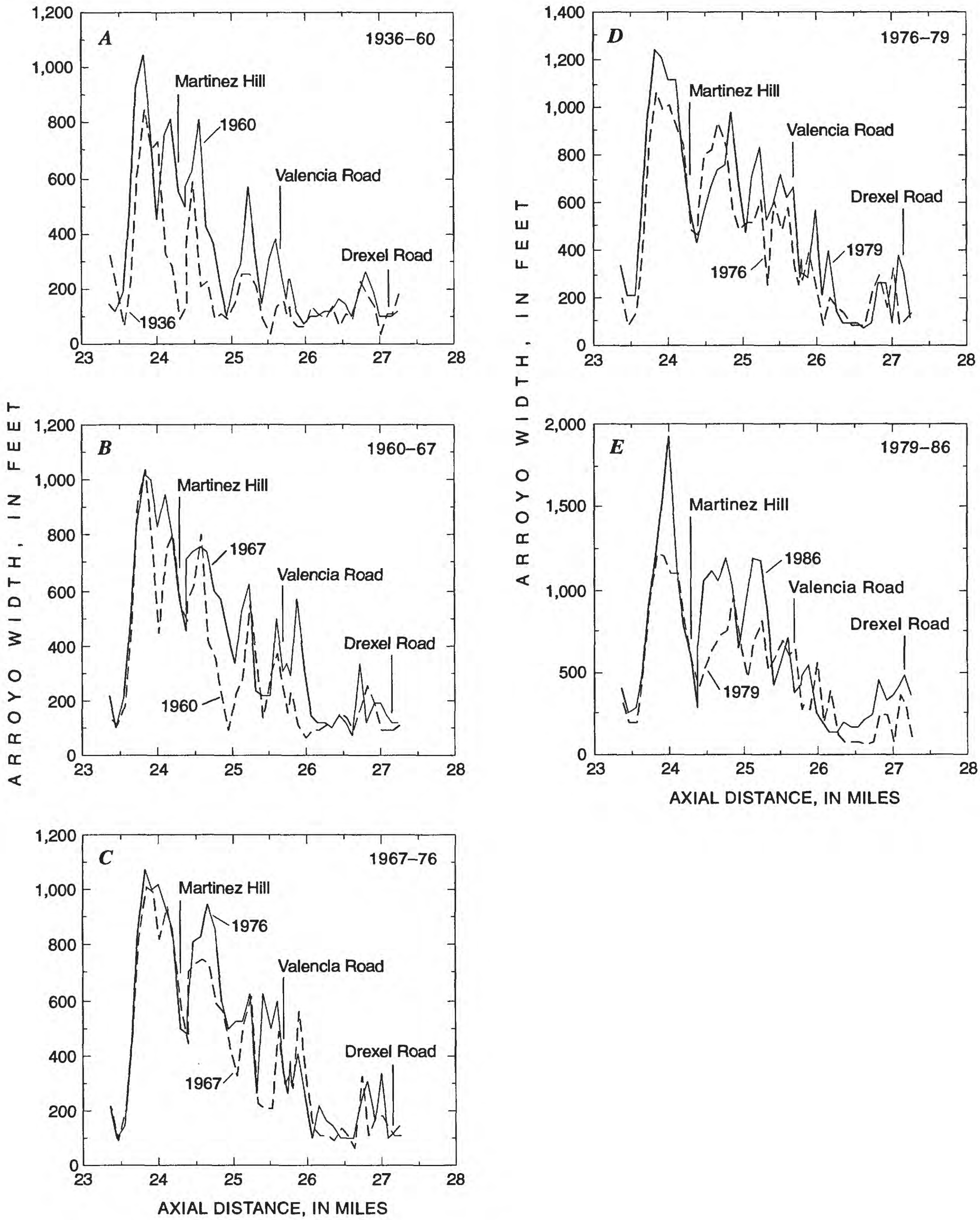


Figure 15. Arroyo widths on the lower San Xavier reach near Martinez Hill, 1936–86.

The rate of arroyo widening of the San Xavier reach near Martinez Hill has varied since 1936 (fig. 16). Twenty-eight percent of the total increase in mean arroyo width through the reach occurred between 1936 and 1960. Another 28 percent of total arroyo widening occurred between 1960 and 1976.

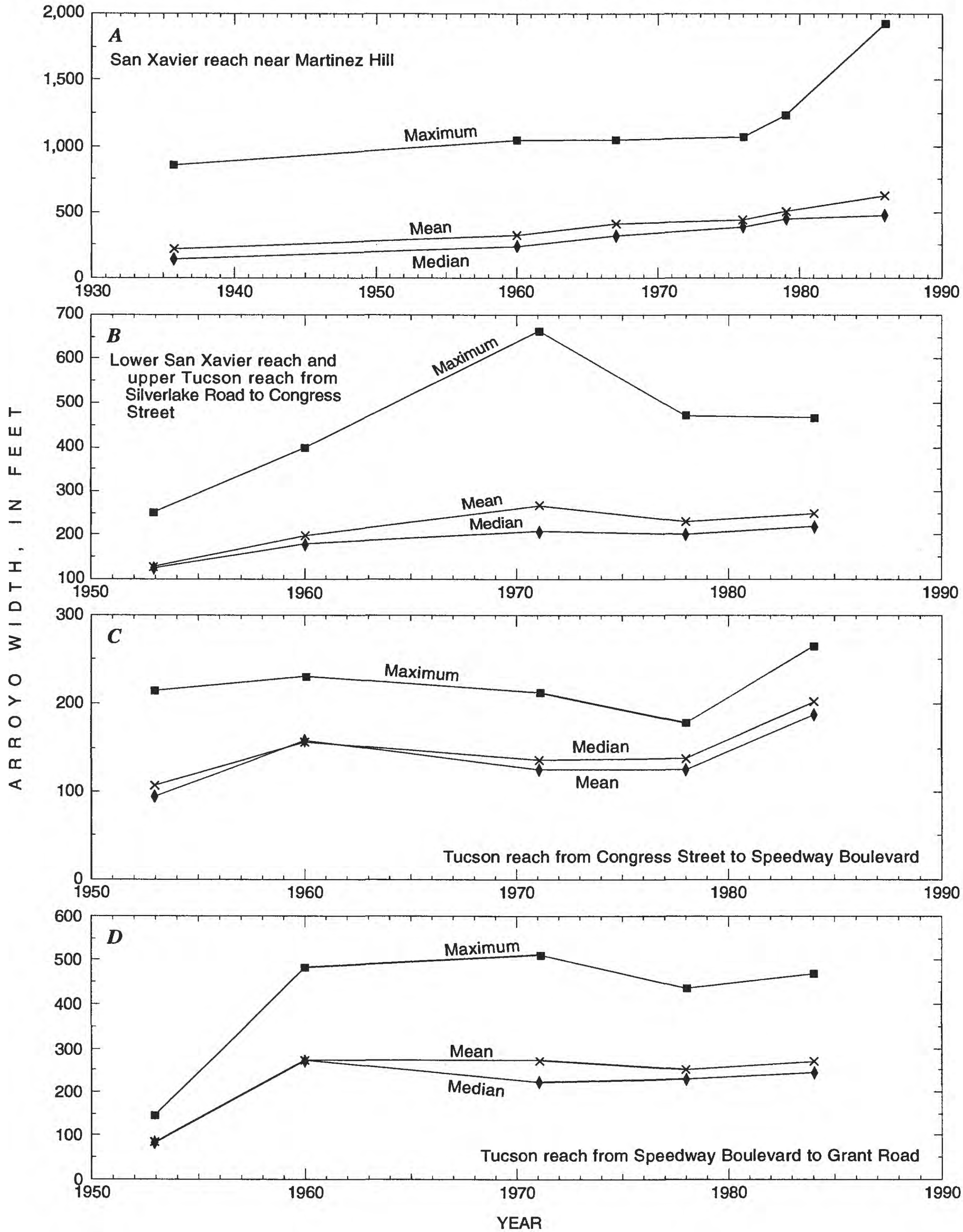


Figure 16. Arroyo-widening statistics for the San Xavier and Tucson reaches.

Artificial narrowing associated with sand-and-gravel operations downstream from Martinez Hill prevented a larger increase in mean width. The remainder of the increase in mean width (44 percent) occurred in the final decade of the study (1976–86), primarily as a result of the floods of 1977 and 1983. The 1983 flood caused a particularly large increase in maximum arroyo width. From 1936 to 1979, maximum width increased about 400 ft; however, after the 1983 flood, maximum arroyo width had increased almost 700 ft more to 1,925 ft. The maximum increase in width measured at any one location was more than 800 ft during the flood of 1983.

The highest rates of arroyo widening on the San Xavier reach occurred in association with migration of the entrenched channel against the arroyo walls (fig. 17; Parker, 1989). Meanders generally shifted position by lateral extension with little downstream translation, causing arroyo widening to occur repeatedly at about the same locations throughout each time interval (fig. 15). Such a pattern suggests that arroyo-wall retreat generally is caused by flows that are unable to rework and transport the coarsest material in the point bars but are capable of eroding the weakly cemented, fine-grained arroyo walls (Meyer, 1989). Braided and straight arroyo segments generally widened much more slowly on the San Xavier reach, but the rate of arroyo widening may eventually increase in such reaches when penetrated by downstream migrating meanders (fig. 18).

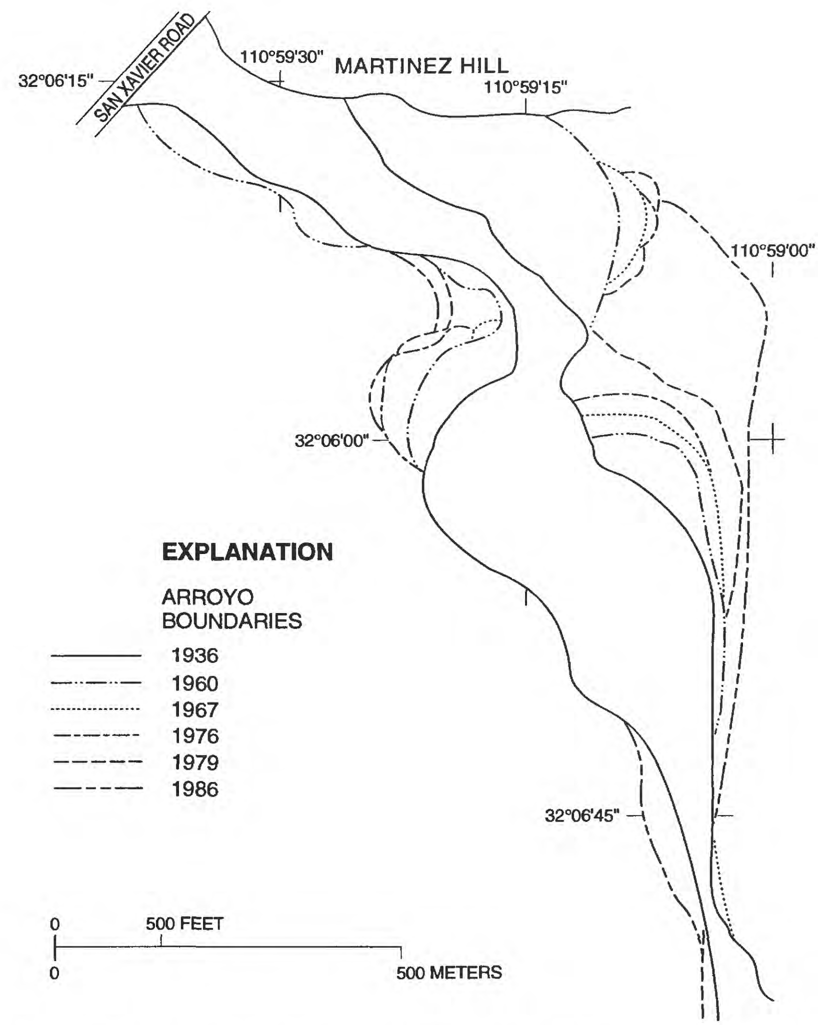


Figure 17. Arroyo widening caused by migration of entrenched meanders in the San Xavier reach at Martinez Hill, 1936–86. (Source: Data from U.S. Soil Conservation Service, 1936; Cooper Aerial Survey, 1960, 1967, 1979, 1986; Kucera and Associates, 1976.)

Although the most persistently unstable reaches of the Santa Cruz River have also been the most deeply entrenched, a quantitative relation is difficult to determine between channel incision and bank or arroyo-wall retreat. According to some models of channel change in entrenched systems (Schumm and others, 1984; Simon, 1989), an initial period of incision typically is followed by vertical stabilization or slight aggradation and then by maximum rates of bank retreat. Lack of a time series of streambed-elevation changes for the San Xavier reach where it crosses the San Xavier Indian Reservation hampers attempts to test the model in this study. The upper to middle San Xavier reach in the reservation is the only entrenched reach that is not directly affected by artificial bank stabilization. Other entrenched reaches have been artificially changed so that assessment of the model is difficult.

Arroyo Change on Disturbed Reaches

Arroyo change along other reaches of the Santa Cruz River is difficult to evaluate because the Tucson and Sahuarita reaches have been subject to extensive human alteration and much of the apparent lateral stability of the reaches is artificial (fig. 4). For example, according to bridge specifications prepared in 1916, the channel at Congress Street in the Tucson reach widened to 375 ft during the floods of 1914–15, but subsequent artificial filling reduced width at that location to less than 200 ft. Two motels now

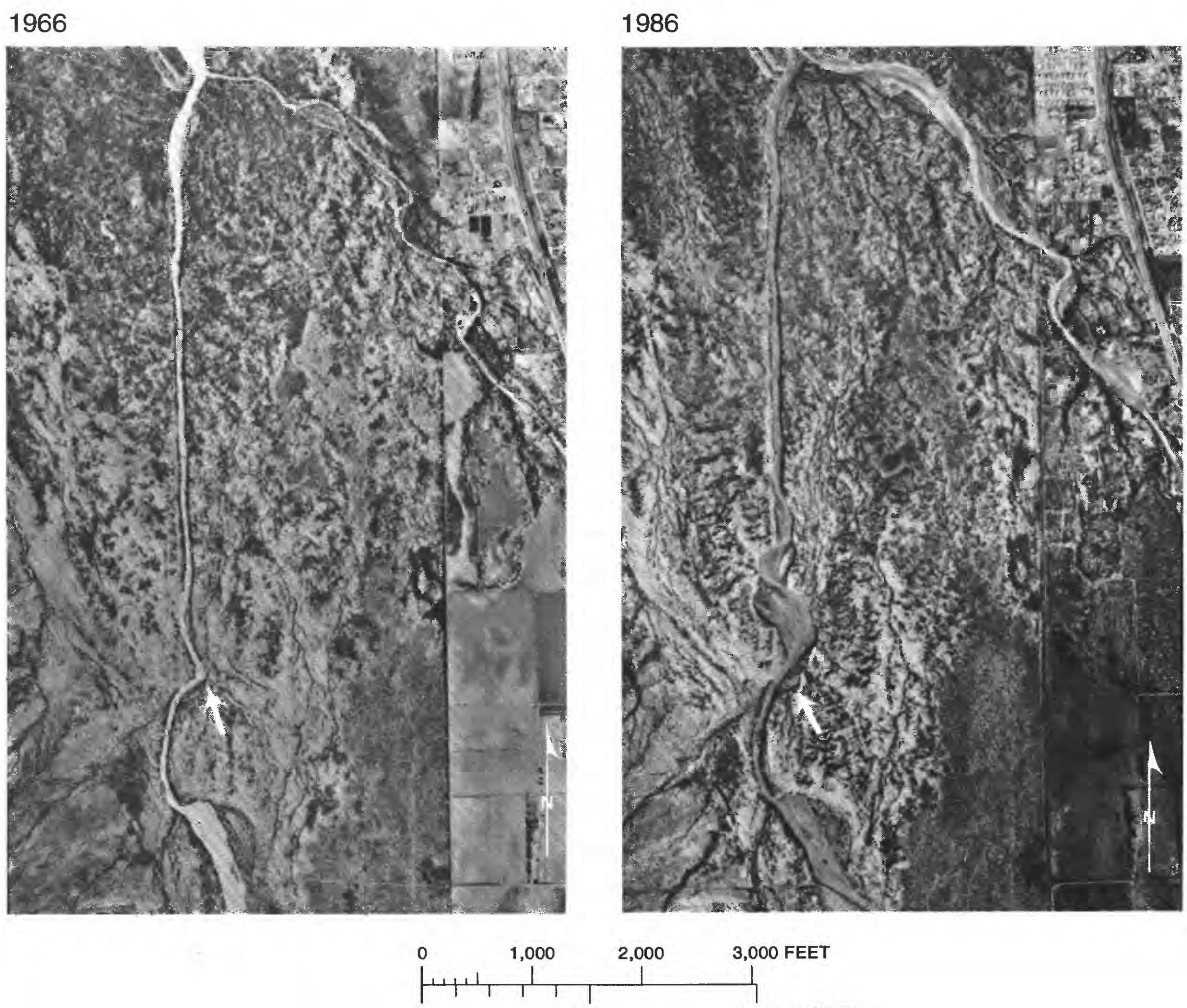


Figure 18. Changes on straight segment of the upper San Xavier reach, 1966–86. Arroyo width changed little except at the upstream end of the reach, where an entrenched meander was migrating into the straight segment. Most of the change occurred during the flood of 1983. (Aerial photographs by U.S. Geological Survey, EROS Data Center, 1966; Cooper Aerial Survey, 1986.)

stand on landfill above the site of the migrating meander that destroyed the Congress Street bridge in 1915 (Betancourt and Turner, 1988). In contrast to the San Xavier reach, most arroyo widening of the upper Tucson reach took place in the 1950's, and little widening occurred thereafter except locally as a result of the flood of 1983 (fig. 16). Some of the arroyo widening that took place between Silverlake Road and Congress Street in the 1950's may have been associated with construction activity that is visible in aerial photographs of 1960.

The relation between degradation and arroyo widening is not apparent in the Tucson reach. The most pronounced arroyo widening occurred from Silverlake Road to Grant Road (fig. 16) during 1953–60 before degradation had begun at most locations in the Tucson reach. Between Silverlake Road and Congress Street, the rate of arroyo widening was constant from 1953 to 1971. From Congress Street to Grant Road, however, no significant arroyo widening occurred between 1960 and 1978 even though this was a period of maximum incision and subsequent vertical fluctuation. After the flood of 1983, only the part of the Tucson reach from Congress Street to Speedway Boulevard showed a significant increase in mean arroyo width.

The poor relation between vertical and lateral change in the Tucson reach is only partly explained by artificial channel changes. As late as 1983, arroyo walls along a third of the reach between Silverlake Road and Congress Street were unprotected and arroyo walls from St. Mary's Road to Grant Road were mainly unprotected (Saarinen and others, 1984). Artificial armoring was presumably even less of a factor from 1953 to 1960, when maximum arroyo widening and minimum channel degradation occurred. The timing of maximum arroyo widening on the Tucson reach suggests that arroyo walls generally were less resistant to erosion than was the channel bed before 1960. Besides bank protection, possible reasons for the change in resistance in arroyo walls relative to the channel bed include depletion of nonresistant arroyo-wall material or changes in inner-arroyo topography that affect the direction of maximum boundary shear stress.

FACTORS THAT CONTROL THE TEMPORAL AND SPATIAL PATTERNS OF CHANNEL CHANGE

Hydroclimatic factors, such as magnitude, duration, intensity, and frequency of precipitation and floods, control timing and magnitude of channel change at a particular location. Time-related changes in hydraulic factors, such as changes in channel geometry caused by successive floods or changes in roughness caused by vegetation growth, also contribute to the temporal variability of channel change. Spatial variability of channel change—the location of channel change and its magnitude in response to a given discharge—is controlled mainly by topographic, hydraulic, geologic, and artificial factors that control size and quantity of bedload, resistance to erosion, valley slope and channel gradient, and channel geometry.

Hydrologic and Climatic Controls

Different storm types in the Southwest generate floods with different characteristics. A number of investigators have suggested that winter flows are more erosive than summer flows of equivalent magnitude, in part because of lower sediment concentration (Burkham, 1972; Saarinen and others, 1984; Slezak-Pearthree and Baker, 1987). Graf and others (1991) found that summer and fall flows on the Paria River of Utah and Arizona accounted for only 48 percent of annual flow volume but 91 percent of annual sediment load. Other factors that might be expected to increase the erosiveness of winter flows relative to summer flows of similar stage include antecedent conditions that are more conducive to bank failure, such as saturated channel banks, and the longer duration of winter flows. The frequency, magnitude, and intensity of floods depend in part on the type of storms occurring over the region. Furthermore, the frequency of different storm types is linked to low-frequency changes in global climatic patterns (Webb and Betancourt, 1992). Consequently, hydroclimatic factors can be a major control on temporal variability of channel change on the Santa Cruz River.

Because of the regional extent and longer duration, frontal systems and tropical storms of sufficient magnitude might be expected to generate basinwide runoff with steadier discharge than would monsoonal thunderstorms. Less variability in flow characteristics on the Santa Cruz River might be expected from one site to another during winter and fall floods than during summer floods, and thus storm type might also affect the spatial variability of channel change.

Flood History

The flood history of the Santa Cruz River in this century shows three distinct periods (table 5, fig. 19;

Table 5. Relation of hydroclimatic regimen and channel change, Santa Cruz River at Tucson

[Data from Webb and Betancourt (1992)]

Time interval	Number of years	Discharge[1] of five largest annual floods in interval, in cubic feet per second	Date of flood	Rank[2]	Mean annual flood, in cubic feet per second[3]	Standard deviation	Number of floods above base discharge in interval[4]	Frequency of floods above base discharge by storm types, in percent		
								Monsoonal	Frontal	Tropical
1915–29	15	15,000 F	12-23-14	5	5,180	4,115	14	57	21	21
		11,400 T	09-28-26	8						
		10,400 T	09-24-29	12						
		7,500 M	09-08-17	25						
		5,000 F	01-21-16	37						
1930–59	30	11,300 M	08-14-40	9	5,890	2,960	42	87	3	10
		10,900 M	08-03-55	10						
		10,800 M	08-10-45	11						
		10,300 M	09-01-35	13						
		9,570 M	07-24-54	15						
1960–86	27	52,700 T	10-02-83	1	9,400	10,530	38	53	26	21
		23,700 T	10-10-77	2						
		16,600 M	08-23-61	3						
		16,100 F	12-20-67	4						
		13,500 F	12-19-78	6						

See footnotes at end of table.

Table 5. Relation of hydroclimatic regimen and channel change, Santa Cruz River at Tucson—Continued

	Nature and magnitude of channel change		
Time interval	**Canoa**	**Sahuarita**	**San Xavier**
1915–29	Period not documented in this study; aerial photographs of 1936 show wide meandering ephemeral channel. Faint channel scars on photographs indicate occurrence of abrupt channel shifts possibly in this interval or in 19th century.	Poorly documented. Betancourt and Turner (1988) refer to destruction of Twin Buttes railroad bridge in lower reach during December 1914 floods, suggesting possible bank erosion. Large distinct paleochannel immediately downstream from Sahuarita in aerial photographs of 1936 may indicate recent shift of channel position.	Headcut migration and cienega destruction during floods of 1914–15; arroyo entrenchment through San Xavier Indian Reservation (Betancourt and Turner, 1988). Aerial photographs of 1936 seem to show reach below Lee Moore Wash to be incised deeper than reach above junction.
1930–59	Mean width decreased as much as 30 percent, mainly from artificial channelization that was in place by the 1950's. Unchannelized parts of reach generally were stable.	Headcut migration in lower reach completed cutoff of previous channel course. Meander cutoff upstream in response to channel incision. Little change in width.	Persistent arroyo widening at upstream end of reach and near Martinez Hill, where mean width increased 13 percent. Point bars and terraces within arroyo generally were stable. Further entrenchment above Lee Moore Wash.
1960–86	Little or no natural change before 1977. During 1977 flood, mean channel width in upper reach increased more than 50 percent, maximum width doubled, and flood-plain deposition was more than 3 feet thick in places. During 1983 flood, mean channel width increased about 25 percent; maximum width increased from about 750 feet to almost 1,700 feet.	Not extensively examined in this study. Arroyo widths generally were wider by end of interval, but timing was difficult to establish from aerial photographs because of channel maintenance practices. Little or no natural change in channel position.	Mean arroyo width near Martinez Hill increased 35 percent between 1960 and 1976; maximum width increased slightly. Mean width increased by about 13 percent during 1977 flood; maximum width increased by 16 percent. During 1983 flood, mean width increased almost 25 percent; maximum width increased from about 1,150 feet to almost 1,800 feet. Guber (1988) shows minor widening of low-flow channel and little erosion of point bars and terraces as a result of October 1977 flood, substantial erosion after flood of December 1978, and near-total destruction of point bars and terraces from flood of October 1983.

See footnotes at end of table.

Table 5. Relation of hydroclimatic regimen and channel change, Santa Cruz River at Tucson—Continued

Time interval	Nature and magnitude of channel change		
	Tucson	Cortaro	Marana
1915–29	Extensive arroyo widening during 1914–15 floods throughout reach; destruction of Congress Street bridge (Betancourt and Turner, 1988).	Not well documented. Aerial photographs of 1936 show meandering, ephemeral channel, sparsely vegetated banks, and flood plain. Channel scars indicate channel shifts possibly in this interval or in 19th century.	Channel widths increased as much as 600 percent, mainly during floods of 1914–15 (Hays, 1984). Aerial photographs of 1936 show reach to be mainly braided with sparsely vegetated banks and flood plain.
1930–59	Extensive widening in places, especially between Speedway Boulevard and Grant Road. Degradation begins near end of interval.	Channel position highly unstable. Shifts in channel position of more than 1,100 feet. Sinuosity decreased because of meander cutoffs. Mean width decreased 25 percent. Change was slight in arroyo upstream from Cañada del Oro.	Channel position highly unstable. Shift in channel position of more than 3,000 feet. Hays (1984) reported large decline in braiding, little change in sinuosity, and decrease in mean sinuosity and channel width from more than 400 feet to less than 300 feet.
1960–86	Arroyo widths generally stable. Apparent narrowing at some locations caused by channelization and landfill operations (Betancourt and Turner, 1988). As much as 15 feet of arroyo incision. Baker (1984b) and Saarinen and others (1984) report substantial arroyo wall retreat along unprotected segments of reach as a result of flood of 1983.	Before 1977, sinuosity increased and mean width decreased; generally minor to moderate amounts of channel migration. Slight increase in mean width from 1977 flood, but almost no change in channel position from migration or avulsion-meander cutoff. Flood of 1983 cut off almost all meanders, shortened channel 10 percent, and doubled channel width in places. Maximum shift in channel position of more than 1,300 feet occurred. Arroyo upstream from Cañada del Oro widened substantially.	Single-channel system formed through most of reach by 1974. Increase in vegetation density because of artificial perennial flow. Sinuosity increased between 1966 and 1982; mean channel width decreased to about 200 feet before 1977 flood, and increased slightly after flood (Hays, 1984). Widespread avulsion during 1983 flood produced lateral shifts in channel position of as much as 2,000 feet; mean width increased 75 to 100 percent.

[1]Letters indicate storm type. M, monsoonal; F, frontal; T, tropical.
[2]Ranked from largest to smallest out of 71 annual floods between 1915 and 1986.
[3]Mean annual flood is maximum discharge of year.
[4]Base discharge is 1,700 cubic feet per second.

Webb and Betancourt, 1992). The period before 1930 is characterized by generally variable flow conditions. Half the annual flood discharges at Tucson were less than 350 ft^3/s during this period, but the flood of 1915 was 15,000 ft^3/s and was the flood of record for almost 50 years. More than half of all floods above base flow before 1930 were the result of winter or fall storms. From 1930 to 1959, peak discharges generally were moderate. Although the mean annual flood was slightly higher for 1930–59 than for 1915–29, variability was lower. Summer monsoonal storms generated all but one of the annual floods and accounted for almost 90 percent of all floods above base flow during this period. From 1960 to 1986, annual floods at Tucson were variable; the four highest annual floods of record and the lowest annual flood of record occurred during this period. Frontal systems or tropical cyclones generated 9 of the 23 annual floods and almost half of all floods above base flow between 1960 and 1986. For the entire period of record through 1986 at Tucson, fall and winter storms accounted for 7 of the 10 largest annual floods on the Santa Cruz River. Record floods in October 1977 and October 1983 from tropical storms had a particularly large geomorphic effect (Aldridge and Eychaner, 1984; Saarinen and others, 1984; Roeske and others, 1989) and forced a reevaluation of flood-frequency methods and estimates for the Santa Cruz River and other large streams in southern Arizona (Hirschboeck, 1985; Webb and Betancourt, 1992).

Webb and Betancourt (1992) attributed increased flood frequency on the Santa Cruz River to climatic variability resulting in a change in seasonality of flooding after 1960. They developed flood-frequency estimates for the Santa Cruz River using maximum-likelihood analysis and mixed-population analysis in which floods caused by different flood types were treated as independent populations. Depending on the set of assumptions used, Webb and Betancourt's (1992) estimates of the 100-year discharge at Tucson ranged from 11,400 ft^3/s for 1930–59 to 58,600 ft^3/s for 1960–86. A change in the seasonality of annual flood peaks after 1960 was noted on other large streams in southern and central Arizona including Rillito Creek (Slezak-Pearthree and Baker, 1987), the

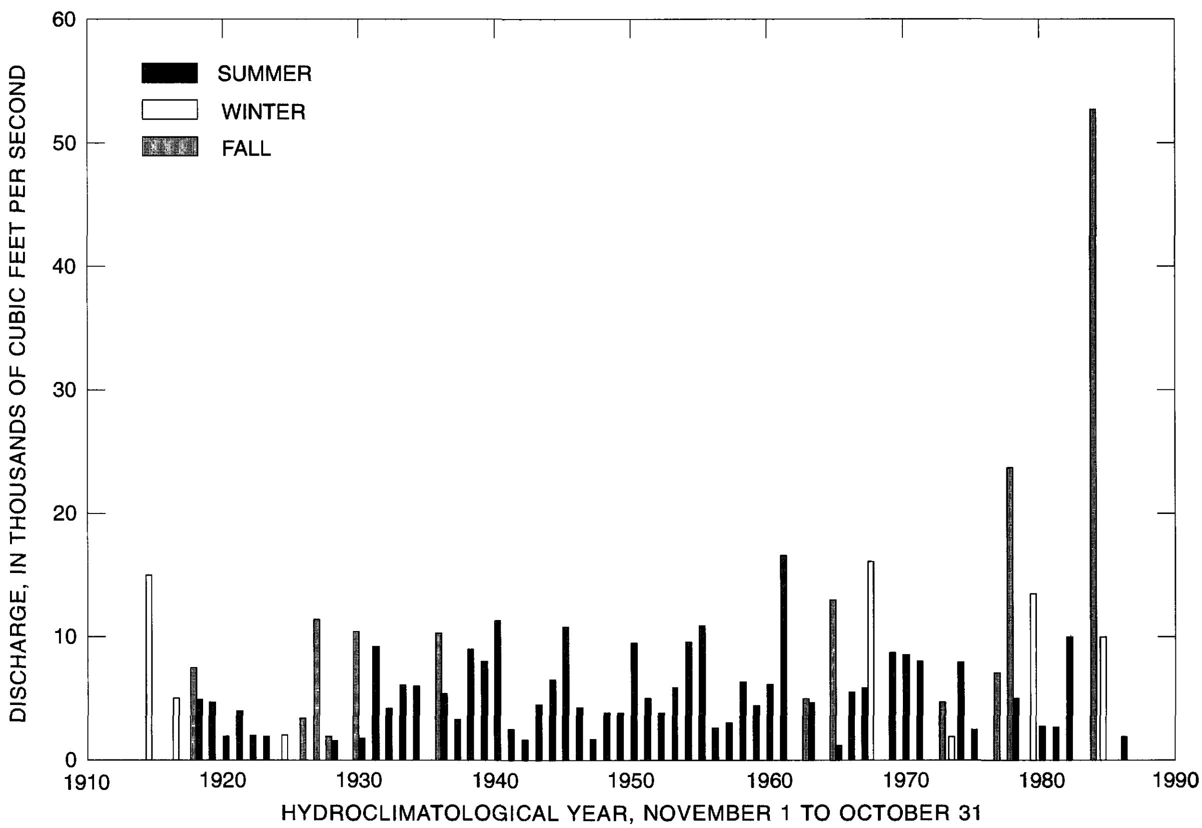


Figure 19. Annual flood series for the Santa Cruz River at Tucson. (Source: Data from Webb and Betancourt, 1992.)

San Francisco River (Hjalmarson, 1990), and the Gila and San Pedro Rivers (Roeske and others, 1989). Fall and winter precipitation on those rivers typically accounts for the largest floods.

Flow Characteristics Caused by Different Storm Types

Flow in the Santa Cruz River generally is flashy with a rapid increase and recession of discharge, especially in response to summer monsoonal thunderstorms that generate most annual floods (Webb and Betancourt, 1992). Such storms generate flow locally, and transmission losses into the channel can be high, especially when the channel is dry (Condes de la Torre, 1970). Consequently, summer flood peaks at different locations within the basin seldom result from the same storm. Frontal systems in winter tend to be regional and produce low-intensity precipitation and little runoff. Stalled winter systems or a series of closely spaced systems in winter can generate larger floods. Tropical storms, which occur mainly in the late summer and fall, typically are regional in extent and can produce high-intensity precipitation and high runoff. The seasonality of the different storm types can vary from the general pattern. A frontal system occurred in August 1933, and tropical cyclones occurred in July 1954 and 1958 (fig. 20).

All three storm types produce floods with considerable spatial variability among four streamflow-gaging stations on the Santa Cruz River in peak discharge, duration, mean daily discharge, and flood volume (fig. 21). The number of floods analyzed is insufficient to generalize confidently about the causes of variability in characteristics of flow events generated by different storm types. Tentatively, however, the data seem to reflect orographic and meteorologic effects on precipitation as well as flood-peak attenuation and transmission losses caused by geomorphic or topographic factors.

The highly localized distribution of summer monsoonal precipitation is reflected in flood patterns of August 23, 1961, and August 1–2, 1978 (fig. 21*A*). The 1961 flood—the third largest of record at Tucson (table 5) and the eighth largest at Cortaro—produced a modest peak discharge at Continental and no flow at all at the Nogales streamflow-gaging station. Such a pattern is a product of the limited areal extent of intense precipitation during monsoonal thunderstorms. Spatial and temporal patterns of flow are more complex for the August 1978 flood. The timing and maguitude of peak discharge varied considerably among the four stations, and there was no direct relation between peak discharge and the other flow characteristics of duration and mean and total discharge (fig. 21*A*). Flow was considerably more flashy at

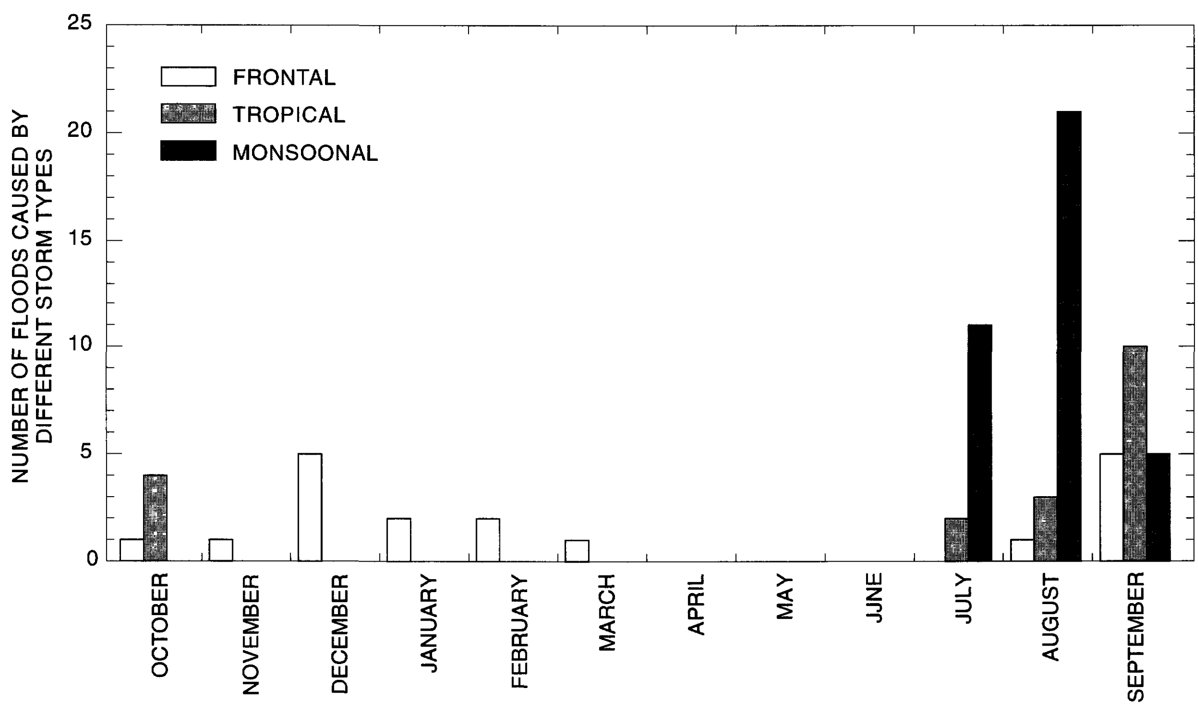


Figure 20. Seasonal occurrence of floods at Tucson caused by monsoonal thunderstorms, frontal systems, and dissipating tropical storms, 1914–84. (Source: Data from Webb and Betancourt, 1992.)

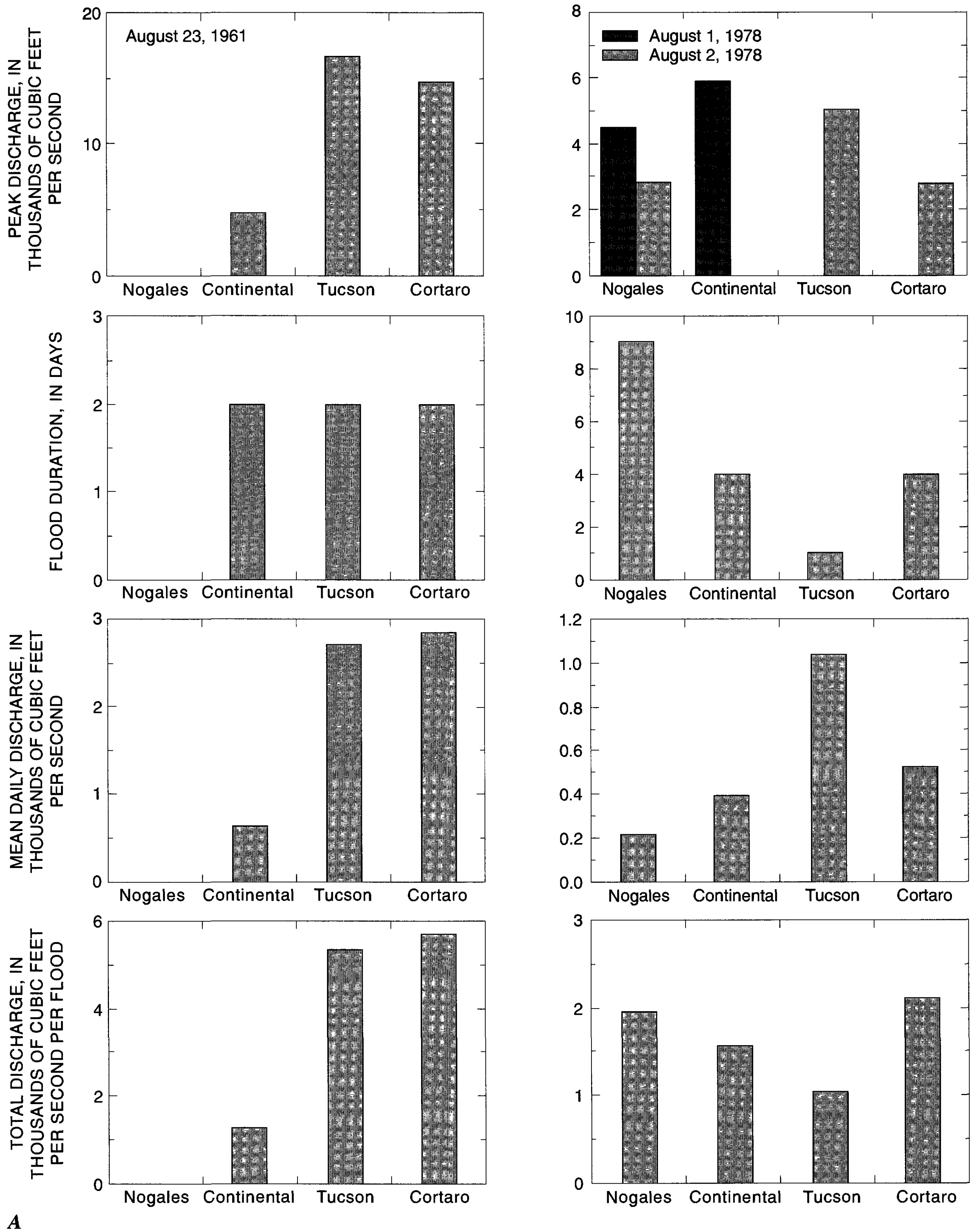
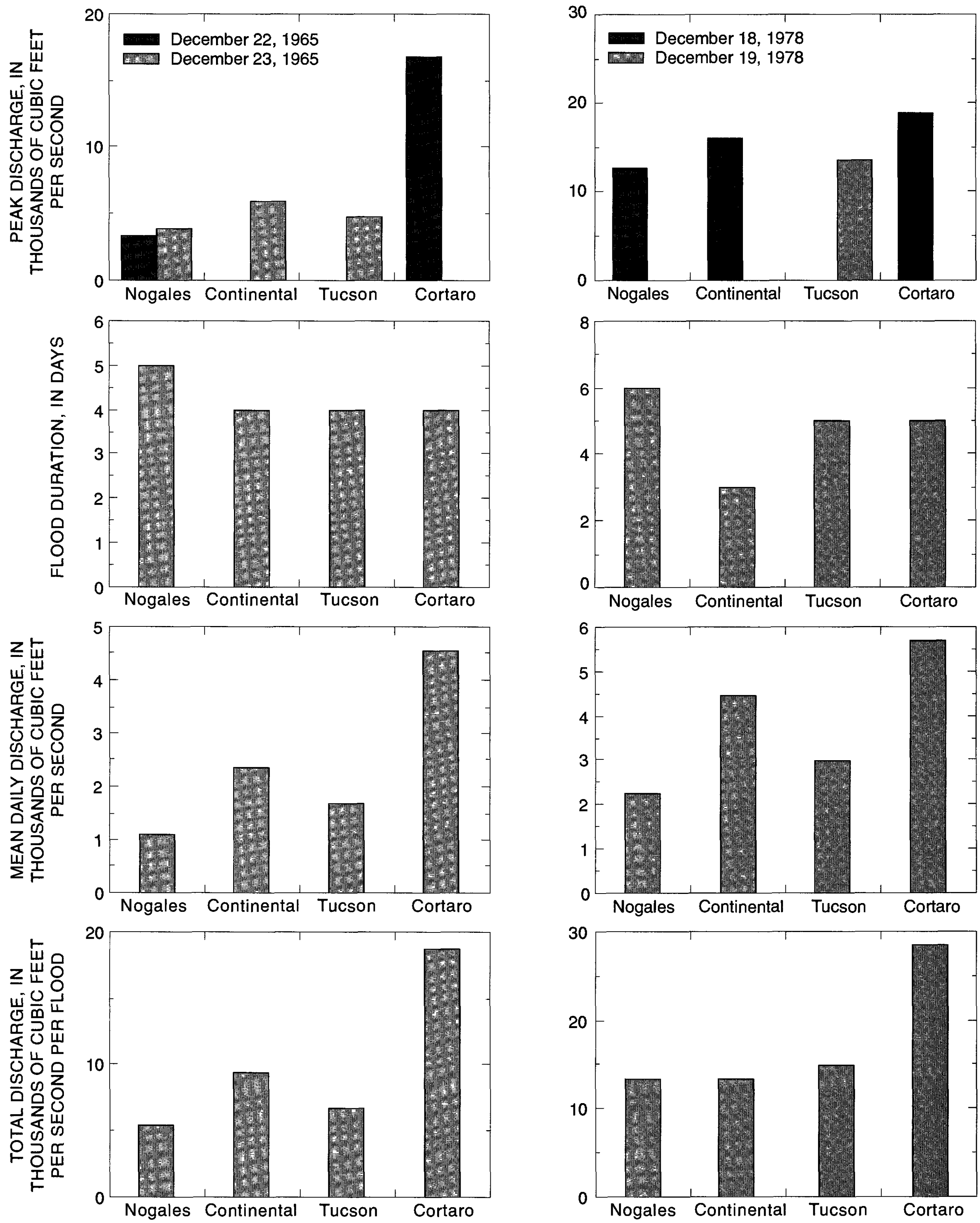


Figure 21. Flow characteristics of floods caused by different storm types at four stations on the Santa Cruz River. (Source: Data from Webb and Betancourt, 1992.) *A*, Floods of August 23, 1961 (no flow recorded at Nogales), and August 1–2, 1978, caused by monsoons. *B*, Floods of December 22–23, 1965, and December 18–19, 1978, caused by frontal storms. *C*, Floods of October 9–10, 1977, and October 2, 1983, caused by tropical storms. In 1983, the Tucson station was not in operation and peak discharge was determined indirectly.

Tucson, where the flood lasted 1 day, than at Nogales where the flood lasted 9 days but produced only twice the total flood volume. The variability among the four stations may reflect precipitation patterns but may be further influenced by different antecedent hydrologic or hydraulic conditions at each site.



B

Figure 21. Continued.

On the basis of the two events examined here, patterns of floods generated by frontal systems seem no less variable than monsoon-caused floods (fig. 21*B*).

During the floods of December 1965 and 1978, peak discharge and flood volume were greater at the Cortaro station than at the Tucson station. The station records

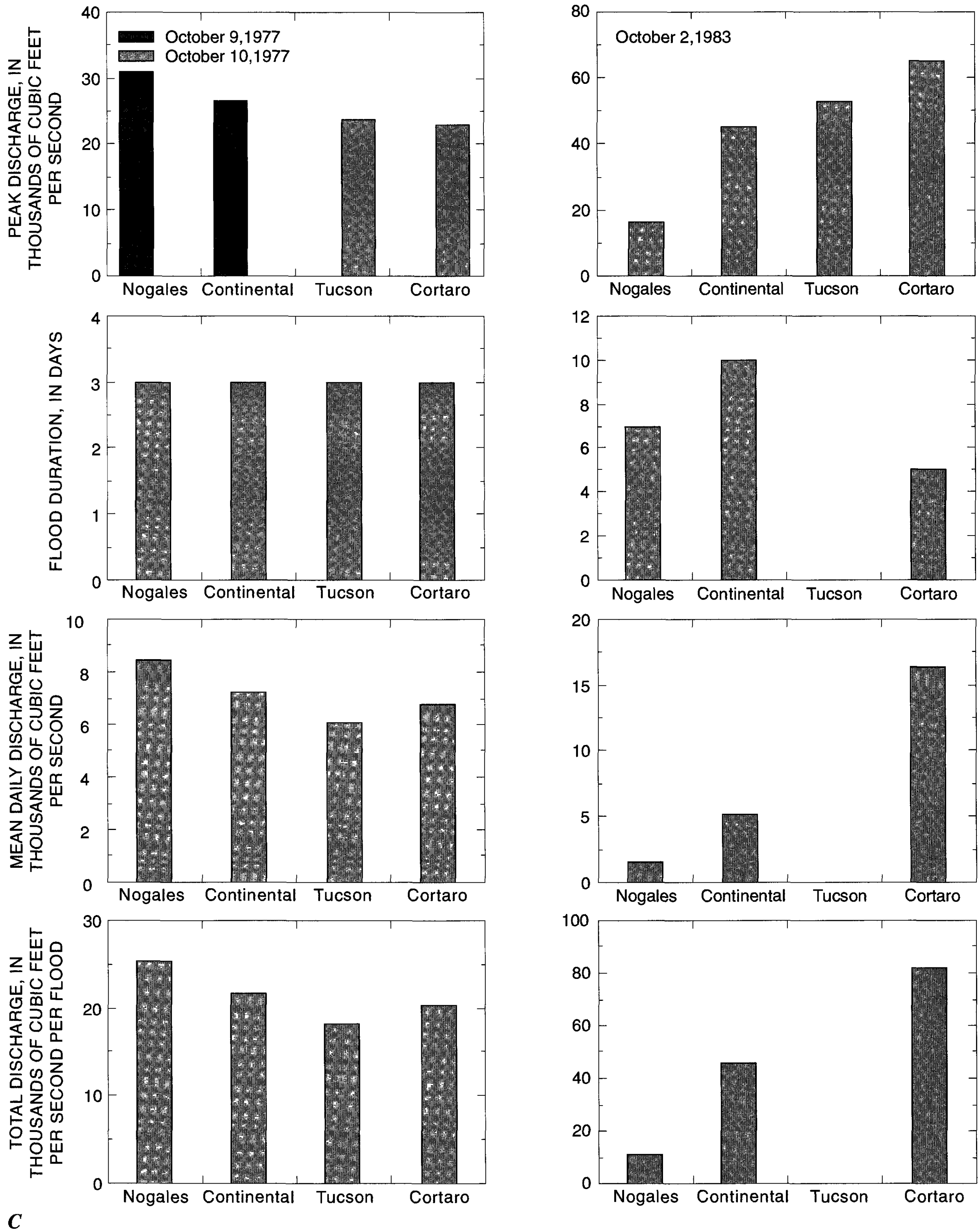


Figure 21. Continued.

reflect orographic intensification of precipitation in the Catalina Mountains, which are drained by tributaries that enter the Santa Cruz River just upstream from Cortaro. The flood of December 1965 also showed a reduction of flood volume between Continental and Tucson, indicating that transmission losses are not restricted to summer floods.

Flood patterns of October 1977 and 1983 resulted from regionally extensive precipitation during dissipating tropical storms that had distinct areas of concentrated precipitation (fig. 21*C*). The remnants of Hurricane Heather that stalled over the upper drainage basin were responsible for the flood of 1977. The flood peak was highest at Nogales (31,000 ft^3/s), and discharge attenuated downstream to 23,000 ft^3/s at Cortaro. The flood of October 1983, caused by dissipating Tropical Storm Octave, produced only about half the peak discharge of the 1977 flood at Nogales but greatly exceeded the flood of 1977 downstream from Continental. At Cortaro, peak discharge was two and a half times greater and total flood volume was four times greater in 1983 than in 1977. At least part of the cause of the large flows at Cortaro was the strong orographic influence of the Catalina Mountains on the tropical storm (Saarinen and others, 1984).

Sediment Concentration and Seasonality of Floods

Suspended-sediment data on the Santa Cruz River are too few to demonstrate a clear difference between summer and winter suspended-sediment concentrations (table 6, fig. 22*A*). A *t*-test of the

Table 6. Suspended-sediment concentrations, Santa Cruz River at Congress Street, Tucson

[Data from Laney (1972) and USGS (this report)]

Date	Discharge, in cubic feet per second	Suspended-sediment concentration, in milligrams per liter
	Summer flows	
08-18-66	1,200	39,000
08-19-66	1,900	44,300
08-19-66	1,700	46,600
08-22-66	160	28,600
08-26-68	59	12,400
07-09-89	495	8,400
08-02-89	199	3,120
08-17-89	517	8,300
08-17-89	1,020	10,400
08-17-89	475	4,650
	Fall flows	
09-13-66	120	18,800
09-15-66	41	15,100
10-03-67	203	21,800
10-05-89	578	4,160
10-05-89	896	6,850
10-05-89	588	5,366
	Winter flows	
12-23-65	4,000	44,500
02-08-66	1,100	30,100
02-11-66	350	20,300
02-11-66	430	20,200

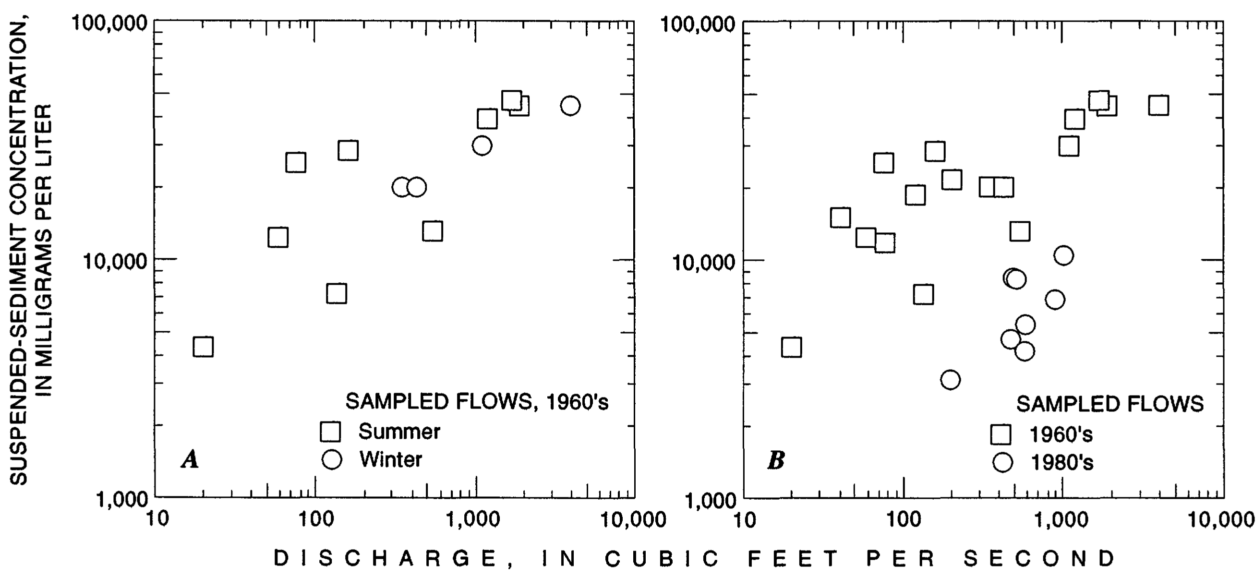


Figure 22. Relation of suspended-sediment concentration to discharge, Santa Cruz River at Tucson.

mean summer and winter concentrations of samples collected in the 1960's (Laney, 1972) did not yield a significant difference. Additional suspended-sediment data were collected in the 1980's during summer and fall floods, but by that time an unexplained significant decrease in suspended-sediment concentration had occurred and the data could not be compared with winter data of the 1960's (fig. 22*B*).

Temporal Variability of Channel Change and Hydroclimatic Factors

If hydroclimatic factors were the main control on the timing and magnitude of channel change on the Santa Cruz River, the history of channel change would be expected to reflect temporal variability in those factors. In particular, periods characterized by generally moderate discharges generated by summer thunderstorms would coincide with periods of little change except where local physical factors were causing extreme bank instability. Periods characterized by higher flood magnitudes caused by winter frontal systems or fall dissipating tropical storms would correspond to periods of generally high channel instability. The chronology of channel change and hydroclimatic variation on the Santa Cruz River (table 5) gives some indication of their linkage, but imprecise resolution of the data on channel change and the effects of nonhydrologic processes on channel instability complicate and obscure the relation.

1915–29

Documentation of channel change between 1915 and 1929 is poor except for historical accounts of bank erosion and arroyo incision during the 1914–15 floods. Channel widening as a result of those floods was apparently extensive through much of the study area (Hays, 1984; Betancourt and Turner, 1988), but no data were located for this study that would indicate channel behavior for the rest of the period. In aerial photographs from 1936, channel widths are greater than at any subsequent time before 1983, evidence that channel morphology at the time was a product of large floods. Whether the 1936 channel was still primarily a product of the 1914–15 floods or of large tropical storms in 1926 and 1929 (table 5) is unknown.

1930–59

Through the 1940's and 1950's, the hydrologic regimen of the Santa Cruz River was characterized by moderate annual floods and lower flood variability caused primarily by summer thunderstorms. Channel widths narrowed throughout the system. Much of the narrowing was artificial, however, making a connection between climatic fluctuation, flow conditions, and a decrease in channel width difficult to establish. Considerable channel instability occurred during this period, including further incision and headcut migration of the arroyo in the upper San Xavier and lower Sahuarita reaches; expansion of arroyo boundaries in the lower San Xavier and upper Tucson reaches (fig. 16); and major shifts in channel position by meander migration and meander cutoff and avulsion in the Cortaro and Marana reaches (fig. 9). Although the channel instability of this period may be the product of the largest floods from 1930–59 (table 5), no data are presented that clearly link channel change to one or more specific floods. In some cases, the primary cause of channel change may not have been hydrologic. In particular, incision and headcut migration of the arroyo may reflect continued adjustment of the Santa Cruz River to the initial period of arroyo formation in the 19th century.

1960–86

The four largest floods of record occurred in the interval 1960–86 (table 5). Two of the floods were caused by dissipating tropical storms and one by a frontal storm. Along most of the Santa Cruz River, however, evidence of a connection between increased channel instability and hydroclimatic changes during this period is slight and equivocal until the floods of 1977 and 1983. Three large floods in the 1960's (fig. 19) may have contributed to the channel incision between Valencia and Grant Roads (fig. 5), but resolution of the data is inadequate to determine the timing of incision closer than 8 to 14 years. Furthermore, the incision may have had less to do with flood occurrence than with landfill operations in the channel (Betancourt and Turner, 1988). An increase in the rate of arroyo widening near Martinez Hill is evident for 1960–67 compared with 1936–59 (fig. 16*A*), but the shorter time interval between data points may account for the apparent increase.

The flood of 1977, which was the flood of record when it occurred, caused significant channel widening along parts of the Canoa reach (fig. 13*A*) and large amounts of arroyo widening along parts of San Xavier reach (fig. 14). The magnitude of channel change from the flood of 1977 was greatly exceeded by that of the flood of 1983. The 1983 flood caused the single largest episode of channel change on the Santa Cruz River since at least 1915 and possibly since the 19th century. Throughout much of the Santa Cruz River, the terraces, point bars, channel bars, and flood-plain surfaces adjacent to the channel were stripped of vegetation. Channel changes included extreme magnitudes of channel widening in the Canoa reach, even along protected sections of channel. About 800 ft of arroyo-wall retreat occurred in the San Xavier reach. Lesser amounts of arroyo widening occurred in the Sahuarita, Tucson, and upper Cortaro reaches. Major channel widening and extensive shifts in channel position occurred in the Cortaro and Marana reaches. The floods of 1977 and 1983 were caused by tropical storms. Most flows caused by such storms on the Santa Cruz River are not of particularly great magnitude. Nonetheless, the most extreme floods—those capable of producing the most widespread channel change on the Santa Cruz River—have been the product of tropical storms. Consequently, episodes of catastrophic channel change on the Santa Cruz River can be linked to periods of global climatic conditions that increase the likelihood of tropical storm occurrence in southern Arizona.

Temporal Changes in Resistance to Erosion

Although large floods have been major factors in determining the timing of lateral channel change on the Santa Cruz River, variables other than floods also influence temporal patterns of change. Artificial bank armoring has increased resistance to erosion through much of the study area, so that discharges that would have previously caused significant arroyo or channel widening at many locations no longer do so. Some reaches have also undergone changes in vegetation density along banks and flood plains.

The effects of artificial armoring or vegetation are such that little or no channel change can occur until boundary shear stress exceeds some threshold. Once that threshold is exceeded, armoring layers are eroded and change may be catastrophic because underlying erodible banks and flood plains are suddenly unprotected and abruptly subjected to extreme boundary shear stresses.

On the upper Canoa reach, for example, where banks have been armored since at least the 1950's, little or no channel widening appears to have occurred before 1976 in response to floods with a peak discharge of as much as 18,000 ft^3/s (fig. 13*A*). The flood of 1977, which had a peak discharge through the reach of 26,500 ft^3/s, produced a 0- to 100-percent increase in channel width through armored sections of the reach. The flood of 1983 (peak discharge of 45,000 ft^3/s), however, caused almost total failure of the bank revetment, especially upstream from the unchannelized part of the reach (fig. 13*A*, 1978–86), resulting in width increases of more than 500 percent.

Changes in vegetation density over time can have a similar effect as armoring. Before 1966, flow in the Cortaro and Marana reaches was ephemeral and the banks and flood plain were sparsely vegetated. The channel in the two reaches was considerably less stable before 1966 than between 1966 and 1978, even though the latter interval included annual floods 35 and 11 percent larger than the pre-1966 flood of record. Increased vegetation on the flood plain prevented any significant incision of new channels that would have caused avulsion and meander cutoff despite the occurrence of record flows after 1966. The flood of October 1983, however, was of sufficient magnitude and possibly duration (fig. 21*C*) to strip away vegetated surfaces and then cause widespread incision of new channels on the exposed flood plain.

Geologic and Topographic Controls on Channel Morphology and Change

Channel morphology and the spatial variability of channel change on the Santa Cruz River are determined largely by geologic and topographic controls. Major geologic controls include the location and type of sediment sources and the location of outcrops of bedrock or consolidated sediments relative to the channel. Topographic controls include large-scale features and small-scale features. The large-scale features include spatial distribution of landforms, geometry of intramontane basins, valley slope, and proximity of tributary confluences. The small-scale features include paleochannels, ridges, and swales on flood plains. Geologic and topographic controls generally are not independent of each other. The spatial distribution of landforms can be a function of sediment source as in the case of alluvial-fan development, which is dependent upon the lithology, climate, and tectonic activity of adjacent mountain ranges. The distribution of alluvial fans then becomes a control on availability of sediment for delivery to the

Santa Cruz River. In this section, major geologic and topographic controls are described with a discussion on how the controls operate together to affect morphology and channel change on the Santa Cruz River. Small-scale topographic controls, which are less closely linked to geologic controls, are discussed briefly at the end of this section.

Sediment Sources

The type of sediment available for transport and its proximity to the channel affect the size of bed material. The relation of bed material to bank material affects channel morphology. Where bed material is difficult to transport and banks are easy to erode, channel widening can be expected; where bed material is easy to transport and banks are resistant, incision can be expected to be the main channel-changing process (Brotherton, 1979; Osterkamp, 1980).

A systematic survey of sediment sources was not done during this study, but field observations and a review of geologic maps of the Santa Cruz River drainage basin (fig. 23) indicate that coarse-grained sediment sources of varying significance include (1) upland tributaries draining bedrock mountain ranges such as the Santa Rita and Santa Catalina Mountains; (2) conglomeratic rock formations of Cenozoic age incised by the Santa Cruz River or its tributaries from the Sahuarita reach upstream to the headwaters and along the base of mountains ringing the city of Tucson; (3) gravel beds within terraces of late Pleistocene or Holocene age throughout the study area; and (4) gravel stored in active channel sediments that is subject to reworking on a time scale of several years to several decades. Sand and finer grained sediment sources include (1) drainage basin slopes and valley floors subject to overland flow; (2) flood plains or terraces entrenched by gullies and tributaries such as along much of the San Xavier reach; (3) channel banks and arroyo walls; and (4) active channel sediments.

Channel-bed material was not sampled in this study to determine downstream trends in particle-size distribution. Data on Santa Cruz River bed material collected by Meyer (1989) are too few to draw definite conclusions about the spatial relations between bed material and sediment sources, but the data indicate a possible decrease in particle size downstream from major source areas. Bed material was much finer grained on the lower San Xavier reach than on the upper Canoa reach, which is closer to coarse-grained sediment sources such as the Santa Rita Mountains and the gravel-bearing sediments of Cenozoic age that flank the upper Santa Cruz River. The coarsest grained bed material sampled by Meyer (1989) was on the upper Cortaro reach downstream from Cañada del Oro and Rillito Creek, which receives sediments from tributaries that drain the Santa Catalina Mountains and are deeply incised into coarse-grained alluvial fans and basin fill of early Pleistocene to Miocene age at the base of the mountains (Davidson, 1973; Anderson, 1987). At the end of the Marana reach near the Pima–Pinal County line, bed material was much finer grained than at the Cortaro reach sampling site.

Location of Consolidated Sediments and Bedrock

Most channel banks on the Santa Cruz River are composed of active sediments. Arroyo walls are composed mainly of fine-grained materials of late Holocene age (Waters, 1988) that are poorly cemented and fail readily when undercut by streamflow. In some places, however, the channel impinges on or is incised into older, well-indurated alluvium that resists undercutting. Where the channel is confined on both sides by such alluvium, a high degree of lateral stability has been observed.

Along most of the Sahuarita reach, the channel is incised into alluvium that, based on its red color and strong cementation, is evidently considerably older than the material that forms most arroyo walls and streambanks within the study area. Immediately downstream from Pima Mine Road on the Sahuarita reach, the arroyo of the Santa Cruz River cut off the former meandering, unincised channel shortly after 1936 (fig. 4) and migrated upstream by headcutting into the older, indurated alluvium. The rate of arroyo widening just below Pima Mine Road since entrenchment of the channel has been less than can be measured from aerial photographs. Farther upstream, the arroyo is entrenched various depths into the older alluvium. Consequently, much of the Sahuarita reach has exhibited lower rates of arroyo widening and less migration of channel position than other incised reaches of the Santa Cruz River. Because of the resistance of the older alluvium to erosion, the arroyo through the Sahuarita reach has not undergone the large increases in cross-sectional area that has occurred in other reaches during large floods. Consequently, conveyance is lower through the reach and flows have overtopped the arroyo during large floods.

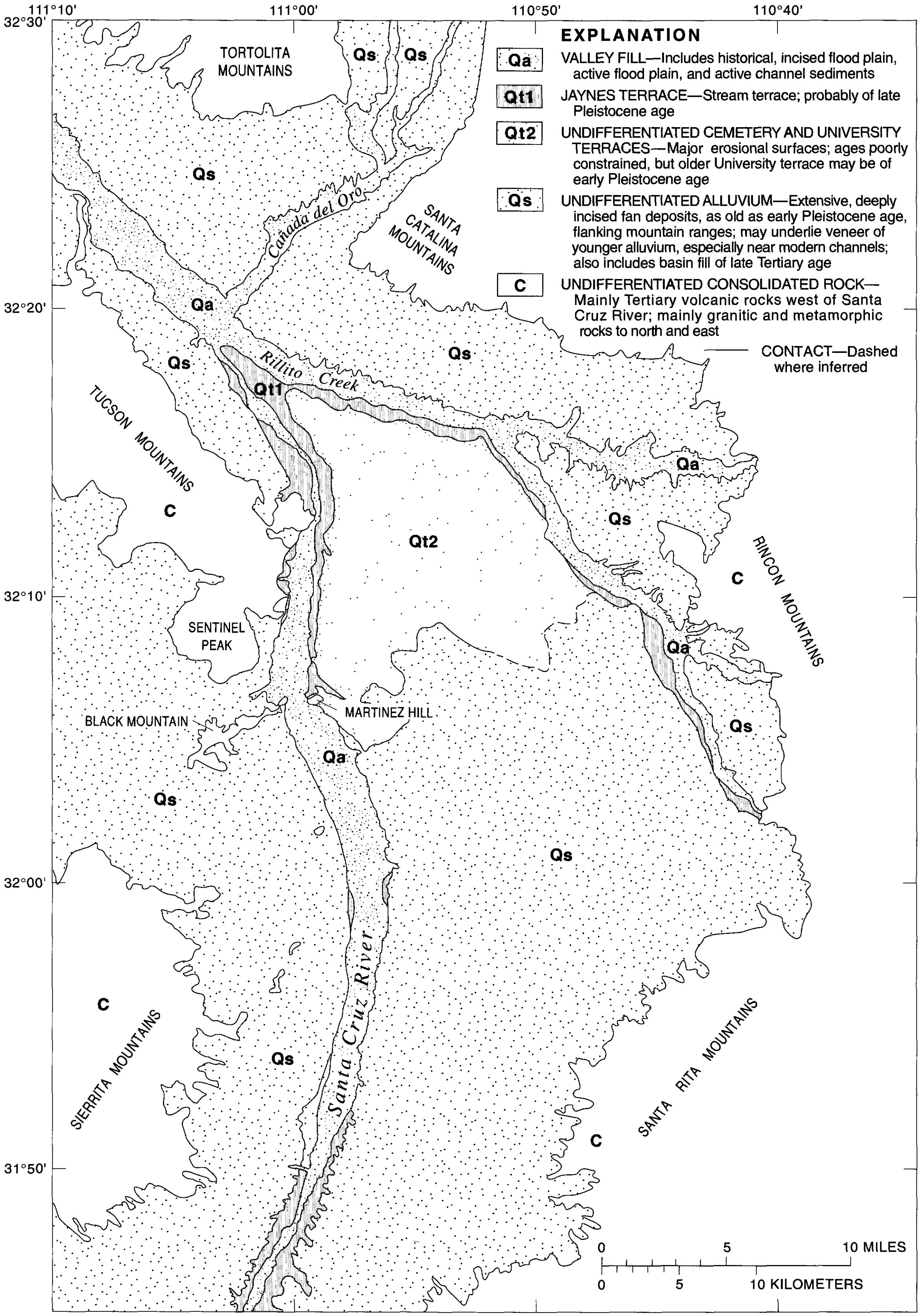


Figure 23. Geomorphology and surficial geology of the Tucson basin. (Source: Modified from Davidson, 1973; McKittrick, 1988; Jackson, 1989.)

During the 1983 flood and during floods in the winter of 1993, overbank flow moved as shallow sheetflow across the terrace on the east side of the river and reentered the main channel through Lee Moore Wash and smaller tributaries in the San Xavier reach.

Few bedrock exposures are found within the channel of the Santa Cruz River in Pima County. Where such exposures occur, the effects on channel change have not been uniform nor are the mechanisms apparent by which the exposures affect channel change. Martinez Hill (fig. 23), which is part of a basaltic dike that is continuous with Black Mountain to the west (Brown, 1939; Davidson, 1973), clearly affects the stability of the Santa Cruz River as indicated by the extreme rates of arroyo widening immediately upstream and downstream from the hill and the rapid downstream attenuation of lateral instability (fig. 14). The abrupt increase in bank resistance by the bedrock exposure probably results in perturbation and deflection of flow against arroyo walls. A similar though less pronounced zone of arroyo widening occurred downstream from Sentinel Peak in the upper Tucson reach between 1953 and 1960. Whether widening in that reach was predominantly natural or artificial is not known. The only other bedrock exposure along the Santa Cruz River within the study area is at the north end of the Tucson Mountains immediately downstream from Avra Valley Road in the lower Cortaro reach. In contrast to the other bedrock locations on the Santa Cruz River, the channel above and below Avra Valley Road generally has been stable.

Large-Scale Topographic Controls

The geometry of the intramontane basins through which the Santa Cruz River flows and the spatial distribution of landforms within those basins strongly influence channel morphology and the nature of channel-changing processes occurring in a reach. Other large-scale topographic controls, such as valley slope and the proximity of tributary junctions, seem to be of secondary importance and are not discussed further here. This discussion is concerned largely with the effects of large-scale topographic features on the Santa Cruz River under natural conditions. Although human alteration of the channel and drainage basin has not eliminated topographic controls and their effects on channel processes, they have undoubtedly altered the relative importance of those controls.

Along the Canoa and most of the Sahuarita reaches, the valley of the Santa Cruz River reaches one of its narrowest points within the study area. The valley is confined between the Santa Rita and Sierrita Mountains and the highly dissected alluvial fans that slope from the base of the mountains to the edge of the low terraces and flood plain flanking the channel (fig. 23). Although the alluvial fans generally are inactive as depositional systems, erosion of the fans by incised channels probably makes them a significant sediment source. As the Santa Cruz River enters the San Xavier reach, the intramontane basin widens greatly; the river valley is less narrowly confined and is more than four times wider than it is along the Canoa reach. The space available for sediment storage is considerably greater on the San Xavier reach than on the confined upper reaches.

Under natural conditions, the Canoa and Sahuarita reaches probably are areas of frequent sediment removal. Because the reaches are close to major sediment sources, sediment delivery rates to the channel also are probably high, resulting in considerable lateral instability. Some indication of past lateral instability is seen in 1936 aerial photographs where meander scars are visible, indicating a previous episode of meander cutoff and subsequent reformation of meanders. The San Xavier reach is farther from upland sediment sources, and thus sediment delivery is less frequent and the sediment delivered is finer grained than in the Sahuarita and Canoa reaches. The lower rates of sediment delivery coupled with the greater volume of sediment storage space available indicate that the reach is an area of long-term sediment storage. Geologic evidence indicates that for the past several thousand years at least, the San Xavier reach generally has been a depositional reach (Haynes and Huckell, 1986; Waters, 1988). Sediment is episodically removed from the reach during periods of channel entrenchment and arroyo widening. Generally, the volume of sediment removed from the reach during periods of incision has been small relative to the volume in storage. A hiatus in sedimentation from 8,000 to 5,000 years ago through the San Xavier reach and on a number of other drainage basins throughout the Southwest has been interpreted as a period of widespread erosion and destruction of flood plains as a result of major climatic change (Haynes, 1968).

As the Santa Cruz River enters the Tucson reach, the valley once again narrows. The channel and valley are confined between the Tucson Mountains and associated fan deposits on the west and a series of terraces on the east, which from youngest to oldest include the Jaynes, Cemetery, and University terraces (fig. 23; Smith, 1938). The arid, low-elevation Tucson Mountains do not represent a significant sediment source. Of the terraces, only the Jaynes, which in some places forms the arroyo walls within the Tucson reach, represents a possible locally significant sediment source. The most extensive surface in the middle Tucson basin—the planated, calichified University terrace on which much of the city of Tucson is built—is not likely to be a major contributor of sediment to the Santa Cruz River. Rillito Creek and its major tributaries cut off the Tucson reach from sediment sources to the north and east. Because of its confinement by generally erosion-resistant older alluvium and bedrock, most of the Tucson reach has little space available for sediment storage. Sediment resident times probably have been quite variable. Because of its isolation from sediment sources, long-term sedimentation rates probably are low and sediment resident times high. During periods of incision of upstream flood plains, sedimentation rates within the Tucson reach increase and sediment resident times are low because of the limited storage capacity. Episodic entrenchment of the channel and arroyo widening, as in the San Xavier reach, probably have been the main processes removing sediment from the reach.

Downstream from the confluence of Rillito Creek and Cañada del Oro on the Cortaro reach, the valley of the Santa Cruz River widens considerably, but channel morphology and channel-changing processes are much different from those on the San Xavier reach. Along much of the Cortaro reach, the modern flood plain is incised about 6 ft into the historical flood plain (Katzer and Schuster, 1984), indicating that the reach is also subject to episodic channel entrenchment. Sedimentation rates are high, however, and sediment is more coarse grained because of the proximity of the reach to sources such as the incised alluvial fans at the base of the Tortolita and Santa Catalina Mountains (fig. 23). Consequently, entrenchment was not as deep as in the upstream reaches and the channel generally has been aggradational or stable in elevation. Lateral channel-changing processes—meander migration and cutoff—are dominant because of the high sedimentation rates. Periods of lateral channel instability may reflect episodes of high sediment input, either from large floods or from sustained periods of channel incision upstream from the reach.

As the Santa Cruz River continues past the Tucson Mountains, its valley becomes completely unconfined and gives way to a broad, indistinct alluvial plain—the Santa Cruz Flats—at the end of the Marana reach near the Pinal County line (fig. 1). The main topographic control is the Picacho basin, an area of little topographic relief that has undergone substantial subsidence from ground-water withdrawals in this century and possibly earlier from natural causes (Laney and others, 1978; Carpenter, 1993). The Picacho basin serves as a local base level for the upper Santa Cruz River and, consequently, is also a trap for most of the sediment that is transported beyond the Marana reach. The Santa Cruz Flats evidently represent an area of long-term sediment storage. No evidence has been reported of prehistoric periods of channel entrenchment and sediment removal as in upstream reaches, although a modern arroyo that began as a headcut from Greene's Canal early in this century intersects the Santa Cruz River about 7.5 mi below the Pinal County line.

Small-Scale Topographic Controls

Small-scale topographic features created by the Santa Cruz River such as terraces, meander scars, paleochannels, gravel bars—evidence of past behavior of the channel—also can control the lateral extent of future changes. The many shifts of channel position on the Cortaro and Marana reaches from 1936 to 1986 were all within the flood plain that is confined by the lowest terrace adjacent to the high-flow channel. On the Marana reach, the shift in channel position between 1978 and 1986, almost entirely a result of the 1983 flood, appears as virtually a mirror image of channel-position shifts between 1936 and 1978 (fig. 9*B*). Such a pattern indicates that the flood caused the river to reactivate paleochannels (as suggested in fig. 7*B*); the river's new course was controlled largely by preexisting topography.

CHANNEL CHANGE AND FLOOD-PLAIN MANAGEMENT

Government agencies and private landowners manage laterally unstable channels with structural works, especially bank armoring. Structural approaches, however, are expensive and often have undesirable consequences, such as degradation in response to channelization (Schumm and others, 1984; Rhoads, 1990) and increased erosion of unprotected banks adjacent to protected banks (Baker, 1984b; Saarinen and others, 1984). An early objective of this project was to model lateral erosion along the Santa Cruz River channel. Prediction of the frequency and magnitude of bank erosion at a location would give flood-plain managers the information to determine costs and benefits of bank protection.

Modeling Channel Change

Most models of sediment transport and scour are based on one-dimensional equilibrium hydraulics (Fan, 1988), which may not be appropriate for modeling highly unsteady flow that occurs in ephemeral rivers. Most models, such as HEC–6 (U.S. Army Corps of Engineers, 1977), can predict scour but cannot predict lateral channel change. All models require substantial sediment-transport and channel-change data for verification, and such data are scarce for ephemeral rivers. GFLUVIAL (Chang, 1990), the most recent version of FLUVIAL–12 (Chang, 1988), uses an equilibrium energy approach to predict scour and channel widening. The algorithm for widening is based on a bank-stability factor and not on physical processes. The model also can be used to predict meander migration only if the rate of bank retreat is known in advance (Chang, 1990). Models such as GFLUVIAL are useful design tools, but they cannot independently predict processes such as avulsion and meander cutoff or meander migration.

Although many models have been developed for sediment transport in meandering rivers (Ikeda and Parker, 1989), most models predict sediment transport, bedforms, and changes in sand bars without erosion of the channel banks. These models (Nelson, 1988; Nelson and Smith, 1989) couple multidimensional flow with sediment-transport models and generally are used to predict changes in point bars or other midchannel or lateral bars (Andrews and Nelson, 1989). Application of these models to channel change in ephemeral rivers would require quantification of bank-erosion processes such as corrasion and mass wasting.

Graf (1984) recognized the complexity of relations among geomorphic and hydraulic variables governing channel instability and presented a probabilistic approach to evaluating spatial variability in channel instability. The method is not applicable for evaluating arroyo widening such as that on the San Xavier reach. On the Cortaro and Marana reaches, lateral instability is predominantly characterized by shifts in channel position; however, Graf's (1984) approach is of doubtful applicability on those reaches as well. Use of a probabilistic method for predicting channel change requires that the physical properties of the system remain essentially unchanged over time. On the lower reaches of the Santa Cruz River, however, changes in hydrologic regimen, vegetation growth, and aggradation of the flood plain have greatly altered the physical conditions, and as noted previously, the system's response to given levels of discharge appears to have changed since 1970.

Channel-Changing Processes and Associated Hazards

Although the ability to predict lateral channel change is limited, a review of the processes operating on the Santa Cruz River, the conditions associated with channel change, and the history of such change does permit an assessment of the degree of hazard associated with channel change. The channel-changing processes operating on a particular reach (table 3) control the nature of the hazard associated with channel change. Topographic and geologic controls and human alteration of a channel govern the spatial variation in channel stability of a reach and modify the effects of a given flow on channel morphology. The timing and magnitude of channel change are controlled largely by the magnitude of flow and by the nature of the storms that generate the flow.

Meander Migration

Meander migration is dominant only on the Cortaro and Marana reaches and in low-flow channels throughout the Santa Cruz River system. The main hazard associated with meander migration is loss of property that is on or immediately adjacent to the flood plain. Meander migration generally increases sinuosity, and some studies have indicated that channels tend to maintain stable values of sinuosity (Graf, 1983a; Guber, 1988). Consequently, channels that have been straightened by floods or have been channelized can undergo rapid rates of migration by meander formation (Lewin, 1976; Schumm and others, 1984). Along the Santa Cruz River, the banks of channelized reaches generally are well armored with soil cement, and therefore meandering processes have not eroded the banks and thus have not affected the morphology of the artificial channel. Although low-flow channels have not been extensively examined in this study, migration of such channels is a concern because the migration can change the direction of flow and the distribution of shear stresses at bridges and other structures (Sabol and others, 1989).

Avulsion and Meander Cutoff

Avulsion and meander cutoff present a direct erosion hazard mainly on the Cortaro and Marana reaches, although any part of the river subject to overbank flow has the potential for such change. Avulsion and meander cutoff threaten mainly structures and property on the flood plain; however, when a channel abruptly shifts position hundreds of feet, areas adjacent to the flood plain that had previously been well removed from potential bank erosion can become subject to erosion by meander migration. In the lower Marana reach near the Pinal County line, the potential may exist for avulsion of the Santa Cruz River out of the present-day flood plain. Although this reach was not surveyed, the flood plain, which is confined between levees near the county line, is as much as 5 to 10 ft above the alluvial plain that lies outside the levee. During the 1983 flood, overbank flow spilled onto the lower surface at several locations (fig. 24). A detailed field survey, in addition to flood-frequency and sediment-transport data, is necessary to determine whether a major channel shift from prolonged overbank flow and in-channel deposition is a realistic possibility within the next several decades.

Knowledge of the potential for avulsion or meander cutoff on a reach is important where channel modifications are being considered. If modifications on such a reach do not include steps to prevent channel shifts, the engineered channel may be abandoned during subsequent overbank flows.

Channel Widening

The widening of channels on flood plains occurs mainly on the Canoa, Cortaro, and Marana reaches. Destruction of property and structures, particularly bridges, on the flood plain is a hazard associated with channel widening. Channel widening is associated with high flows, although the effects of a given discharge will vary with resistance to erosion within a reach. Channels in reaches that have high resistance because of vegetation or artificial protection may widen only during the most extreme floods. Such channels are of concern to flood-plain managers because they can be stable over a wide range of discharges and then undergo catastrophic widening when a threshold of resistance to erosion is passed, such as on the Canoa reach during the 1983 flood.

Arroyo Widening

Failure of arroyo walls poses a threat to property beyond the flood plain, as seen during the flood of 1983 when homes and office buildings were swept away (Saarinen and others, 1984; Slezak-Pearthree and Baker, 1987; Kresan, 1988). Along the lower San Xavier reach, houses were destroyed that were within the designated 500-year-flood boundary (Saarinen and others, 1984).

The degree of hazard associated with arroyo widening is not simply a function of flood magnitude. Considerable arroyo widening occurred on parts of the San Xavier reach from 1936 to 1960 (fig. 14*A*), which was a period dominated by low to moderate annual floods. Slope-stability factors, as well as channel processes, must be considered in assessing the potential for arroyo widening. The stability of arroyo walls depends primarily on the cohesiveness of the alluvium and the height of arroyo walls. Those reaches of the Santa Cruz River with 20- to 30-ft arroyo walls composed of weakly cohesive fine-grained sand and silt are persistently unstable, particularly where associated with a meandering, entrenched channel. The highly unstable alluvium generally underlies the historical flood plain. Outside the San Xavier Indian Reservation, most such arroyo walls are artificially protected, especially since the flood of 1983. Although arroyo instability appears to be primarily a function of bank material, the rate of widening along an unstable arroyo is governed mainly by channel processes, in particular the magnitude of the peak flow, the frequency of high flows, and the duration of flow.

Arroyo widening presents some of the most difficult problems in the management of unstable channels because of the persistence of widening in unstable reaches and because of the magnitude of widening that can occur during a single high flow. Along much of the Santa Cruz River arroyo, however, little widening has occurred during the study period, which suggests that expensive bank-protection measures are not always warranted. Where the river

Figure 24. Floodwaters breaking through levees (indicated by arrows) on the lower Marana reach during the flood of October 1983. (Aerial photograph by Cooper Aerial Survey, 1983.)

is incised into more resistant, generally older alluvium, such as along the lower Sahuarita reach, arroyo widening has been slow during the study period. If geologic controls are the dominant influence on the stability of some arroyo reaches, such reaches may continue to be stable well into the future. Other factors, however, such as the stage of development of the arroyo, also could be significant, in which case future destabilization of the reaches would be possible. A detailed geomorphic analysis is necessary before the importance of different controls on the long-term stability of historically stable arroyo reaches can be assessed.

EFFECTS OF ARTIFICIAL CHANGES ON CHANNEL PROCESSES

Since the late 19th century, human modification of the Santa Cruz River has affected the hydraulic properties of the channel and influenced subsequent channel morphology. During the study period, channel modifications have included (1) channelization, (2) artificial narrowing, (3) bank protection, (4) discharge of sewage effluent into downstream reaches, (5) sand-and-gravel operations within the flood plain, and (6) channel-maintenance operations. The first four modifications may have had the greatest effect on channel morphology. The effects of discharge of sewage effluent are discussed in the section entitled "Temporal Changes in Resistance to Erosion" and are not discussed here.

Channelization typically shortens stream length and increases gradient and stream power (Schumm and others, 1984). Bank protection prevents an alluvial channel from adjusting its dimensions laterally in response to increased discharge; the increased resistance creates conditions analogous to bedrock channels where extreme magnitudes of stream power may be generated (Baker, 1984a). Bank protection also can remove a major sediment source by preventing bank erosion, thus lowering sediment concentration at a given discharge (Knighton, 1984). Sediment concentrations in samples collected at the Congress Street bridge in the 1980's typically are lower than those collected at similar discharges 20 years earlier (fig. 22*B*, table 6). Additional study is necessary to determine whether bank protection, which was emplaced along much of the reach upstream from Congress Street between the two sampling periods, is the cause of lower sediment concentrations. Lower sediment concentrations may enhance the erosiveness of streamflows. The initial expected effects of channelization and artificial bank protection include degradation within and upstream from the altered reach, aggradation downstream from the altered reach, and increased bank erosion at unprotected sites (Schumm and others, 1984; Simon and Robbins, 1987; Rhoads, 1990). Continued degradation can initiate a period of channel widening by producing oversteepened banks in unprotected reaches that fail readily (Simon and Hupp, 1986; Simon, 1989). Continued aggradation can result in plugging of downstream channels and a shifting of channel position by avulsion (Coleman, 1969; Graf, 1981). Emplacement of artificial fill along channel margins narrows the channel, thus reducing capacity, and can armor the banks against erosion, producing the same effects as channelization and bank protection. If resistant fill, such as highway-construction debris, is emplaced primarily on the channel bottom, increased resistance to incision can cause increased erosion of unprotected channel banks.

On the Santa Cruz River, the timing of degradation on the Tucson and lower San Xavier reaches corresponds to a period of increased landfill operations south of Tucson (Betancourt and Turner, 1988). On the Canoa reach, incision of the channel had occurred by the 1950's and was probably a result of extensive channelization and bank-protection works that were in place by 1953. On the Sahuarita reach, degradation that occurred after 1936 as a result of headward extension of the arroyo may have been caused by continued disequilibrium associated with the earlier arroyo initiation rather than by human activity.

Enhanced erosion on the Santa Cruz River during the 1983 flood resulting from partial bank protection has been described by Baker (1984b) and Saarinen and others (1984). In 1990, following large summer flows, channel changes were observed in the lower San Xavier reach at Ajo Way where arroyo walls had been newly armored. The arroyo bottom was incised as much as 2 ft within the armored reach upstream from Ajo Way, and fresh failures of the unprotected walls occurred downstream from the bridge.

CONSIDERATIONS FOR FURTHER STUDY

The methods used in this study have identified mechanisms of channel change on the Santa Cruz

River, timing and magnitude of channel change with respect to floods, and physical conditions associated with channel instability. A relation exists between hydrologic regimen and the rate and magnitude of channel change. That relation is highly modified by resisting forces and by hydraulic conditions such as channel morphology. Resisting forces are not constant and can vary considerably over time scales of decades or less.

Further analysis of the historical data base would increase understanding of the operation of the Santa Cruz River as a system but probably would not produce the quantitative information necessary to predict channel change in response to floods.

Additional research needs that have been identified as a result of this study include analysis and evaluation of the following factors: (1) the nature of bank materials, particularly their cohesive properties and how such properties are affected by changing moisture levels and flow conditions; (2) mechanical processes, such as cracking and piping, that lower the structural integrity of channel banks; (3) the nature of the streambed, including bed-material composition, depth of active bed layer, and resistance of bank materials relative to streambed materials; (4) the interactions between streamflow and soil-hydrologic processes in channel banks; (5) downstream variability in flow conditions, including attenuation of flood peaks, increases or decreases in total discharge, changes in sediment concentration, and the relation of such variation to different flood types; (6) the formation of armored channel and point bars in rapidly varying flow; and (7) a more precise and quantitative time series of channel change than is presently available, developed from repeated postflood field measurements of physical and hydraulic properties (particularly channel geometry, bedforms, and bed material).

SUMMARY AND CONCLUSIONS

The Santa Cruz River has a long history of channel instability that has resulted in extensive property damage since the late 19th century, particularly in Pima County. An analysis of channel change on the Santa Cruz River from 1936 to 1986 using aerial photographs and historical and field data demonstrated that the timing, magnitude, and nature of channel change vary considerably over space and time.

The Santa Cruz River exhibits great physical variation through the 70-mi study area. In this study, six reaches from upstream to downstream—Canoa, Sahuarita, San Xavier, Tucson, Cortaro, and Marana—were defined on the basis of morphology, historical stability, and dominant channel-changing processes.

From 1936 to 1986, channel change was characterized by an increase in width and a decrease in river length throughout most of the study area. Much of the channel straightening was artificial, especially on the Canoa and Sahuarita reaches. The increase in mean width of the Santa Cruz River would have been considerably greater without bank armoring. Most channel widening was caused by the record floods of 1977 and 1983; arroyo widening occurred throughout the study period. The deeply entrenched San Xavier reach was the most persistently unstable reach, where mean and maximum arroyo width more than doubled through the study period. Most channel change in the Cortaro and Marana reaches involved lateral shifts in channel position, and mean width decreased during the entire study period. Both reaches also underwent a change in channel form and in resistance to erosion as a result of an increase in vegetation density caused by sewage-effluent discharge into the river.

Lateral channel change occurs by three basic mechanisms: meander migration, avulsion and meander cutoff, and channel widening. The dominant mechanism within a reach at any one time depends on channel morphology and flood magnitude.

Meander migration is the spatially continuous movement of the channel across its flood plain by initiation of meanders and their subsequent lateral extension, downstream translation, and rotation of meander axis. Meander migration tends to be the dominant mechanism of change during periods of low to moderate discharge. High rates of meander migration can occur during the waning stages of large floods. Meander migration is often an important component of channel and arroyo widening.

Avulsion and meander cutoff produce large, abrupt shifts in channel position when overbank flow incises a new channel course into the flood plain. Meander migration and avulsion and meander cutoff have been the main mechanisms of lateral channel change on the Cortaro and Marana reaches. Both processes contributed to considerable lateral instability between 1936 and 1966. A period of channel stability in the 1970's on those reaches was interrupted by the 1983 flood, which was the single most extensive episode of avulsion and meander cutoff on the Santa Cruz River during the study period. Almost 23,000 ft of channel was abandoned in the Cortaro and Marana reaches when lateral channel shifts of as much as 2,000 ft occurred.

Channel widening results primarily from high flows that erode cohesionless banks. The highest rates of channel widening on the Santa Cruz River occurred on the upper Canoa reach during the floods of 1977 and especially 1983. Channel widening also resulted from high flows on other reaches. During intervening periods of low to moderate flows, channels generally narrowed because of vegetation growth and sediment deposition on channel margins.

Vertical channel change on the Santa Cruz River has been primarily degradational since the 1950's, especially from the San Xavier Indian Reservation through the city of Tucson. In the middle of the Tucson reach, 10 to 15 ft of degradation occurred from the mid-1950's to the early 1970's. Data are sparse elsewhere. Streambed elevations may have been stable between the 1950's and 1976 in the lower Santa Cruz River, but a more complete record at one site suggests that the interval was a period of fluctuating bed elevations. On the upper Santa Cruz River, about 24 ft of incision occurred at Pima Mine Road between 1936 and 1976. Lesser amounts of degradation in that period occurred above Pima Mine Road to the upstream end of the study area.

Vertical and lateral channel-change mechanisms operate in concert with bank-retreat mechanisms to produce widening of arroyos on entrenched reaches, which include much of the Sahuarita and Tucson reaches and all of the San Xavier reach. The most persistent arroyo widening has occurred where the channel is deeply incised into poorly resistant silt and sand. The most rapid rates of arroyo widening have occurred in connection with the migration of confined meanders. Unlike channel widening, arroyo widening is not readily reversed. Although the most unstable reaches of the Santa Cruz River have been on the most deeply incised parts of the San Xavier reach, a quantitative relation is difficult to establish between channel incision and arroyo-wall retreat. On parts of the lower San Xavier and upper Tucson reaches, periods of maximum arroyo widening precede or coincide with periods of degradation, contrary to some models of channel change in entrenched systems.

Hydrologic and climatic factors—magnitude, duration, intensity, and frequency of precipitation and floods—generally control the timing and magnitude of channel change on the Santa Cruz River at a particular location. Time-related changes in hydraulic factors—changes in channel geometry caused by successive floods or changes in roughness caused by vegetation growth—also contribute to temporal variability of channel change. Spatial variability of channel change on the Santa Cruz River—the location of channel change and its magnitude in response to a given discharge—is controlled largely by topographic, geologic, and artificial factors. These factors, which include sediment sources, bank material, vegetation density, and preexisting topography, control size and quantity of bedload, resistance to erosion, valley and channel slope, and channel geometry.

The flood history of the Santa Cruz River in this century shows three distinct periods—1915–29, 1930–59, and 1960–86. The middle period was characterized by generally low to moderate annual floods, almost all of which were caused by monsoonal summer thunderstorms. The other two periods were characterized by greater variability in flood magnitude and a much higher percentage of floods occurring in response to winter frontal systems and fall dissipating tropical storms. The four largest floods recorded on the Santa Cruz River occurred from 1960 to 1986, and the fifth largest flood occurred during 1915–29.

Large floods in 1915–29 and 1960–86 caused substantial channel change throughout the study area. Some reaches, however, were characterized by considerable lateral instability throughout the study period, including 1930–59 when annual floods generally were moderate. Other locations showed greater instability before the 1960's than any time afterward until the flood of 1983.

The floods of 1977 and 1983 were the two largest floods of record on the Santa Cruz River. Although the 1977 flood was of greater magnitude at Nogales, upstream from the study area, the 1983 flood was much larger in Pima County. The 1977 flood caused considerable channel widening in the Canoa reach and arroyo widening in the San Xavier reach but little change in the Cortaro and Marana reaches. The 1983 flood was the single largest episode of channel change to occur on the Santa Cruz River since at least 1915. That flood produced enormous magnitudes of channel and arroyo widening and lateral shifts in channel position throughout most of the study area.

Channel morphology and the spatial variability of channel change on the Santa Cruz River are determined mainly by geologic and topographic controls. Major geologic controls are the location and type of sediment sources and the location of outcrops of bedrock or consolidated sediments relative to the channel. Major topographic controls include large-scale features, such as spatial distribution of landforms and geometry of intramontane basins, and small-scale features, such as paleochannels, ridges, and swales on flood plains. Topographic controls, especially large- scale features, and geologic controls operate together to constrain the morphology and position of the Santa Cruz River. Reaches where the river valley is confined by large, inactive alluvial fans and bedrock mountain ranges have little space for sediment storage and are areas of frequent sediment reworking and transport. Where the valley widens and is unconfined, a greater volume of sediment storage is available and reaches are generally depositional in nature except during episodes of channel incision and sediment removal.

Available models for prediction of channel change generally do not address lateral change, and those that do are limited in the type of channel-changing mechanisms that are modeled. Changes resulting from meander migration, avulsion and meander cutoff, and the retreat of partially cohesive stream banks or arroyo walls are not predictable with current methods. The application of probabilistic models of channel change is not appropriate on the Santa Cruz River because of changes in resistance to erosion with time. Nonetheless, the general stability of various reaches can be evaluated by recognition of the major channel-changing mechanisms operating in a reach and identification of the local topographic, geologic, and cultural controls on channel change. On unentrenched reaches, the hazard associated with lateral channel change is restricted almost exclusively to the flood plain; on entrenched reaches, arroyo widening presents a threat mainly to structures on the terrace that was formed from entrenchment of the historical flood plain.

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GLOSSARY

Much of the terminology used in fluvial geomorphology is not standardized, in part because the great variability in fluvial systems makes application of rigidly defined terms inappropriate. Following are definitions of terms as used in this report.

Arroyo. An entrenched channel system. Channel has so deeply incised its former flood plain that flow generally does not overtop the arroyo walls, which can be as much as 30 feet high on the Santa Cruz River. Arroyo boundaries are contiguous with channel boundaries in some locations, but elsewhere arroyo boundaries enclose a channel system that can include a flood plain and multiple terraces. The Santa Cruz River flows through an arroyo from about the Continental bridge near Green Valley to the reach between the confluence of Rillito Creek and Cañada del Oro north of Tucson.

Bank. Channel boundary. The top of a channel bank was defined using a combination of vegetation patterns and bank morphology, which ranged from sharp, vertical scarps to indistinct, low-angle berms merging gradually with the adjacent flood plain. Generally, a distinction is made between channel banks, which are features formed by the modern channel itself, and arroyo walls, which are composed of alluvium that may have accumulated in a much different depositional environment from the present one. To avoid cumbersome sentence structure, however, the term *bank erosion* is used to include the process of *arroyo-wall retreat.*

Channel. The part of the river that carries flow. Because flow in the Santa Cruz River is so variable in magnitude and frequency, the channel boundaries can be difficult to delineate. A *low-flow channel* is formed by base flows or by receding floodflow and may occur as a distinct, incised feature or may be distinguished only by subtle changes in composition of bed material or occurrence of vegetation. Because low-flow channels on the Santa Cruz River typically are indistinct and discontinuous, no attempt was made to map changes in low-flow channels through time. A *high-flow channel* is formed by floodflow. Immediately following a flood, high-flow channels generally are distinct features delineated by vegetation boundaries and well-defined channel banks, but degradation of the banks and revegetation can rapidly obscure boundaries of the high-flow channel. A high-flow channel, which is incised by a well-defined low-flow channel, forms a *compound channel.*

Channel change. Change in channel geometry or bed elevation; change in its position, course, or pattern; and change in bed material, bank material, or vegetation density. Although the terms *channel* and *arroyo* are not synonymous, for simplicity, *channel change* is used to include changes in arroyo dimensions or other physical properties.

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