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The Influence of Climate Change and Climatic Variability on the Hydrologic Regime and Water Resources (Proceedings of the Vancouver Symposium, August 1987). IAHS Publ. no. 168, 1987.

Paleoflood hydrology and hydroclimatic change

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ABSTRACT Important recent advances have been made in the reconstruction and interpretation of ancient floods, particularly in the use of slackwater deposits and paleostage indicators (SWD-PSI). For certain appropriate geomorphic settings, relatively accurate estimates of paleoflood discharges and ages can be made over time scales of centuries and millennia. New statistical tools are available to extract the maximum information content from this unconventional hydrologic data. Preliminary SWD-PSI study results from the southwestern United States indicate that certain time intervals in the last several thousand years have been characterized by occurrences of extraordinary floods, while other intervals have been relatively free of such events. Hydroclimatic change is a likely cause of this nonstationarity.

Introduction

Paleoflood hydrology concerns the study of past or ancient flow events using physical or botanical information, irrespective of any direct human observation. The flow events usually have occurred prior to the possibility of direct measurement by modern hydrologic procedures, although paleoflood hydrologic techniques can be applied to modern floods at ungaged sites (Baker *et al.*, in press). Recent advances in geochronology, flow modeling, and statistical analysis of paleoflood data have greatly increased the ability to extract useful hydrologic information from one variety of paleoflood investigation: slackwater deposit-paleostage indicator (SWD-PSI) studies (Stedinger & Baker, 1987). SWD-PSI investigations can provide reconstructions of discharges and magnitudes for multiple paleofloods with remarkably high accuracy over time scales of centuries and millennia. However, such SWD-PSI studies require special combinations of geological circumstances that must be carefully evaluated in each application.

An outline of SWD-PSI paleoflood hydrology

The methodology of SWD-PSI paleoflood hydrology is discussed by Baker *et al.* (1983) and by Baker (in press). This section will briefly review important aspects of that methodology, emphasizing recent research developments.

Figure 1 Photograph of an accumulation of slackwater deposits downstream of a bedrock spur on the Salt River in central Arizona.

(a) Slackwater deposits consist of sand and silt (sometimes gravel) that accumulate relatively rapidly from suspension during major floods, particularly at localities where flow boundaries result in markedly reduced flow velocities (Figure 1).

(b) Other important paleostage indicators include silt lines, high level scour marks, and flood-modified vegetation.

(c) Sites of slackwater sediment accumulation occur at the following locations: (i) tributary mouths, (ii) abrupt channel expansions, (iii) in the lee of bedrock flow obstructions, (iv) in channel-margin caves and alcoves, (v) at meander bends, and (vi) upstream of abrupt channel expansions.

(d) Regional factors useful in locating river reaches appropriate for SWD-PSI studies include the following: (i) adequate concentrations of sand and silt in transport by floods, (ii) resistant-boundary channels not subject to appreciable aggradation, (iii) depositional sites with high potential for preservation of SWD-PSI features, and (iv) narrow, deep canyons or gorges in resistant geological materials.

(e) Although initially developed and applied in arid and semiarid regions (Baker et al., 1979; Kochel & Baker, 1982; Kochel et al., 1982), SWD-PSI paleoflood hydrology has been extended to the study of humid-region rivers (Kochel & Baker, in press; Patton, in press).

(f) Computer flow models for step-backwater analysis are used to calculate water surface profiles for various discharges in appropriate SWD-PSI study reaches. Paleodischarges are determined by comparing elevations of the various paleostage indicators to the water surface profiles.

(g) Recent research has concentrated on strategies for reducing error in paleodischarge estimation. Important concerns in this regard include: (i) paleoflow cross-sectional stability, (ii) relatively deep paleoflows, and (iii) relatively uniform reaches.

(h) Long-term channel stability is necessary for accurate hydraulic calculations. This can be assured for reaches developed in bedrock, immobile sediment, or other resistant boundary materials.

(i) Narrow-deep channel cross sections are most useful, since increasing flood discharge results in relatively large stage increases (Baker, 1984).

(j) Accuracy of the predicted water-surface profiles can be improved when relatively large flows in a systematic gage record are available to test and calibrate the flow model (Ely & Baker, 1985; Partridge & Baker, 1987).

(k) At ideal SWD-PSI sites thick sequences of multiple sedimentation units record numerous paleofloods (Figure 2). Individual flood units are distinguished by sedimentologic properties such as the following: (i) silt-clay or organic drapes, (ii) buried paleosols, (iii) organic layers, (iv) intercalated tributary alluvium or slope colluvium, (v) abrupt vertical grain size variations, (vi) mudcracks, (vii) color changes, and (viii) induration properties.

(l) Recent advances in geochronology, particularly radiocarbon analysis (Baker et al., 1985), provide excellent opportunities to determine paleoflood ages. As little as 1 to 2 mg of elemental carbon can be analyzed by the new technique of tandem accelerator mass spectrometry (Taylor et al., 1984).

(m) The usual "worst case" end member for SWD-PSI paleoflood information content is a single, vertically-stacked sequence of slackwater deposits (Figure 2). In this case, an informational censoring level (the elevation of each succeeding deposit) increases with time.

(n) Most commonly, SWD-PSI sequences provide much more paleoflood information than in the worst-case scenario. This is achieved by lateral tracing of individual flood deposits to their highest elevations, by correlation of flood deposits among multiple sites, by documenting evidence of limiting high-water levels, and by studying inset stratigraphic relationships.

(o) The information content in SWD-PSI sequences can be structured for flood-frequency analysis through the concept of censoring levels. Flood experience for various time intervals is then analyzed in terms of exceedances or nonexceedances of the censoring levels or threshold discharges (Stedinger & Baker, 1987).

(p) The goal of stratigraphic analysis in SWD-PSI studies is to reconstruct a complete catalog of discharges exceeding censoring levels over specified time periods.

(q) New statistical tools are now available to make optimum use of the information content in appropriately structured paleoflood data (Stedinger & Cohn, 1986; Stedinger & Baker, 1987).

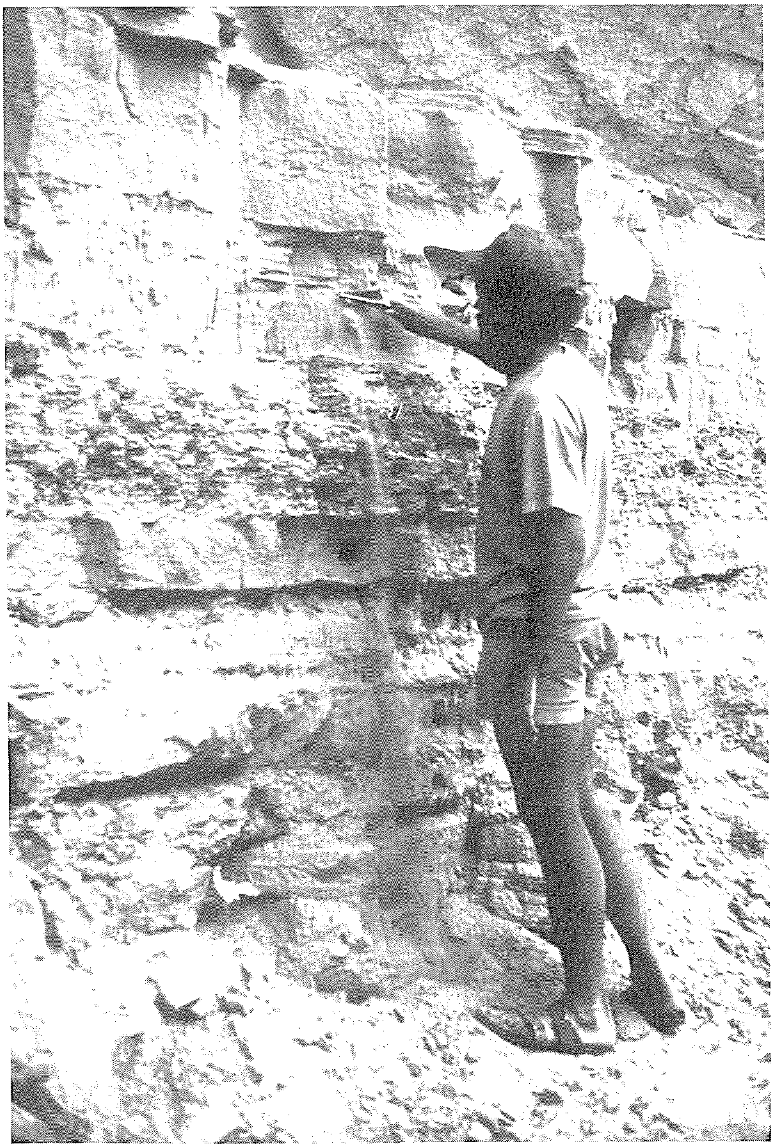

Figure 2 Photograph of The Alcove slackwater sedimentation site (Webb, 1985) on the Escalante River in south-central Utah.

Flood hydroclimatology

Conventional flood-frequency analysis relies on the following assumption: "... the array of flood information is a reliable and representative time sample of random homogeneous events" (U.S. Water Resources Council, 1981, p. 6). Two possible violations of this assumption may be induced by (1) a mixed underlying parent distribution for the flood events, and (2) variation through time in the mean of the underlying probability distribution for flood recurrence (nonstationarity). Both of these situations may derive from climatologic causes (Hirschboeck, in press). Although short-term systematic records are generally ambiguous with regard to such interpretive problems, SWD-PSI paleoflood hydrology provides excellent opportunities to test assumptions. In southern Arizona, for example, annual flow peaks are dominated by floods induced by regional snowmelt, local summer convective storms, and winter frontal storms (Hirschboeck, 1985). More rarely, incursions by tropical storms lead to extraordinary floods that appear as outliers in the systematic flood records. Here the systematic flow record is biased toward one hydroclimatologically induced distribution: that controlling the relatively common, smaller annual floods. Only with the expanded time base provided by paleoflood hydrology can an adequate sample be achieved for the unusually large and rare floods related to another hydroclimatologically induced distribution.

Of course, paleoflood hydrology generally cannot identify the hydroclimatic cause for a given paleoflow event. Nevertheless, the time base of centuries or millennia is ideal for evaluating long-term trends. Knox (1985) documented a pronounced nonstationarity for upper Mississippi Valley floods over the past 9500 years. Early Holocene alluvial fills indicate very low probabilities for large floods between 6000 and 9500 yr B.P. Increased probabilities for large floods are evidenced by boulder gravel in overbank sediments deposited in the following age intervals: (1) 6000 to 4500 yr B.P., (2) 3000 to 1800 yr B.P., and (3) 1000 to 500 yr B.P. (Knox, 1985). Similarly, Patton & Dibble (1982) presented evidence from the Pecos River of western Texas that floods were relatively infrequent during an arid interval between approximately 9000 and 3000 yr B.P., but the extraordinary floods occurring in this interval were unusually large. Between approximately 3000 and 2000 yr B.P. a humid interval resulted in more frequent flooding, but flood magnitudes were moderated. The last 2000 years has been most similar to the early Holocene arid interval.

On a shorter time scale, detailed SWD-PSI studies also have an immense potential for evaluating nonstationarity. For the Columbia River in central Washington, Chatters & Hoover (1986) showed that during the approximate interval 1000 to 1400 A.D. large floods were three to four times more common than at present. Flood frequency characteristics similar to those at present prevailed from approximately 200 to 1000 A.D. and from approximately 1400 A.D. to present. This use of paleoflood hydrology illustrates the fallacy of overly simplistic characterizations of paleoflood records as illustrated by the computer simulations of Hosking & Wallis (1986). Rather than a vague rationalization with which to criticize paleoflood hydrologic studies (Hosking & Wallis, 1986), nonstationarity can be an object of scientific study utilizing the remarkable capability of SWD-PSI studies to generate accurate and complete paleoflood records.

Applications in the southwestern United States

Since 1981 the new procedure of SWD-PSI paleoflood hydrology has been used in a regional study of ancient floods in the southwestern United

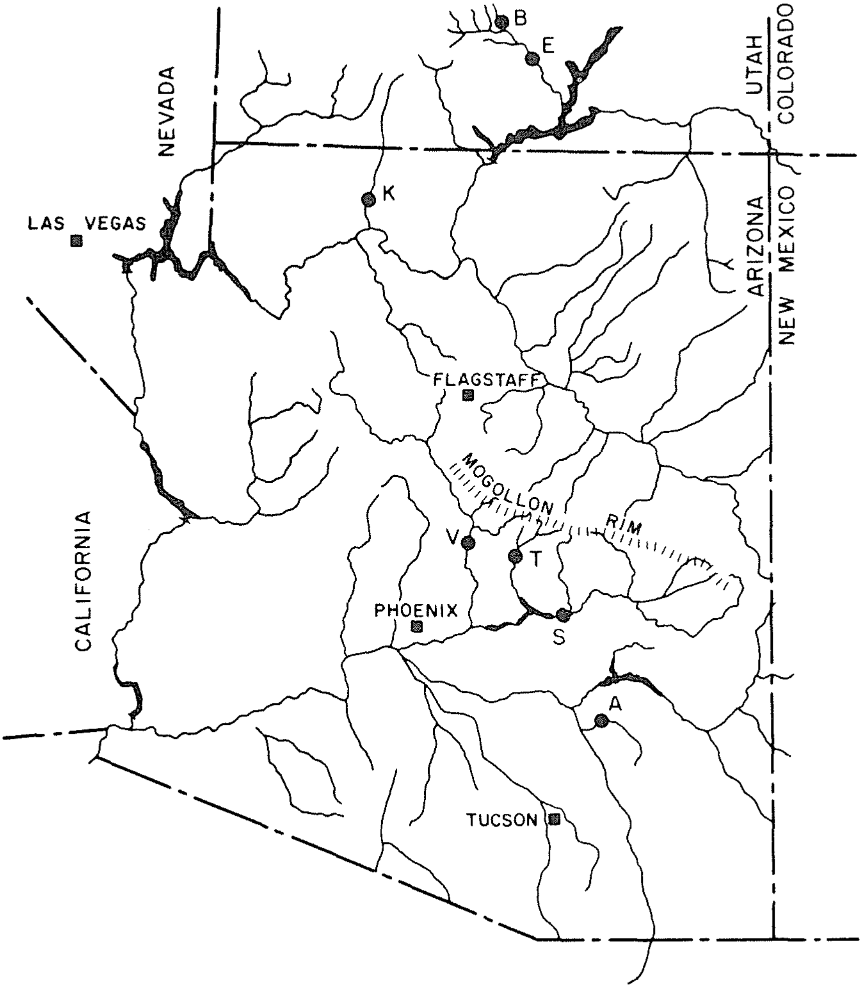

Figure 3 Location of SWD-PSI paleoflood hydrologic investigations in the southwestern United States. Studies were done in south-central Utah on Boulder Creek (B) and the Escalante River (E). In Arizona, studies were done on Kanab Creek (K), Tonto Creek (T), Aravaipa Creek (A), and on the Salt (S) and Verde (V) Rivers.

States (Figure 3). One goal of this regional analysis has been to identify temporal and spatial patterns in extraordinary floods.

The paleoflood record of the Escalante River of south-central Utah (Figure 3) illustrates the trends seen at other study sites. Paleofloods documented by Webb (1985), Webb *et al.* (in press), and O'Connor *et al.* (1986) fall into major time groupings. During the period 2000 to 1300 yr B.P. floods were relatively small. Three major floods occurred between 1200 and 1000 yr B.P., including the largest flood of the record. This period was also one of major arroyo cutting and is well-documented throughout the southwestern U.S. No floods were recorded between 900 and 600 yr B.P., but three floods were recorded between 600 and 400 yr B.P. The next major phase of flooding occurred in the last century, which is the period of most extensive arroyo formation in the region (Webb and Smith, 1986).

The most detailed long-term record of paleofloods in the Southwest occurs just southeast of Phoenix, Arizona (Figure 3). Prehistoric irrigation canals constructed by the Hohokam indians are filled with flood deposits (Masse, 1981). Current research by J.E. Fuller (written communication, 1986) documents that, since 1100 yr B.P., the Hohokam canals recorded a minimum of 25 and a maximum of 30 floods that exceeded 5000 m^3s^{-1}. Of these the largest (>12,000 m^3 s^{-1}) occurred about 1100 yr B.P. during a 250-yr period of pronounced flooding. Large floods again appeared in the last 400 years, including three exceedences of 7000 m^3s^{-1}. The last of these was the 1891 flood with a discharge of between 7000 and 8000 m^3s^{-1} .

Essentially the same timing of paleoflood events is observed on upstream reaches of the Salt River (Partridge & Baker, 1987) and the Verde River (Ely & Baker, 1985). Additional work on these streams and Tonto Creek (Figure 3) by J.E. O'Connor and J.E. Fuller (written communication, 1986) confirms the same sequence. The largest flood occurred approximately 1000 yr B.P. on both the Salt and Verde Rivers. Unusually large floods also occurred during the last century.

Discussion

All SWD-PSI paleoflood studies conducted thus far in Arizona and adjacent areas (Figure 3) reveal a remarkably consistent record. Certain time intervals during the past few millenia have been characterized by occurrences of extraordinarily large floods, while other intervals have been relatively free of such events. Major episodes of flooding occurred from approximately 1000 to 1200 yr B.P. and during the past century or two. A somewhat less intense phase of flooding occurred between approximately 400 and 600 yr B.P. Time intervals between these flood phases were characterized by fewer, smaller floods. In addition, there are many indications that channel entrenchment on alluvial streams (arroyo formation) was coincident with flood phases, while aggradation was generally coincident with phases of reduced flooding (Webb, 1985).

The regional coincidence of flood phases in the southwestern United States suggests a hydroclimatologic cause. A possible mechanism is the variable influence of tropical moisture in the region. Work on evaluating this mechanism is currently in progress.

Considerable potential exists for combining SWD-PSI paleoflood studies with other paleoclimatic indicators. For example, tests of nonstationarity in long-term flood series might be achieved by evaluating other paleohydrologic indicators. Long-term tree-ring series and regime-based paleoflow estimates (RBPE) both can be related to various measures of mean streamflow or mean floods. RBPE studies are accomplished in alluvial channels, which are much more common than the resistant-boundary (non-alluvial) channel conditions required for accurate SWD-PSI studies. Accurately dated mean flow estimates plus chronologies of other paleoclimatic indicators, such as pollen records, plant macrofossils, and isotopic records, can be used to evaluate nonstationarity in paleoflood records and interpret the role of climate change in generating such records. Past climatic change may serve as a guide to the potential for future climatic change. Precise data on the magnitudes of past hydroclimatic change may prove useful in testing models intended to predict future change.

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Streamflow in the Upper Santa Cruz River Basin, Santa Cruz and Pima Counties, Arizona

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GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1939-A

Prepared in cooperation with the city of Tucson, the U.S. Bureau of Reclamation, and the University of Arizona

U.S. DEPARTMENT OF THE INTERIOR
March 3, 1849

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By ALBERTO CONDES DE LA TORRE

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STREAMFLOW IN THE UPPER SANTA CRUZ RIVER BASIN, SANTA CRUZ AND PIMA COUNTIES, ARIZONA

By Alberto Condes de la Torre

ABSTRACT

Streamflow records obtained in the upper Santa Cruz River basin of southern Arizona, United States, and northern Sonora, Mexico, have been analyzed to aid in the appraisal of the surface-water resources of the area. Records are available for 15 sites, and the length of record ranges from 60 years for the gaging station on the Santa Cruz River at Tucson to 6 years for Pantano Wash near Vail. The analysis provides information on flow duration, low-flow frequency and magnitude, flood-volume frequency and magnitude, and storage requirements to maintain selected draft rates. Flood-peak information collected from the gaging stations has been projected on a regional basis from which estimates of flood magnitude and frequency may be made for any site in the basin.

Most streams in the 3,503-square-mile basin are ephemeral. Ground water sustains low flows only at Santa Cruz River near Nogales, Sonoita Creek near Patagonia, and Pantano Wash near Vail. Elsewhere, flow occurs only in direct response to precipitation. The median number of days per year in which there is no flow ranges from 4 at Sonoita Creek near Patagonia to 335 at Rillito Creek near Tucson. The streamflow is extremely variable from year to year, and annual flows have a coefficient of variation close to or exceeding unity at most stations.

Although the amount of flow in the basin is small most of the time, the area is subject to floods. Most floods result from high-intensity precipitation caused by thunderstorms during the period July to September. Occasionally, when snowfall at the lower altitudes is followed by rain, winter floods produce large volumes of flow.

INTRODUCTION

The growing demand for water in the upper Santa Cruz River basin (fig. 1)—in response to the increase in population, agricultural development, and industry—has created a need for information on the amount of surface water available and the nature of its occurrence. Therefore, streamflow records of sufficient length to define the flow characteristics of the streams are important in long-range planning

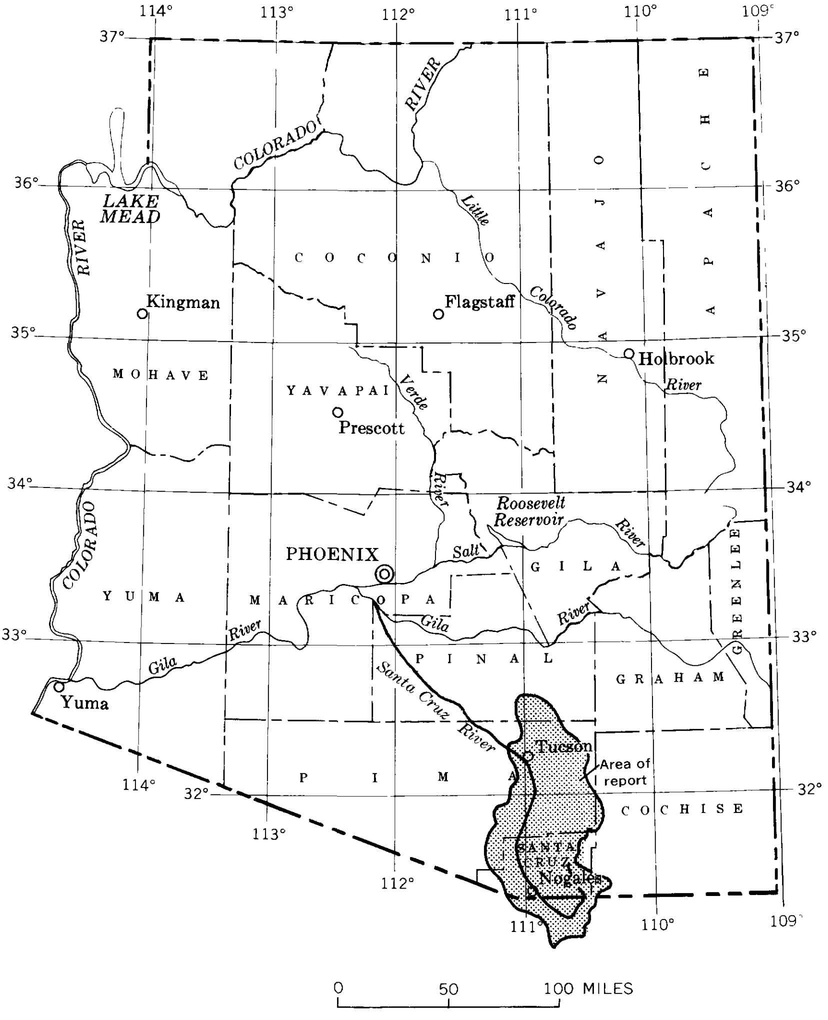


FIGURE 1.—Location of upper Santa Cruz River basin.

and development. The U.S. Geological Survey analyzed the streamflow records for the upper Santa Cruz River basin in conjunction with a cooperative water-resources investigation of the Tucson basin, conducted under the immediate supervision of H. M. Babcock, district chief of the Water Resources Division in Arizona. The cooperating agencies were the city of Tucson, the U.S. Bureau of Reclamation, the University of Arizona, and the Geological Survey.

The purpose of the investigation was to define the magnitude and occurrence of streamflow by summarizing the data available from gaging-station records and to present the information in a usable form. Streamflow records are available from 15 U.S. Geological Survey gaging stations (pl. 1). The length of record at these gaging stations ranges from 60 years (1905–65) for the Santa Cruz River at Tucson to 6 years (1959–65) for Pantano Wash near Vail (table 1).

METHODS OF ANALYSIS USED IN THE INVESTIGATION

The streamflow records were analyzed by statistical and graphical methods for this report. Flow duration, low-flow frequency, flood frequency, flood-volume frequency, daily-flow duration, storage analysis, and the annual occurrence of days having no flow were determined. Daily mean discharge was used in the flow-duration, low-flow, and flood-volume frequency analyses. The analyses were made from data recorded by gaging stations in the upper Santa Cruz River basin through 1963 and later were arranged and sorted by an electronic computer. The period 1936 to 1963, inclusive, was used for the flow-duration curves. The period of record for each gaging station was used for the curves showing low-flow frequency, flood frequency, flood-volume frequency, and days of no flow. Because most streams in the basin are dry for long periods of time, the daily flow-duration graphs are given only for streams having flow adaptable to this type of presentation—Sonoita Creek near Patagonia, Santa Cruz River near Nogales, and Sabino Creek near Tucson. The data for each gaging station in the basin are presented in each type of analysis if the length of record is sufficient for interpretation. The years of record used in this report are water years, unless otherwise specified.

GEOGRAPHY

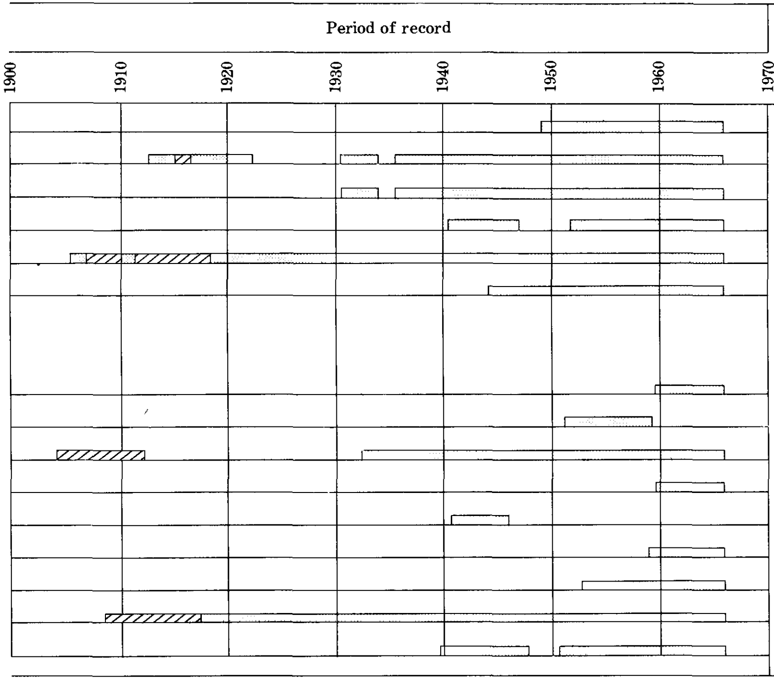
The upper Santa Cruz River basin, defined as that part of the Santa Cruz River basin above Cortaro, occupies 3,503 square miles in southern Arizona, United States, and northern Sonora, Mexico (pl. 1). The upper basin is bounded on the south by the drainage divide between streams that enter the basin and streams that enter the Rio de Concepcion dainage basin in Mexico; on the east by the Tortolita, Santa Catalina, Tanque Verde, Rincon, Whetstone, and Huachuca Mountains and the Canelo Hills; on the north by the drainage divide between the upper and the lower Santa Cruz and lower San Pedro River basins; and on the west by the Atascosa, Tumacacori, Cerro Colorado, Sierrita, and Tucson Mountains.

The basin is in the Basin and Range physiographic province (Fenneman, 1931) and is characterized by isolated mountain blocks separated by broad alluvial-filled valleys. The altitude of the valleys ranges from 2,100 to 4,700 feet above mean sea level, and the mountains are as much as 9,400 feet above mean sea level.

The Santa Cruz River drains the west side of the Huachuca Mountains and the east side of the Patagonia Mountains and flows south past Lochiel into Mexico; in Mexico, flow is contributed to the river

TABLE 1.—*Period of record for streamflow-gaging stations*

EXPLANATION: ▭ Daily discharge ▨ Monthly discharge



Gaging station	Altitude above mean sea level (ft)	Drainage area (sq mi)	Station
Santa Cruz River near Lochiel	4,620	82.2	9-4800
Santa Cruz River near Nogales	3,702	533	9-4805
Sonoita Creek near Patagonia	3,818	209	9-4815
Santa Cruz River at Continental	2,836	1,662	9-4820
Santa Cruz River at Tucson	2,317	2,222	9-4825
Tucson Arroyo at Vine Avenue, Tucson	2,412	27.0 (prior to 1945) 8.2 (since 1956)	9-4830
Tanque Verde Creek near Tucson	2,720	43.0	9-4831
Sabino Creek near Mount Lemmon	7,250	3.19	9-4833
Sabino Creek near Tucson	2,720	35.5	9-4840
Bear Creek near Tucson	2,670	16.3	9-4842
Tanque Verde Creek at Tucson	2,460	221	9-4845
Pantano Wash near Vail	3,205	457	9-4846
Rincon Creek near Tucson	3,120	44.8	9-4850
Rillito Creek near Tucson	2,284	918	9-4860
Santa Cruz River at Cortaro	2,137	3,503	9-4865

from a 348-square-mile drainage area. The river then flows north, enters the United States 5½ miles east of Nogales, and continues northwest to Tumacacori. In this reach the Santa Cruz is joined by Sonoita Creek and Josephine Canyon and by tributaries that drain the east slopes of the Pajarito and Atascosa Mountains. The river flows almost due north from Tumacacori to Tucson and receives drainage from the Santa Rita, Tumacacori, and Sierrita Mountains. At Tucson, the river is joined by Rillito Creek, which has a 934-square-mile drainage basin that extends into the Empire and Whetstone Mountains near Benson and the Santa Catalina and Rincon Mountains near Tucson. The river flows northwest from Tucson and leaves the upper basin at Cortaro.

HISTORY

The upper Santa Cruz River basin has had an interesting and colorful history under the flags of Spain, Mexico, and the United States. In 1539 Fray Marcos de Niza is believed to have followed the Santa Cruz River, then unnamed, north from Mexico in his search for civilizations and treasure. The first attempt to settle and Christianize the friendly Indians was undertaken by Father Kino in a 20-year period beginning in 1691. Father Kino referred to the river in his writings as the "Rio de Santa Cruz," which is Spanish for "River of Holy Cross." Father Kino established several missions in the area, and two of the most famous—San Xavier del Bac and Tumacacori—are near the banks of the Santa Cruz River. When Mexico achieved its independence from Spain in 1821, the basin became part of Mexico, and in 1853 it became part of the United States through the Gadsden Purchase.

Many changes have taken place in the basin landscape since the first Europeans explored the upper Santa Cruz River basin. Erosion has lowered the base level of the Santa Cruz River, and the basin is adapting to it. Early settlers found the flow in the river adequate for their needs, and Smith (1910) showed the water table in the Tucson area higher than the streambed in 1908. Davidson (written commun., 1969) showed that the water table ranged from about 20 to 70 feet below the streambed along the Santa Cruz River in 1940–64. The increase in withdrawal of water by pumping accounts for the lowering of the water table, but the exact causes of the erosional activity are not known.

Previous workers agree that the most recent arroyo cutting and lowering of the channel streambeds in the Santa Cruz River basin began about 1890. Leopold (1951) discussed the journals of early explorers and travelers in the Southwest and compared early photographs with more recent ones taken at the same place. He concluded that the vegetation changes in the 50 years between 1895 and 1946 were not significant and that the vegetation changes that most affected the erosional activity possibly occurred before 1895. Hastings and Turner (1965, p. 288) discussed the changes in vegetation and stated:

> To the extent that arroyo cutting accurately reflects changing vegetative conditions it is possible to be more precise. Arroyo cutting began along many of the streams of the desert region in August, 1890. One can infer, then, that by 1890 the vegetation had been altered enough to affect runoff, but it is an uncomfortable inference, resting as it does on the unproven assumption that a change in the vegetal cover inaugurated arroyo cutting.

Hastings (1958–59, p. 35) discussed three theories of what caused the changes in the landscape: (1) the introduction of cattle, which upset the biological balance involving the soil and things that grow on it, (2) a tilting of the land surface that caused the gradient of local streams to increase, and (3) climatic changes—less rain, change in rainfall pattern, and a change in intensity of storms. Hastings and Turner (1965) stated that the event that may have triggered arroyo cutting was an imbalance between infiltration and runoff caused by a combination of climatic variation and cattle grazing.

PRECIPITATION

The normal annual precipitation in the basin ranges from 30 inches in the mountains to about 10 inches on the valley floor near Tucson (University of Arizona, 1965a, b). Precipitation is extremely variable from year to year. The highest average monthly precipitation occurs in the summer, when the average air temperature is the highest and the evaporation potential is the greatest (pl. 2). The average annual precipitation and the peak maximum monthly precipitation increase with altitude (fig. 2). The peak maximum monthly precipitation shown in figure 2 is the highest value shown on the maximum monthly curves (pl. 2).

Precipitation in July, August, and September is of high intensity and of short duration and usually is from thunderstorms that cover a small area. Occasionally, tropical storms move inland—generally in September—and contribute large amounts of precipitation. Winter storms are the result of frontal activity and usually cover most of the basin; winter precipitation is generally less intense, but is of longer duration than summer precipitation (Sellers, 1960; Sellers, oral commun., 1969).

Precipitation either returns directly to the atmosphere by evapotranspiration, infiltrates into the soil, or reaches the stream channel in ratios dependent on the type of storm, temperature, type and density of vegetation, and topography. In the upper Santa Cruz River basin the percentage of rainfall that reaches the stream channels is extremely low. The average ratio of streamflow to rainfall volumes has been computed as follows (Schwalen, 1942, p. 468–469):

Gaging station	*Average ratio of streamflow to rainfall (percent)*
Sonoita Creek near Patagonia (period of record, 1931–41)	2.5
Santa Cruz River near Nogales (period of record, 1931–41)	3.0
Santa Cruz River at Tucson (period of record, 1923–41)	.6
Rillito Creek near Tucson (period of record, 1923–41)	1.0

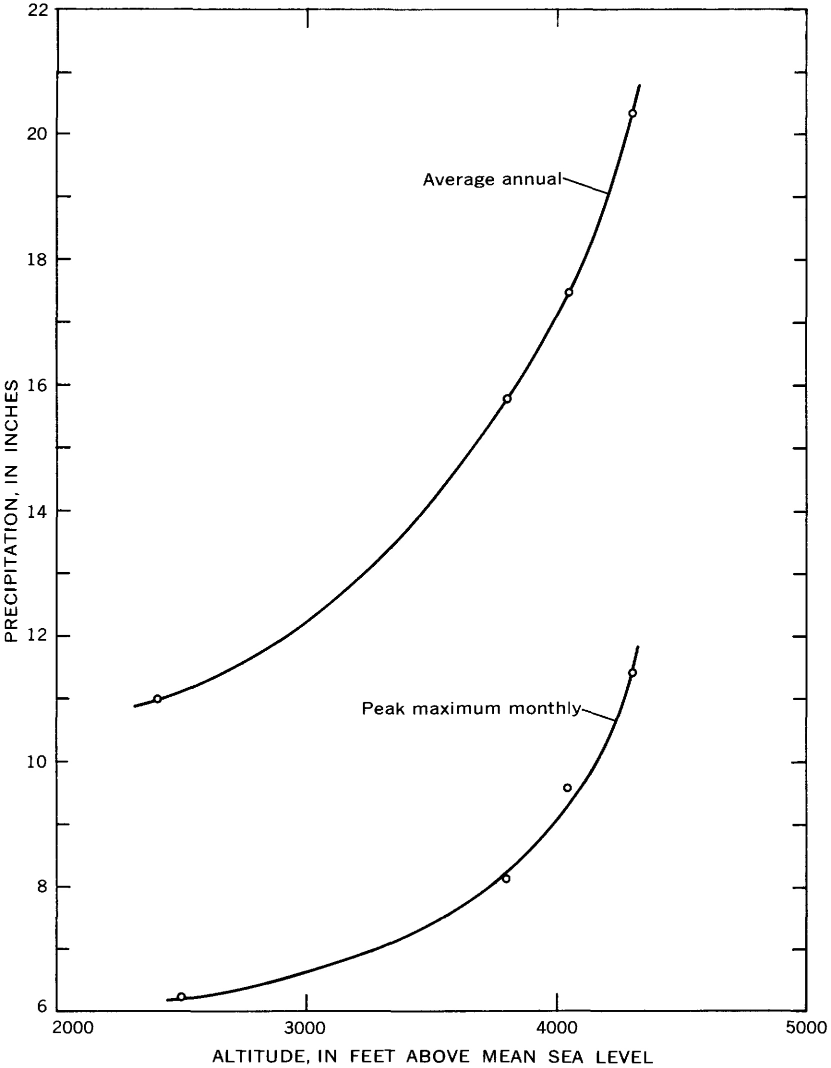


FIGURE 2.—Variation of the average annual and peak maximum monthly precipitation with altitude.

STREAMFLOW

Most streams in the upper Santa Cruz River basin are ephemeral and are dry for long periods of time. Flow in the streams is generally in response to precipitation, except in a few places, such as Santa Cruz River near Nogales, Sonoita Creek near Patagonia, and Pantano Wash near Vail, where ground water is forced to the surface. Streamflow is not used for municipal or irrigation purposes, except for small diversions in Mexico; however, the municipal water supplies for Nogales,

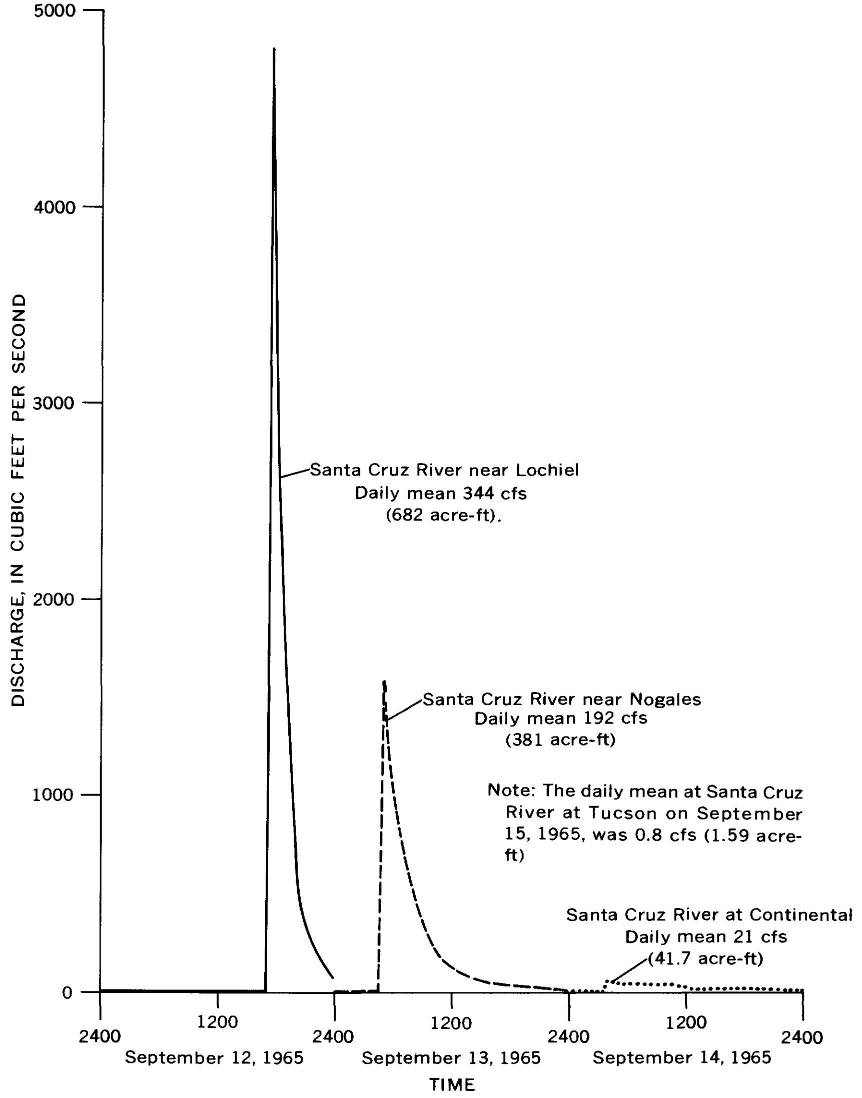


FIGURE 3.—Reduction of the flood peak by channel losses in the Santa Cruz River.

Arizona, and Nogales, Sonora, are from wells drilled in the alluvium near the Santa Cruz River, and, at times, the cone of influence of these wells intercepts and depletes the surface flow in the river.

The streambeds of the Santa Cruz River and its main tributaries are extremely permeable, and water is lost to the subsurface as the flow moves downstream. The flood of September 12–15, 1965 (fig. 3), is an example of the natural channel losses that occur in the main stem of the Santa Cruz River. The flood volume diminished from 682 acre-feet at Lochiel to 1.59 acre-feet at Tucson. The average annual infiltration rate ranges from 320 to 480 acre-feet per mile in the northern part of the main stem of the Santa Cruz River (D. E. Burkham, written commun., 1969). Part of the water lost through infiltration reaches the water table, and water levels in wells near the river fluctuate in response to the streamflow (fig. 4).

Streamflow in the upper Santa Cruz River basin is extremely variable, and the arithmetic average of the annual flow has little meaning with regard to the amount of flow that may be expected each year. The

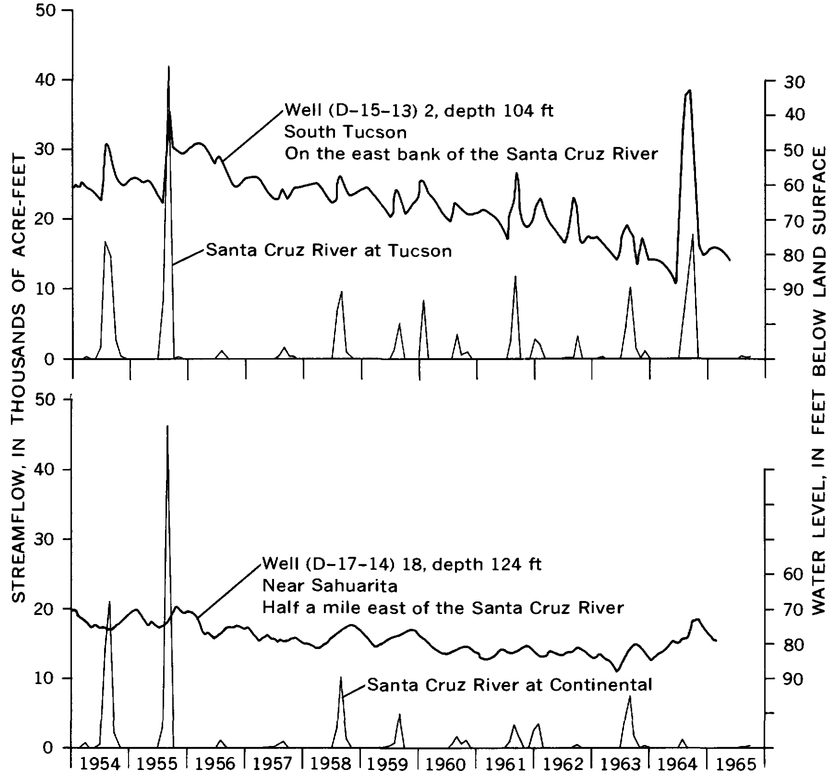


FIGURE 4.—Effects of streamflow on water levels in wells near the Santa Cruz River. See plate 1 for location of wells.

TABLE 2.—*Variation and distribution of annual streamflow*

Station	Drainage area (square miles)	Number of years of record	Annual streamflow					
			Arithmetic average (acre-feet)	Extremes (acre-feet)		Standard deviation (acre-feet)	Coefficient of variation	Skewness
				High	Low			
Santa Cruz River near Lochiel	82. 2	16	2, 540	12, 220	227	3, 020	1. 19	2. 10
Santa Cruz River near Nogales	533	46	15, 530	75, 000	3, 320	13, 490	. 87	2. 51
Sonoita Creek near Patagonia	209	33	5, 230	13, 060	1, 360	2, 520	. 48	1. 30
Santa Cruz River at Continental	1, 662	20	11, 960	49, 220	188	12, 690	1. 06	1. 64
Santa Cruz River at Tucson	2, 222	60	15, 680	80, 920	935	14, 000	. 89	2. 08
Tucson Arroyo at Vine Avenue, Tucson	27. 0–8. 2	21	580	1, 210	84. 4	293	. 51	. 27
Tanque Verde Creek near Tucson	43. 0	6	5, 010	8, 800	1, 910	2, 310	. 46	. 35
Sabino Creek near Mount Lemmon	3. 19	7	1, 180	2, 590	100	757	. 64	. 51
Sabino Creek near Tucson	35. 5	40	8, 190	37, 090	375	7, 240	. 88	1. 81
Bear Creek near Tucson	16. 3	6	3, 080	6, 220	100	1, 980	. 64	. 17
Tanque Verde Creek at Tucson	221	5	12, 500	43, 160	1, 850	15, 640	1. 25	1. 36
Pantano Wash near Vail	457	6	5, 120	9, 340	2, 000	2, 630	. 51	. 36
Rincon Creek near Tucson	44. 8	13	2, 880	5, 680	52	1, 940	. 67	—. 02
Rillito Creek near Tucson	918	57	11, 550	120, 000	315	17, 990	1. 56	4. 18
Santa Cruz River at Cortaro	3, 503	22	19, 890	67, 390	1, 880	15, 320	. 77	1. 65

standard deviation for annual flow at many of the gaging stations in the basin is close to or exceeds the arithmetic average (table 2). The coefficient of variation, a comparative measure of the variability of flow and defined as the ratio of the standard deviation to the mean, for the annual flows at gaging stations in the upper Santa Cruz River basin ranges from 0.46 at Tanque Verde Creek near Tucson to 1.56 at Rillito Creek near Tucson.

FLOW DURATION

The time distribution of streamflow can be expressed by a flow-duration curve, which is a cumulative frequency curve that shows the percentage of time specified discharges are equaled or exceeded in a given period. The flow-duration curves in this report are average curves for the period 1936–63 and do not represent the distribution of the annual flow.

Flow-duration curves for most streams in the upper Santa Cruz River basin have steep slopes, which indicate that the streamflow is in direct response to precipitation and that snowmelt and ground-water discharge do not contribute sufficient amounts of water to sustain flow (pl. 3). The steepness of the flow-duration curves also is indicative of the high variability of streamflow, which is caused by variable precipitation modified by the basin characteristics.

In the upper Santa Cruz River basin the median (50 percent) flow exceeds 1 cfs (cubic feet per second) at only three stations—Sonoita Creek near Patagonia, Santa Cruz River near Nogales, and Pantano Wash near Vail (pl. 3). At these stations, the underlying bedrock forces ground water to the surface. Snowmelt reduces the variability of flow at Sabino Creek near Tucson, Bear Creek near Tucson, and Tanque Verde Creek near Tucson, but the lower end of the curves indicates that there is not sufficient ground-water discharge to sustain perennial flow (pl. 3).

The flow-duration curves can be used to determine the relative suitability of different streams for the development of a water supply. For example, if a water supply of 1 mgd (million gallons per day) is desired without providing storage, comparison shows that Sonoita Creek flows at a rate of 1 mgd (1.55 cfs) for 70 percent of the time and that the Santa Cruz River at Continental flows at 1 mgd for less than 10 percent of the time (pl. 3). If storage is not provided in the basin, streamflow will be available to sustain a 1-cfs draft rate for less than 30 percent of the time at all but four gaging stations, and streamflow will be available to sustain a 10-cfs draft rate for less than 20 percent of the time at all gaging stations (table 3).

TABLE 3.—*Percentage of time in a 28-year period that streamflow would equal or exceed selected discharge rates between 1 and 100 cfs at gaging stations*

Station	Discharge (cfs)				
	1	5	10	50	100
Santa Cruz River near Lochiel	12	5	3	1	0. 5
Santa Cruz River near Nogales	67	34	19	6	4
Sonoita Creek near Patagonia	79	20	7	2	1
Santa Cruz River at Continental	9	7	6	4	3
Santa Cruz River at Tucson	11	8	7	4	3
Tucson Arroyo at Vine Avenue, Tucson	5	2	1	. 3	. 1
Tanque Verde Creek near Tucson	27	16	10	3	1
Sabino Creek near Mount Lemmon	24	5	2	. 2	. 1
Sabino Creek near Tucson	43	25	17	4	2
Bear Creek near Tucson	21	11	7	1	. 5
Tanque Verde Creek at Tucson	19	15	12	5	2
Pantano Wash near Vail	90	7	5	2	1
Rincon Creek near Tucson	17	11	7	2	. 5
Rillito Creek near Tucson	8	6	5	3	2
Santa Cruz River at Cortaro	13	11	9	6	4

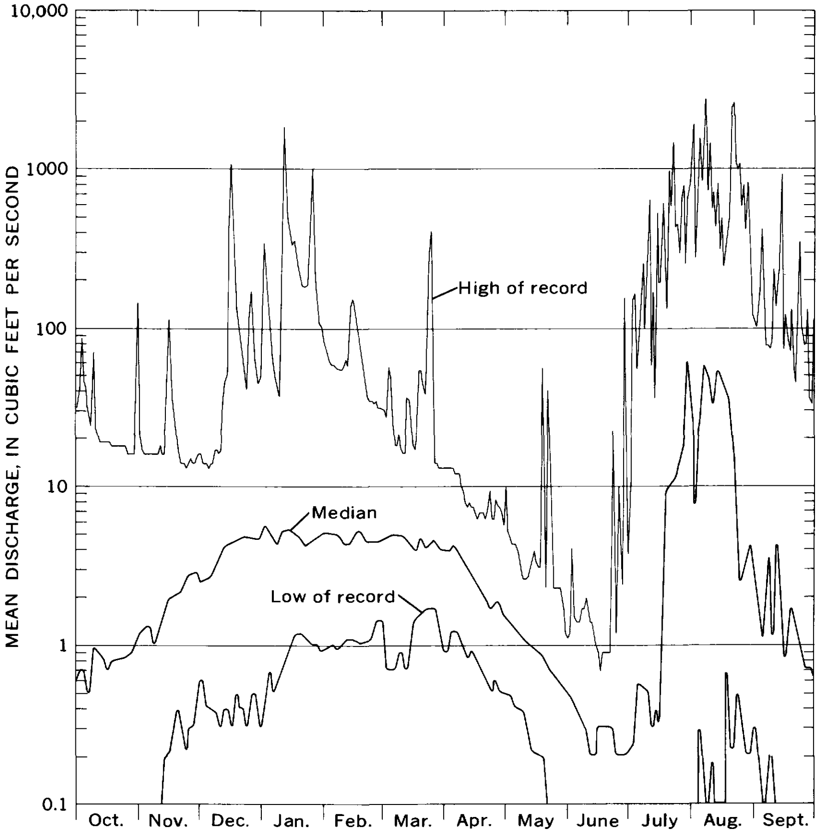


FIGURE 5.—Distribution of the daily high, median, and low flows, 1945–63, for Santa Cruz River near Nogales, Ariz.

Hydrographs of daily flow were prepared to show the seasonal distribution of streamflow at the three stations in the basin where the lowest flow would not be zero on every calendar day (figs. 5, 6, and 7).

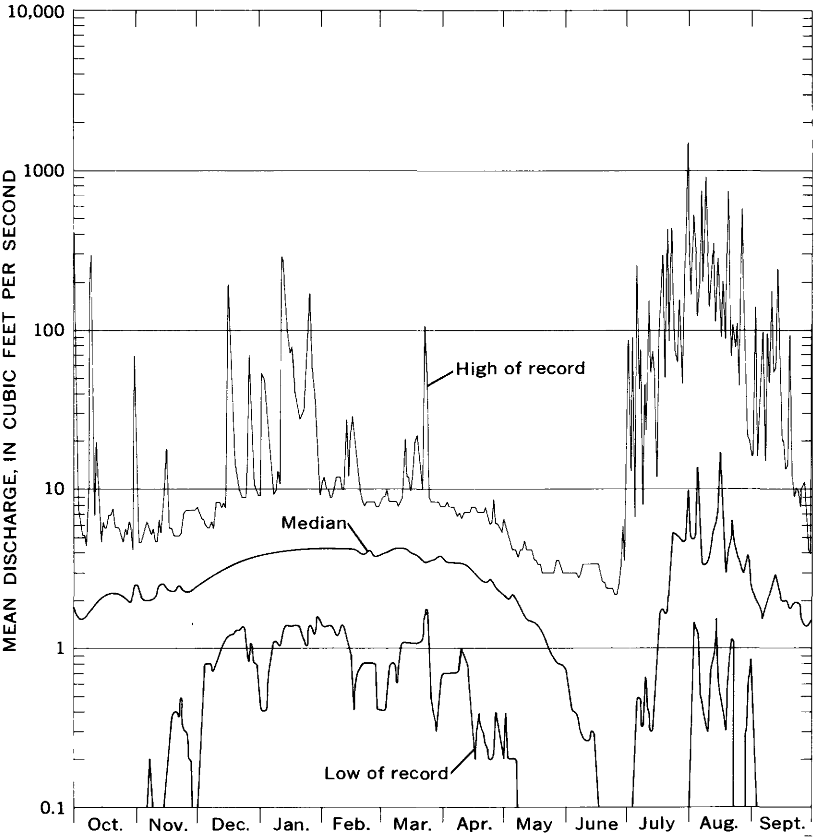


FIGURE 6.—Distribution of the daily high, median, and low flows, 1945–63, for Sonoita Creek near Patagonia, Ariz.

The hydrographs show the highest, the median, and the lowest mean flow for each calendar day. For some days the range in flow is four orders of magnitude. The lowest flows occur in June at all three stations.

ANALYSIS OF LOW FLOWS

An analysis of the low-flow frequency curves indicates a lack of sustained flow in the basin (pl. 4). The flow-duration curves, which were discussed in the preceding section, do not show whether the lowest flows occurred consecutively in a rare drought year or whether there were a few dry days in each year. Low-flow frequency curves, however, are based on the lowest mean discharges for intervals of time ranging from 1 to 274 consecutive days for each year of record and give the recurrence intervals, magnitudes, and the chronological sequences of the occurrence of the low flows.

The sustained flow in the basin was sufficient to define the 1-day and (or) 7-day curves only at Santa Cruz River near Nogales, Sonoita Creek near Patagonia, and Pantano Wash near Vail. The 1- and 7-day means are indicative of the amount of ground-water discharge available to sustain streamflow. At Sabino Creek near Tucson, the 1- and 7-day means were less than 0.01 cfs in each year during the period of record. At the other gaging stations in the basin, the low-flow frequency curves are of little value as a tool for determining the potential of the streams for a water supply or waste disposal, because the streams are dry for long periods during the year; therefore, curves for these stations are not included in the report. A mean flow of 1 cfs or less for a 183-day period will have a recurrence interval of 4 years or less at

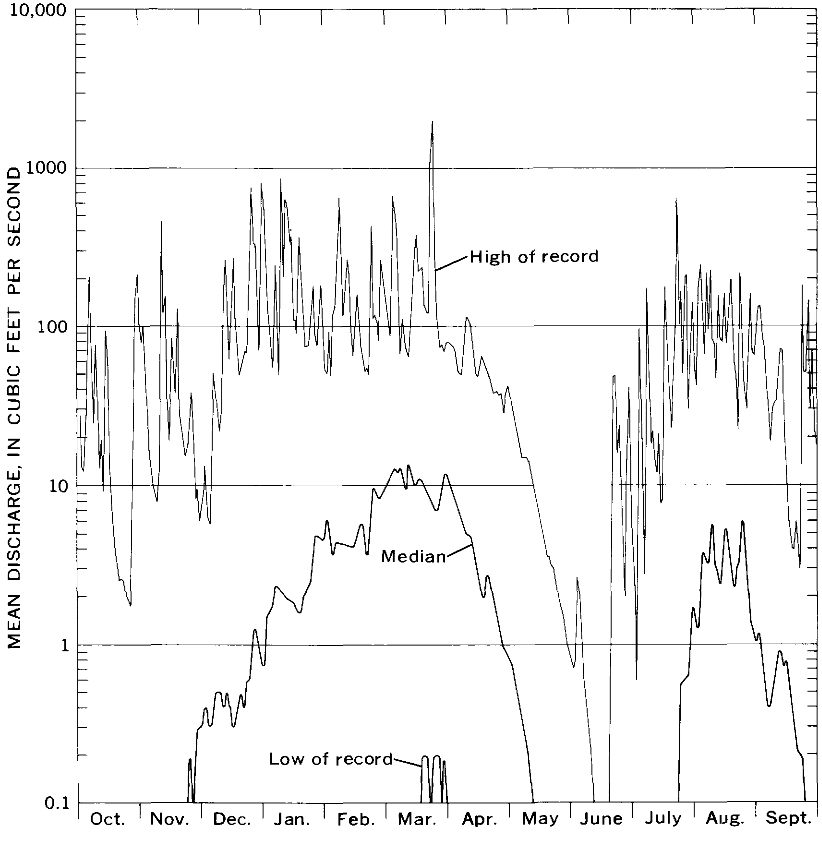


FIGURE 7.—Distribution of the daily high, median, and low flows, 1936–63, for Sabino Creek near Tucson, Ariz.

all gaging stations except Sonoita Creek near Patagonia and Santa Cruz River near Nogales; a 183-day mean of 5 cfs or less can be expected to occur at all gaging stations within a 2-year period (table 4).

TABLE 4.—*Recurrence intervals for 183- and 274-day mean flows of 1 cfs or less and 5 cfs or less at gaging stations*

Station	Recurrence interval, in years			
	Flow of 1 cfs		Flow of 5 cfs	
	183-day mean	274-day mean	183-day mean	274-day mean
Santa Cruz River near Lochiel	<2	2.6	<2	<2
Santa Cruz River near Nogales	14	>50	<2	8
Sonoita Creek near Patagonia	22	>50	<2	2.4
Santa Cruz River at Continental	<2	13	<2	3
Santa Cruz River at Tucson	<2	31	<2	8
Tucson Arroyo at Vine Avenue, Tucson	<2	2	<2	<2
Sabino Creek near Mount Lemmon	<2	<2	<2	<2
Sabino Creek near Tucson	3	6	<2	<2
Rincon Creek near Tucson	<2	2.4	<2	<2
Rillito Creek near Tucson	<2	8	<2	2.2
Santa Cruz River at Cortaro	3.2	>50	<2	10

Most streams in the Santa Cruz River basin are ephemeral and are dry on an average of at least once every 2 years; the number of days of no flow ranges from 4 at Sonoita Creek to 335 at Rillito Creek near Tucson (fig. 8). In any future year there is a 50 percent chance of 4 or more days of no flow at Sonoita Creek near Patagonia and a 5 percent chance of 73 or more days of no flow.

ANALYSIS OF HIGH FLOWS

In the upper Santa Cruz River basin the same streams that are dry for long periods of time carry high flows that have on occasion exceeded the capacity of the channels and overflowed onto the flood plains. Thunderstorms occur in the basin with more regularity and produce more streamflow than do frontal storms. As a result of these high-intensity summer storms, more than 93 percent of the flood peaks above a selected base discharge occur in July, August, and September on the Santa Cruz River (table 5); the base discharge is selected so that an average of three peaks each year is included. The flood peaks are more evenly distributed throughout the year on streams having drainage areas that extend high into the mountains, such as Sabino Creek (table 5). In the Sabino Creek drainage previously precipitated snow commonly is supplemented by rain, and winter floods occur with more regularity than at lower altitudes that have no snow cover. Occasionally, when snowfall at the lower altitudes is followed by rain,

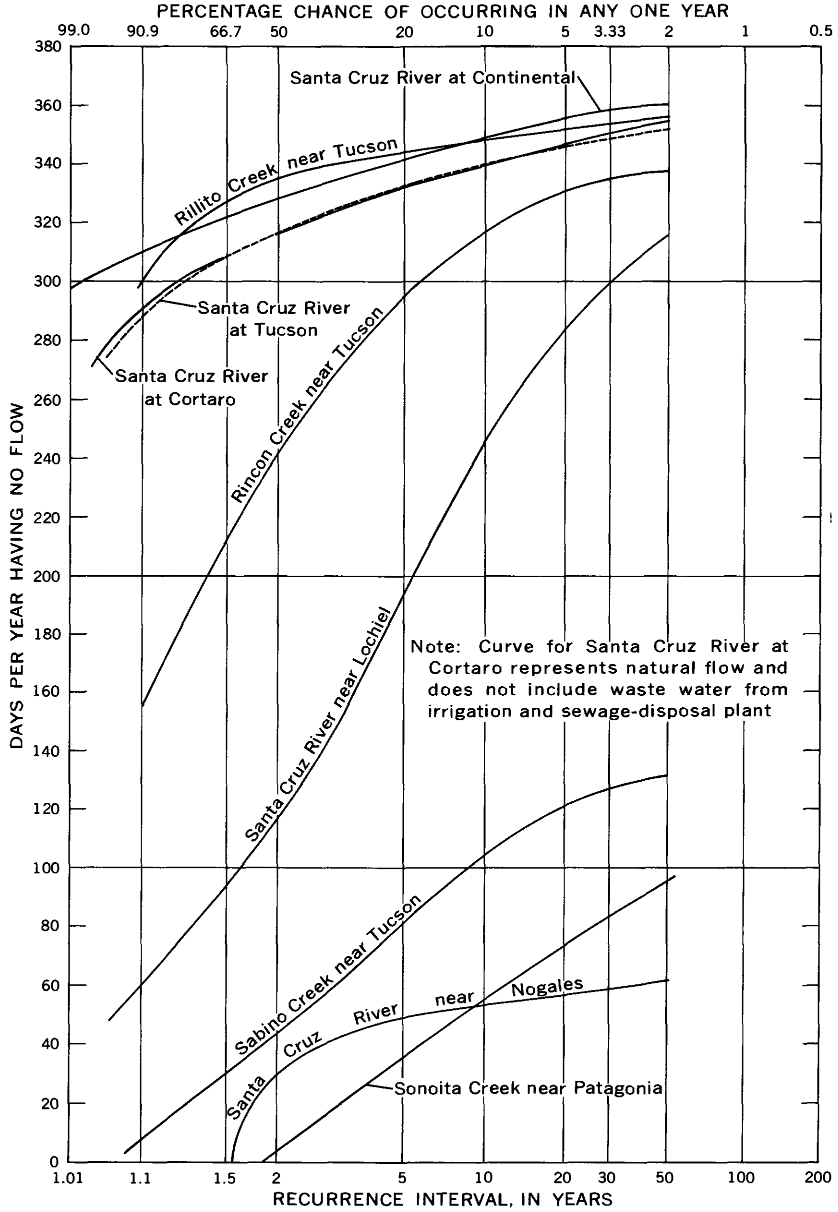


FIGURE 8.—Frequency of days having no flow at selected gaging stations.

the resulting winter flood produces a large volume of flow. Figure 9 compares summer and winter flood volumes on the Santa Cruz River at Tucson.

TABLE 5.—*Monthly distribution of flood peaks above a selected base discharge*

Station	Period of record (water year)	Total number of peaks	Base (cfs)	Percentage of peaks above base												Percentage of peaks in July, August, and September
				Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	
Santa Cruz River near Lochiel	1949–1965	39	1,000							43	49	8				100
Santa Cruz River near Nogales	1930–1965	119	2,000	2					2	38	51	6			1	95
Sonoita Creek near Patagonia	1930–1965	111	1,200		2					32	53	12	1			97
Santa Cruz River at Continental	1940–1965	98	2,000	2						29	53	12	4			94
Santa Cruz River at Tucson	1915–1965	169	1,700	2	1				1	30	50	13	1	1	1	93
Tucson Arroyo at Vine Avenue, Tucson	1940–1965	86	150	2	2		1		1	28	37	18	6	1	4	83
Sabino Creek near Mount Lemmon	1951–1959	31	50	10		6				26	42	3	7	3	3	71
Sabino Creek near Tucson	1932–1965	139	150	8	8	6	1		1	17	32	11	6	3	7	60
Rincon Creek near Tucson	1953–1965	59	100	7	1	3				14	61	8	2	2	2	83
Rillito Creek near Tucson	1915–1965	140	1,000	4	5	4			1	26	39	13	2	2	4	78
Santa Cruz River at Cortaro	1940–1965	97	2,700	2		1			1	34	49	10	2		1	93

FLOOD FREQUENCY

Patterson and Somers (1966) made a regionalized flood-frequency analysis for instantaneous peak flows in the upper Santa Cruz River basin. The term "regionalized" refers to the delineation of the boundaries of regions having similar flood characteristics and to the establishment of relations between pertinent characteristics of the flood-frequency curve and basin or climatological parameters within the homogeneous region (Cruff and Rantz, 1965). For the upper Santa Cruz River basin, the mean annual flood was used as the index flood, and the drainage area was used as the basin parameter.

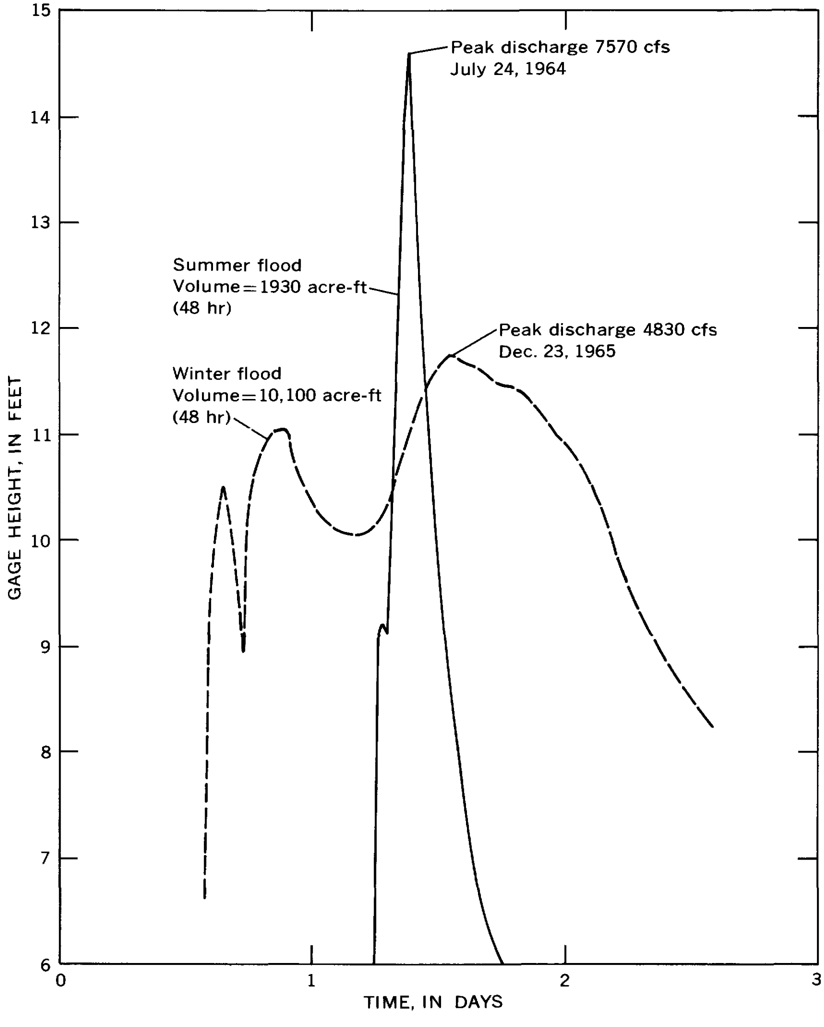


FIGURE 9.—Comparison of a summer flood and a winter flood on the Santa Cruz River at Tucson.

The discharge for a flood of a selected frequency is computed from figures 10 and 11 by the following steps: (1) Determine the discharge of the mean annual flood for the contributing drainage area from figure 10, (2) determine the ratio of the flood of the selected recurrence interval to the mean annual flood from figure 11, and (3) multi-

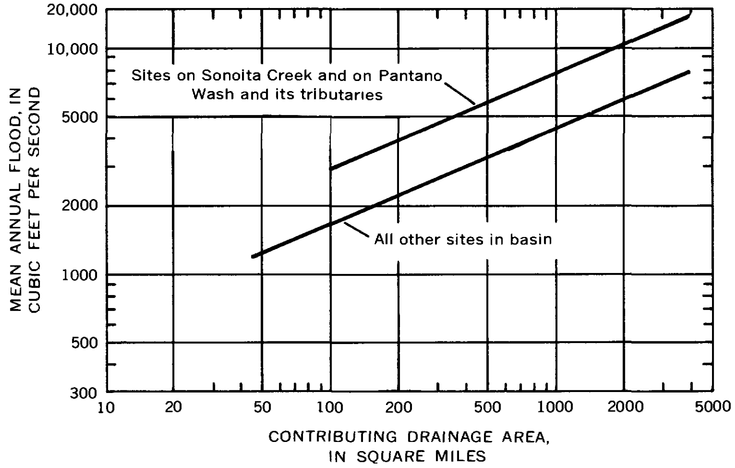


FIGURE 10.—Variation of mean annual flood with drainage area in the upper Santa Cruz River basin. (After Patterson and Somers, 1966.)

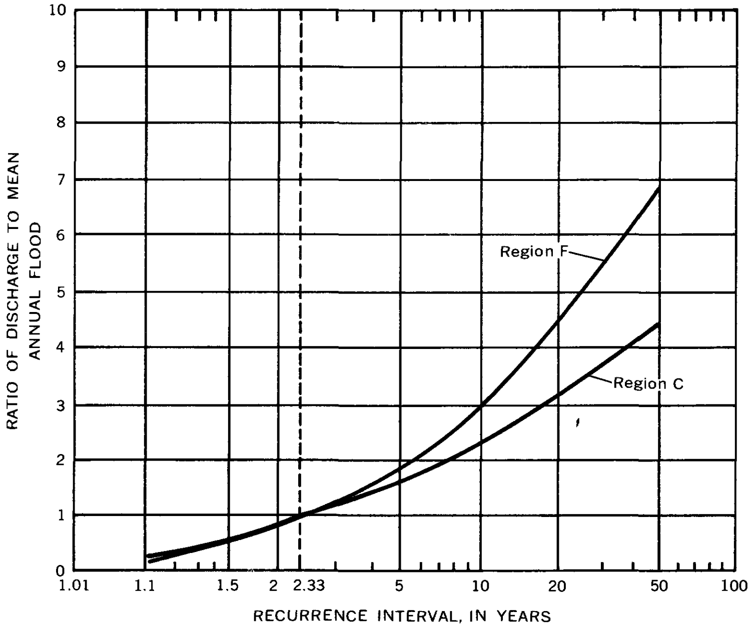


FIGURE 11.—Regional frequency curves for the upper Santa Cruz River basin. (After Patterson and Somers, 1966.)

ply the ratio (step 2) by the mean annual flood to obtain the discharge for a flood of a selected frequency. Additional data collected since Patterson and Somers (1966) made their study indicate that the region F curve (fig. 11) should be used for streams draining directly from the south and west slopes of the Santa Catalina, Tanque Verde, and Rincon Mountains and that the region C curve should be used for the rest of the basin (B. N. Aldridge, written commun., 1968). The magnitudes of floods at gaging stations on the Santa Cruz River for different recurrence intervals follow:

Gaging station	*Mean annual flood (cfs)*	*10-year flood (cfs)*	*20-year flood (cfs)*	*50-year flood (cfs)*
Santa Cruz River near Lochiel	1, 530	3, 550	4, 970	6, 760
Santa Cruz River near Nogales	3, 400	7, 890	11, 000	15, 000
Santa Cruz River at Continental	5, 500	12, 800	17, 900	24, 300
Santa Cruz River at Tucson	6, 250	14, 500	20, 300	27, 600
Santa Cruz River at Cortaro	7, 650	17, 700	24, 900	33, 800

The variability of the annual peak discharge at gaging stations is shown in table 6. The coefficients of variation given in table 6 show that there is less variability in the annual peak flows than in the annual flows relative to their means (table 2). The annual peak discharge usually is the result of a summer storm; summer floods occur more frequently than winter floods (table 5). The less frequent occurrence of a large volume winter flood increases the variability of the annual flow.

FLOOD VOLUMES

Flood-volume frequency curves (pl. 5) were prepared for the 10 gaging stations in the basin having sufficient periods of record. The curves present the floodflow data necessary for studies involving the storage of flood water. The largest volume of flow that can be expected for a selected number of days and a given recurrence interval is determined by multiplying the number of days by the mean discharge for the given recurrence interval. For example, the largest 7-day volume that can be expected to occur once every 20 years on Sonoita Creek near Patagonia is 1,890 cfs-days, or 3,750 acre-feet (pl. 5; table 7).

STORAGE ANALYSIS

Streamflow in the upper Santa Cruz River basin is of small quantity and large variability and causes occasional flooding. The construction of storage reservoirs is a commonly used method of compensating for the variability of streamflow, increasing the usability of available flows, and reducing the magnitude of floods. This section of the report summarizes studies of the magnitude of the storage required to pro-

TABLE 6.—*Variability of annual peak discharge at gaging stations*

Station	Drainage area (square miles)	Period of record	Annual peak discharge					
			Arithmetic average (cfs)	Extremes (cfs)		Standard deviation (cfs)	Coefficient of variation	Skewness
				High	Low			
Santa Cruz River near Lochiel	82. 2	1949–65	1, 840	4, 810	7. 6	1, 430	0. 78	0. 66
Santa Cruz River near Nogales	533	1930–65	4, 540	12, 000	1, 620	2, 730	. 60	1. 14
Sonoita Creek near Patagonia	209	1930–65	3, 740	14, 000	669	2, 740	. 73	1. 85
Santa Cruz River at Continental	1, 662	1940–65	5, 920	17, 500	370	4, 240	. 72	1. 30
Santa Cruz River at Tucson	2, 222	1915–65	5, 900	16, 600	1, 190	3, 670	. 62	. 95
Tucson Arroyo at Vine Avenue, Tucson	27. 0–8. 2	1940, 1943–65	1, 530	5, 000	149	1, 240	. 81	1. 21
Tanque Verde Creek near Tucson	43. 0	1960–65	1, 330	2, 360	789	638	. 48	1. 21
Sabino Creek near Mount Lemmon	3. 19	1951–58	199	344	68	96	. 48	. 10
Sabino Creek near Tucson	35. 5	1933–65	1, 380	5, 100	55	1, 170	. 85	1. 41
Bear Creek near Tucson	16. 3	1960–65	306	575	53	171	. 56	. 12
Tanque Verde Creek at Tucson	221	1940–45	3, 090	9, 000	573	3, 350	1. 08	. 85
Pantano Wash near Vail	457	1959–65	6, 990	9, 960	1, 500	2, 830	. 40	. 72
Rincon Creek near Tucson	44. 8	1953–65	2, 180	8, 250	150	2, 350	1. 08	1. 30
Rillito Creek near Tucson	918	1915–65	6, 310	24, 000	512	4, 570	. 72	1. 47
Santa Cruz River at Cortaro	3, 503	1940–47, 1950–65	8, 640	17, 000	1, 550	4, 430	. 51	. 47

TABLE 7.—*Flood volumes having 20- and 50-year recurrence intervals for 1-, 3-, and 7-day periods at selected gaging stations*

Station	Flood volume (acre-ft)					
	1-day		3-day		7-day	
	20-year	50-year	20-year	50-year	20-year	50-year
Santa Cruz River near Nogales	4,760	6,250	9,520	14,300	14,600	22,200
Sonoita Creek near Patagonia	2,280	3,670	2,920	3,690	3,750	5,410
Santa Cruz River at Continental	10,300	----------	13,700	----------	23,600	----------
Santa Cruz River at Tucson	11,300	15,500	19,000	29,200	23,600	37,500
Tucson Arroyo at Vine Avenue, Tucson	770	----------	830	----------	930	----------
Sabino Creek near Tucson	2,480	3,770	4,400	6,840	5,830	9,020
Rillito Creek near Tucson	9,120	9,820	17,300	23,800	18,700	30,500
Santa Cruz River at Cortaro	14,700	----------	15,500	----------	23,600	----------

vide a continuous reservoir outflow and the release of floodflows at lower rates. The summary is presented only as an aid in preliminary planning of reservoirs, and analyses of the maximum probable floods, which are used for detailed design of reservoir spillways, were not included in this study.

SUSTAINED FLOW

The volume of storage required to provide a sustained minimum flow may be determined either by the within-year-storage method or by the carryover-storage method. The within-year-storage method is based on the assumption that the volume of flow each year is sufficient to replenish the annual storage required to sustain a selected minimum outflow rate. In contrast, the carryover-storage method is based on the concept of storing water for periods greater than 1 year to sustain a minimum outflow rate. In both methods the amount of evaporation from the reservoir surface is not included, and it is necessary to add the amount of evaporation to the computed storage requirements.

Within-year-storage requirements were analyzed by the annual mass-curve method (H. C. Riggs, written commun., 1964) by a digital

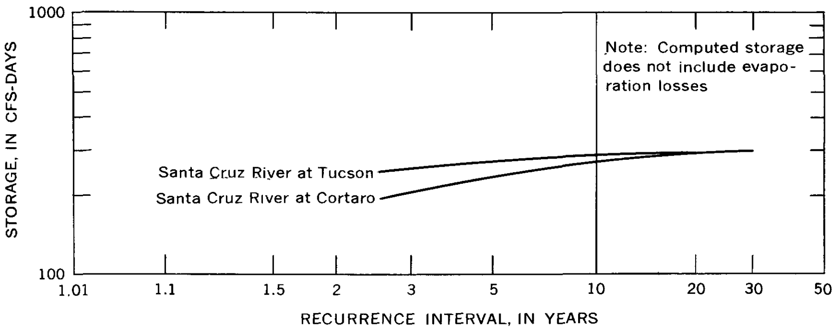


FIGURE 12.—Relation between volume of storage and the average length of time that the indicated storage would be insufficient to sustain a minimum reservior outflow of 1 cfs.

computer. For the period of record, the annual flow was sufficient to replenish the storage required to sustain a flow of 1 cfs at only three of the 15 gaged sites; the annual flow was insufficient to replenish the storage required to sustain a flow of 3 cfs at all the gaged sites (table 8). The length of record at Pantano Wash near Vail is insufficient for reliable analysis; therefore, only the records for Santa Cruz River at Tucson and at Cortaro were used to compute storage requirements by the within-year method (fig. 12).

TABLE 8.—*Percentage of years streamflow would be insufficient to replenish the storage required for selected draft rates*

Station	Number of years analyzed	Percentage of years for draft rate (cfs) indicated					
		1	3	5	7	10	15
Santa Cruz River near Lochiel	14	43	64				
Santa Cruz River near Nogales	31	3	3	10	13	42	58
Sonoita Creek near Patagonia	31	3	10	35			
Santa Cruz River at Continental	17	6	18	18	35	47	
Santa Cruz River at Tucson	49	0	4	12	18	29	51
Tucson Arroyo at Vine Avenue, Tucson	8	62	100				
Tanque Verde Creek near Tucson	4	25	75				
Sabino Creek near Mount Lemmon	6	50	100				
Sabino Creek near Tucson	31	16	42	52	81		
Bear Creek near Tucson	4	50	100				
Tanque Verde Creek at Tucson	4	25	50	75	100		
Pantano Wash near Vail	4	0	25	25			
Rincon Creek near Tucson	11	27	45	55			
Rillito Creek near Tucson	49	6	27	43	57		
Santa Cruz River at Cortaro	19	0	5	5	16	16	26

If streamflow is to be carried over from years when the flow exceeds a desired draft rate and used during years of low flow, then evaporation becomes an even more important factor in the analysis. In the upper Santa Cruz River basin, the average annual lake evaporation is about 5½ feet (Kohler and others, 1959, pl. 2). For example, if a storage reservoir were built on Sonoita Creek to provide a 5-cfs draft rate, a maximum storage of 2,600 cfs-days, or 5,160 acre-feet, would be required. The time that the water must be stored to provide this continuous 5-cfs draft rate is 9 years—from the time the reservoir begins filling in excess of the draft rate to the time when the streamflow deficiency ends (fig. 13). The water level in a reservoir on Sonoita Creek would decline about 50 feet in 9 years as a result of evaporation; therefore, even if storage were available, streamflow would be insufficient to provide a continuous 5-cfs draft rate. At Sabino Creek near Tucson, the maximum storage requirement for a 5-cfs draft rate would be 5,000 acre-feet, and the evaporation loss would be about 38 feet during a 7-year period—for example, if the reservoir had an average depth of 100 feet, the evaporation loss would be 1,900 acre-feet. At Rillito Creek near Tucson the maximum storage requirement for a 5-cfs draft rate would be 8,730 acre-feet, and a storage period

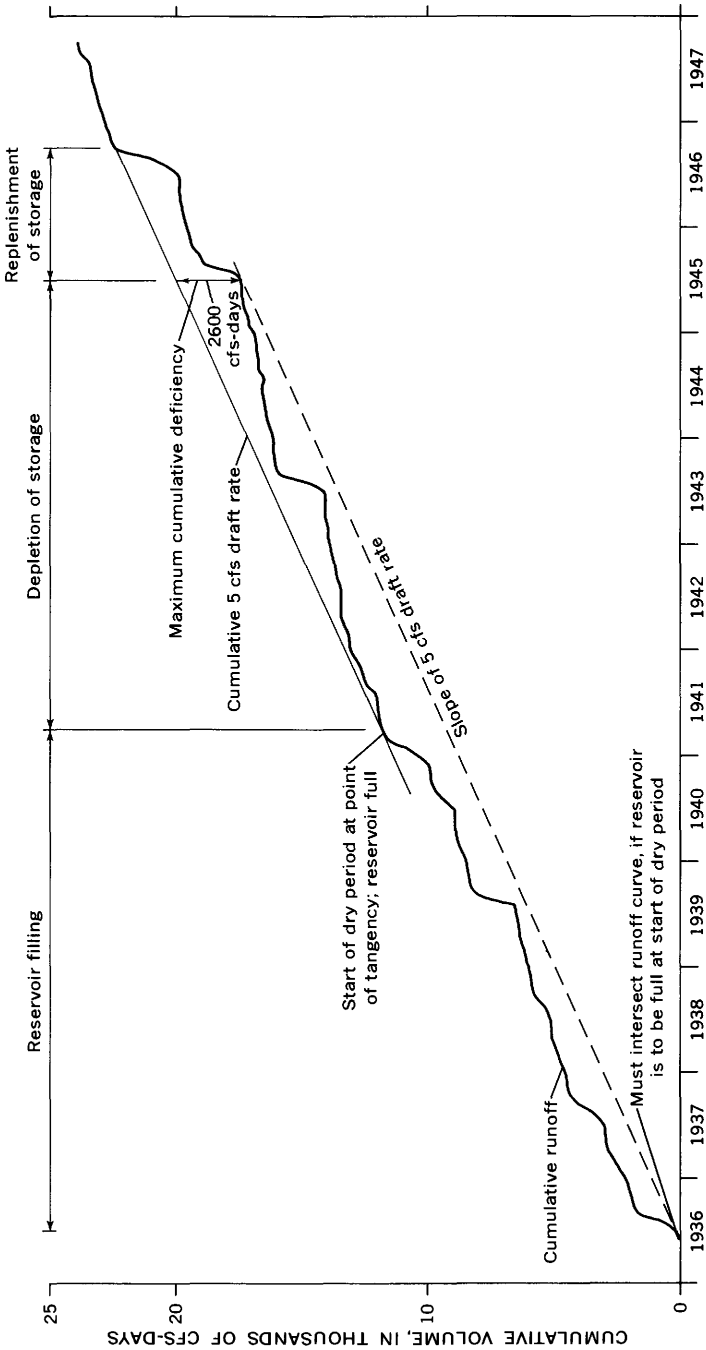


FIGURE 13.—Mass diagram for the determination of storage, Sonoita Creek near Patagonia, Ariz.

of 9 years would be required. At Santa Cruz River at Tucson, the maximum storage requirement for a 15-cfs draft rate would be 24,800 acre-feet, and a storage period of 7 years would be required. The storage requirements for Rillito Creek and the Santa Cruz River would be larger if the losses by evaporation, seepage, and silting were included.

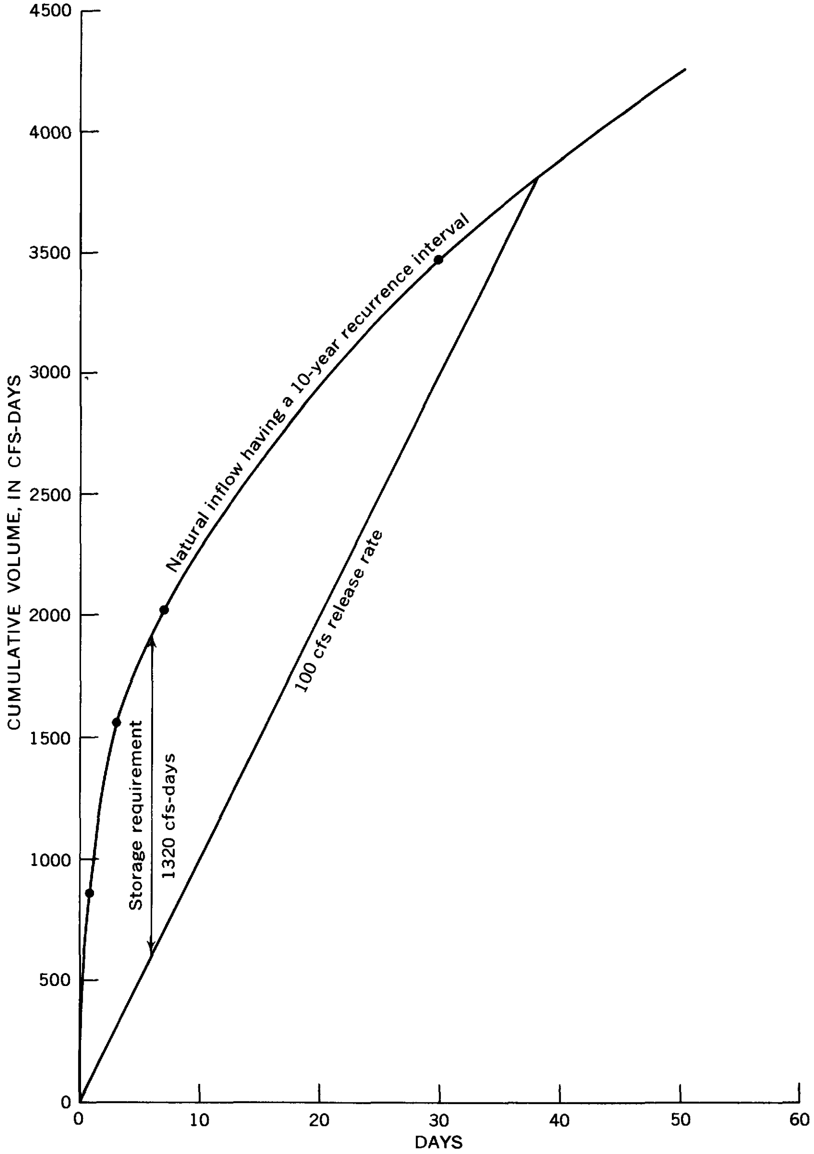


FIGURE 14.—Frequency-mass analysis for Sabino Creek near Tucson.

Because of the high evaporation rates and the extremely low flows in some years, streamflow in the upper Santa Cruz River basin is not a likely source for a continuous water supply of any magnitude. Streamflow, however, could be used in ways other than as a continuous draft. For example, streamflow could be stored and used in a few months to supplement existing ground-water supplies; the short-term storage would reduce the evaporation losses in the reservoirs.

CONTROLLED RELEASE OF FLOODFLOWS

A storage analysis was made to determine the design storage needed to contain floodflows for release at lower sustained rates (pl. 6). The water, when released at lower rates, would increase the amount of ground-water recharge from the floodflows. A frequency-mass curve analysis (fig. 14) of the flood-volume curves (pl. 5) for different release rates was used to develop the storage-release frequency curves.

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With discussion of human induced changes to the natural and ordinary base flow along , sediment contribution to and the morphology along the natural channel of the San Pedro River .

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Contents

Flood-Hazard Zonation in Arid Lands

H. W. HJALMARSON

Potential flood hazards in arid southern and western Arizona stem from different geomorphic and hydrologic characteristics and can be grouped into zones. The zonation is based on the physical features of the terrain, the sources of flooding, the expected frequency of flooding, and the expected erosion and sediment deposition. Various combinations of these factors create differing degrees of hazard. Distributary flow areas have stream channels that convey only a small fraction of the 100-year peak discharge and channels that can completely fill with sediments during a single flood. A basic understanding of the common and different flood hazards of areas in southwestern Arizona can lead to effective flood-plain management and design of hydraulic structures.

Desert floods in the southwestern United States result from large amounts of intense rainfall in the steep headwater areas. When this happens, the normally dry channels can suddenly host dangerous, debris-laden torrents (*1*). Typical floods are characterized by a rapid rise and cessation of discharge that are dramatically referred to as flash floods. Discharge generally is decreased by infiltration as the flood wave moves downstream over sandy alluvial channels (*2*). Large amounts of debris are carried down the channels, and the shapes of the channels generally change during flooding. Channels scour and fill during flooding, and channel banks wetted by floodwater often collapse after flooding.

Bridges on base-level streams often fail because of scour. Culverts located in aggrading alluvial areas fill with alluvial debris, and bank protection is ineffective. Many lives have been lost because of bridge failure, and damage to public and private property has been considerable.

This paper presents some generalizations about the nature of flooding in the deserts of southern Arizona that are based largely on the relationship between flood hazards and desert landforms. Flood hazards unique to the desert areas are described, and zones of potential hazard are characterized. Limitations of Federal Emergency Management Agency guidelines (*3*) are identified.

GENERAL CHARACTERISTICS

Degrees and types of potential flood hazard in the desert are related to geomorphic characteristics. Figure 1 illustrates the relationship between geomorphology and flood hazard and lists some general characteristics of the flood-hazard zones. Zone 1 is defined as the area inundated by the 100-year flood on base-level streams, which conforms to the present regulatory flood used by the Federal Emergency Management Agency (FEMA) (*3*). Zone 2 includes land adjacent to zone 1 that is subject to erosion by floods but not subject to inundation by the 100-year flood. Zone 3 includes relatively flat undissected areas where floodflow is shallow and unconfined; it includes former flood plains of base-level streams. Zone 4 includes areas of distributary flow, such as alluvial fans, where the amount of floodflow at a particular location is impossible to predict. Zones 5 and 6 include a variety of landforms where the 100-year flood is confined to rigid channels that generally drain areas less than 100 mi².

The mountainous areas (zone 6) are the source of weathered rock debris, and the stream channels usually have very little fine-grained material. A sharp break is often present in the gradient at the junction of the mountain front and the piedmont plain (zone 5) (fig. 2). Pediment areas are sparsely covered by a thin veneer of detritus, and stream channels have a mixture of fine- and coarse-grained material, including boulders. The alluvial fan and the base-level plain (fig. 1) have a wide variety of forms caused by natural and human-induced erosion and deposition that have occurred along the entire desert profile including base-level streams (*4*).

The channels of several alluvial streams have become entrenched because a balance was not maintained between factors such as flow, sediment discharge, slope, meander pattern, channel cross-section, and roughness. For example, minor fluctuations in meteorological conditions over a few years can alter the movement, transport, and production of sediment in a basin. During drier years, sediment can accumulate in stream channels, and subsequent wetter years may cause the sediment to be flushed from the basin. Reaches of channel with conditions of both uniform flow and nonuniform flow may appear to be aggrading or degrading. Thus, a reach of channel on an alluvial stream will not necessarily remain stable over a period of a few years.

ZONE 1

Zone 1 includes the channel and parts of the flood plain that would be inundated by the 100-year flood on playas, base-level streams, and larger tributaries. This zone has a high potential for flooding because floodflow normally is concentrated in defined channels and land adjacent to the channels. The velocity of flow in the channels is high, and the adjacent land is susceptible to erosion.

Historic information indicates that the current defined channels for base-level streams were not present until late in the nineteenth century and early in the twentieth century when some channels became entrenched (*3*, *5*). The cause of entrenchment is the subject of considerable debate among hydrologists, but a strong argument can be made for change

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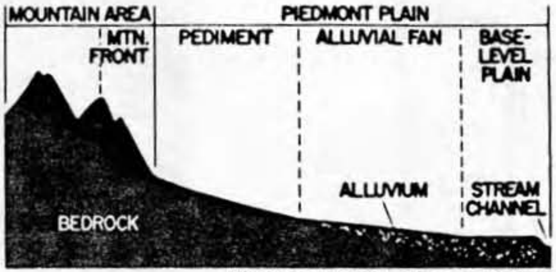
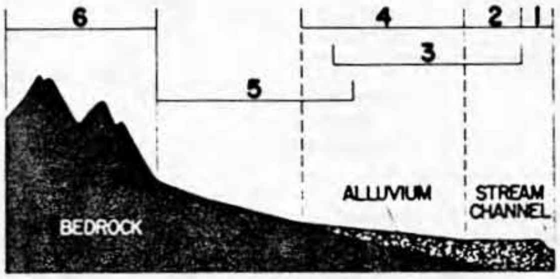


Characteristic desert profile modified from (3)

A. Geomorphic components



B. Flood-hazard zones

Zone	Description
1	Extent of the 100-year flood on base-level stream.
2	Part of flood plain that may be inundated by rare large floods and (or) eroded by frequent small floods.
3	Flooding from sheetflow, standing water, and water that collects in depressions.
4	Flooding in channels and sheetflow on slightly dissected alluvial plains. Flow can be distributary and there is a greater than average chance of sediment deposition.
5	Flooding confined to defined channels of small tributary streams.
6	Sheetflow and flooding in defined clean-scoured channels.

FIGURE 1 Geomorphic features and flood-hazard zones of typical mountain-plain desert profile.

FIGURE 2 View looking north at the western slopes of the Tortolita Mountains. The sharp break in land slope at the junction of the mountain front and piedmont plain is typical of mountain-plain deserts.

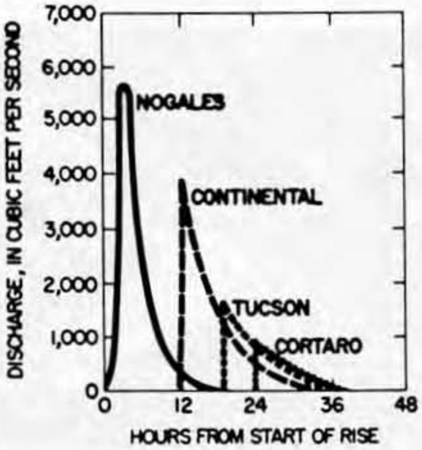
of climate. Floodflow in entrenched channels is more confined and the channel beds are less rough. Flood-wave celerity is greater and wave dispersion is less than for pre-entrenchment conditions. The entrenchment has had a significant effect on the flood characteristics of several base-level streams. Channel beds and banks can scour greatly in short periods during floodflow.

Zone 1 includes a variety of trenched and untrenched channels. Floodwater that is confined within a vertical walled arroyo only a few hundred feet wide can spread over an unchanneled valley for several miles downstream (figs. 3 and 4). Runoff that enters the desert-plain areas crosses progressively more alluvium where there is a great potential for infiltration (fig. 5). Burkham (*2*) found that the amount of loss along channels in the Santa Cruz River basin is related to the length of reach and the infiltration capacity of the channel.

Bridges on base-level streams become vulnerable to failure when the stream channel that supports the bridge is scoured. The abutments of many bridges in southern Arizona failed

FIGURE 3 View looking downstream at the entrenched channel of the Santa Cruz River at Tucson, Arizona. Floodwater of the 100-year flood is confined within the channel of the reach. Lateral erosion of the channel banks is restricted by massive soil-cement banks. Interstate 10 is located to the left of the 200-foot-wide by 20-foot-deep river channel. Since 1914, the channel has widened about 100 feet and deepened about 15 feet.

FIGURE 4 View looking east along Interstate 8 at the Santa Cruz River downstream from Tucson near Casa Grande, Arizona. The width of the flooding in zones 1 and 2 on October 4, 1983, was about 8 miles. Some water is on the road.



Gaging station	Miles from Nogales	Average annual runoff, in percent[1]
Continental	50	29
Tucson	79	19
Cortaro	88	14

[1] Amount of the average runoff at the Nogales gage that reached the indicated gage (1940-46, 1952-68).

FIGURE 5 Typical flow event showing transmission losses and attenuation of peaks for the Santa Cruz River, a base-level stream in southern Arizona (*7*).

during the flooding of October 1983 (figs. 6 and 7). Local scour around abutments and piers is a major cause of bridge failure on base-level streams in Arizona and throughout the United States (*8*).

Playa surfaces are rather flat, generally smooth, and composed of silt and clay. Many small, poorly defined channels are distributary or serve as distributary channels during floodflow as water crosses low divides. For example, during the large storm of early October 1983, runoff from Ash Creek, which is an unentrenched stream draining an area of about 500 square miles, spread laterally for more than 3 miles as floodflow entered the Willcox Playa. Nearly 2 miles of Interstate 10 near the town of Willcox was inundated with shallow floodwater, which resulted in highway closure for a few hours.

ZONE 2

Zone 2 includes areas adjacent to Zone 1 that could potentially be inundated by rare floods larger than the 100-year flood if the conveyance of the main channel changed or the hydraulic gradient changed or was eroded by floodflow. The potential hazard resulting from inundation is less than for areas in zone 1. For areas subject to erosion, the potential hazard is variable and can be greater than that for zone 1. Land adjacent to banks on the outside of bends or at constrictions or obstructions can erode quickly and extensively during frequent small flows of long duration (fig. 8).

Hazards in zone 2 are related more to lateral bank erosion than to inundation, and, at present, FEMA does not include

FIGURE 6 View looking south at one of many abutment failures resulting from floodwaters of October 1983 in southeastern Arizona. The scene is Interstate 10 at the Gila River on October 4, 1983. Flow is to the right.

expected bank movement in the definition of hazard degree. In fact, FEMA does not accept water-surface computations reflecting channel scour even where scour during floodflow is a common occurrence. Many models that predict channel scour, such as HEC-6, are in use, but the models do not consistently produce reliable results for all channels. Thus, improved models are needed to reliably define bank erosion for non-arbitrary flood-plain management of zone 2.

Many zone 2 floods originate in the surrounding mountains, where there is little soil and much exposed rock. Floodflow from these areas may carry sediment that is greater than the load. When floods confined in the channels reach the base-level streams (zone 1), the water picks up sediment from the channel banks. Floodflow in the steep, smooth channels can carry much sediment; thus, the banks in zone 2 areas can erode laterally tens of feet and even 100 feet or more during a single flood.

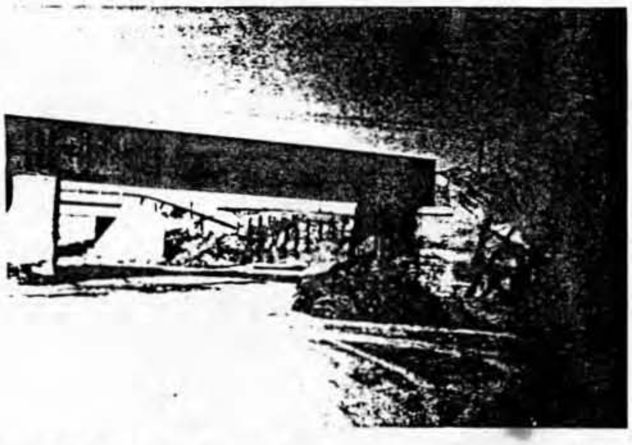


FIGURE 7 View looking downstream at the right bank of Rillito Creek at the Southern Pacific and Interstate 10 bridges at Tucson, Arizona. The failure of the wire-rock revetment at the abutments is typical for base-level streams in the area.

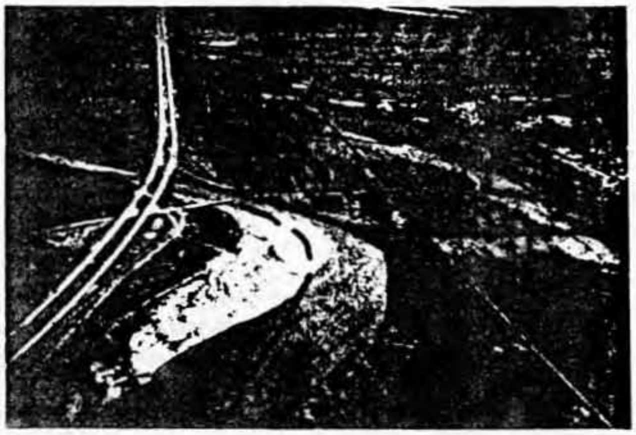


FIGURE 8 View looking south and upstream at the Santa Cruz River at Interstate 19 on October 3, 1983. The right bank abutment of the northbound lane failed and the left bank abutment of the bridge to the right of Interstate 19 was destroyed during flooding on October 1 and 2. The dashed line approximately represents the location of the left bank of the entrenched channel before the flood.

ZONE 3

Zone 3 is former flood plain of base-level streams and other relatively flat undissected areas. Areas are subject to sheetflow of a few inches to about 2 feet deep from floodflow originating in higher zones (figs. 9 and 10). Sheetflow a few inches deep can result from direct rainfall. Runoff generally is unconfined, and flow velocities generally are less than 2 or 3 square feet. The erosion hazard is low except along the few short incised channels.

Floodwater entering zone 3 spreads laterally and coalesces with floodwater entering the zone at other locations. Decreasing depth and velocity of flow as the width increases results in a reduced sediment-carrying capacity. Large amounts of sediment are deposited because of this spreading. Another

FIGURE 9 View looking northeast at floodwater from a small confined wash debouching onto land in zone 3. Floodflow spread to a width of more than 1 mile about half a mile downstream from the confinement. Flooding was on June 22, 1972, upstream from the Arizona canal east of Scottsdale, Arizona.

FIGURE 10 View looking south and downstream at sheetflow in zone 3 on June 22, 1972. The scene is in northeast Phoenix at 44th Street between Bell and Greenway Roads.

factor contributing to sediment deposition is loss of flow due to infiltration.

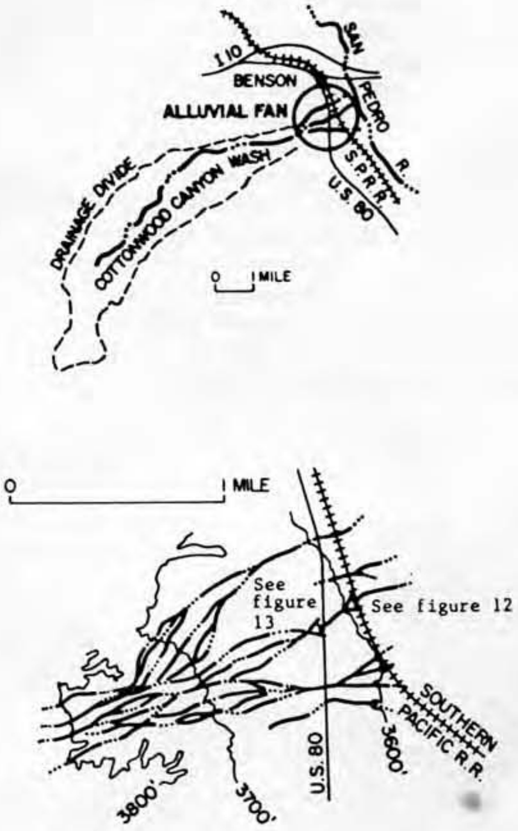
Culverts and bridges in zone 3 are usually not subject to serious erosion hazards unless the structure causes excessive backwater. Where excessive backwater does occur, the high head and corresponding high velocities through the structure opening can result in hazardous erosion of material supporting the structure. Sediment deposition resulting in the filling of structure openings, such as culverts, with debris is an occasional problem.

ZONE 4

Floodwater entering zone 4 from confined channels in zones 5 and 6 spreads into distributary channels (fig. 11) with a corresponding decrease of velocity and depth. The amount of flow also is decreased by infiltration into the sandy beds. There is less water and less energy to transport sediment, and thus sediment is deposited in and along the channels to form a mound of alluvial material. Channels completely fill during flash flows, and culvert and bridge openings become ineffective (figs. 12 and 13). Frequent cleaning of culvert and bridge openings is needed at many stream channels in zone 4.

Zone 4 includes the slightly dissected alluvial slopes that commonly exhibit a distributary drainage system. The flood potential of zone 4 has often been overlooked (*9*). Bajadas and single alluvial fans (fig. 14) are typical landforms in the aggrading area. The rate of sediment deposition, one aspect of the dynamic behavior of the fans, is complex and variable (*3*, *5*). Some fans seem to aggrade at a rapid rate, and the active channels change frequently. Many of the fans in southern Arizona appear to be less dynamic than fans in areas of southern California (*10*) and Nevada (*11*), where tectonic activity is greater. Also, on the basis of soil characteristics such as the age of the bajada soils (*12*), the alluvial slopes in some areas are relatively stable; apparently, little aggradation or degradation occurred during the Holocene epoch (about the past 10,000 years). Many alluvial fans are present in southern Arizona (*13*), and they may occupy about 30 to 40 percent of the area.

FEMA has presented methods for evaluating flood hazards on alluvial fans that assume channels downstream from the fan apex are equally likely to occur any place on the fan



◁ Location and view angle of photograph.

FIGURE 11 Alluvial fan showing contours and distributary channels on Cottonwood Canyon Wash at Benson, Arizona.

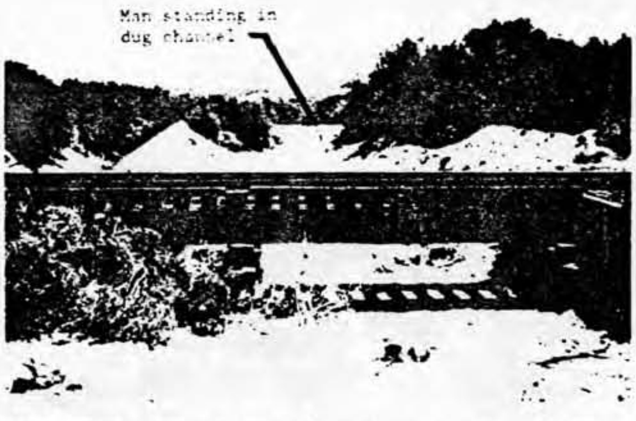


FIGURE 12 View looking downstream at railroad bridge in south Benson, Arizona. The opening was completely filled during a 1-hour flash flood on July 6, 1981. Note the depth of the channel where the filled material has been removed about 100 yards downstream from the bridge. See figure 11 for location of photograph.

FIGURE 13 View looking downstream at culvert on U.S. Highway 80 in south Benson, Arizona. The opening was nearly filled during the flash flood of July 6, 1981. Floodflow velocities in the main channel downstream from the culvert were very high and a local resident observed two standing waves about 20 feet apart at the flood peak. See figure 11 for location of photograph.

surface (*4*). Although this assumption may be valid for estimating the flood hazard of highly active fans, it may not be applicable for the many fan surfaces in southern Arizona that are relatively inactive. The more stable fans have a defined network of distributary channels with some abandoned channels that presently head on the fan surface. Floodflow is more likely in the defined channels that head in mountains, less likely in the abandoned channels, and unlikely on much of the high ground between the channels. Although the amount of discharge in a particular branch of a divided channel is difficult to determine, the likelihood of floodflow at any location on the fan surface is not equal.

The topographic relief across single alluvial fans and bajadas is variable and is an index of the age of the landform. The local relief between channels in zone 4 is commonly less than 5 feet but occasionally more than 20 feet. Alluvial fans with small local relief tend to be more active than alluvial slopes with large relief.

The filling of the stream channel shown in figures 12 and 13 may be offsetting the potentially hazardous headcutting of the channel. The stream is tributary to the San Pedro River, which is entrenched. Tributaries to the San Pedro River also have become entrenched near the river (fig. 15). The hazardous conditions shown in figures 14 and 15 are representative of the variable and dynamic behavior of streams in southern Arizona.

Floodwater on inactive fans generally is in entrenched channels that anastomose, divide, and combine. Much of the land clearly is above the 100-year flood, but flood hazards on fans are unpredictable. Possible consequences of floods in the low-lying land and channels include:

1. Channel erosion and lateral bank movement.
2. Channel filling with deposited sediment and the associated increased flooding of adjacent flood plain.
3. Lateral shifting (avulsion) among distributary channels.

The FEMA type of flood hazard assessment (random distribution of flood depth and velocity) may not be applicable. Flood hazard assessment for bridge or culvert design is difficult because flood response at any given location on channels in zone 4 is unpredictable.

ZONE 5

Zone 5 is defined as the pediment and upper alluvial plain areas with defined channels that commonly form a tributary system. The surface of the pediment areas is a complex mixture of rock, alluvium, and thin soils of various ages. Stream channels commonly have slopes from 0.02 to 0.04 with an upper limit of about 0.2 (*3*). Channel beds in the pediment or upper area of the zone are often composed of scattered boulders with cobbles, gravel, and some sand. Channel beds in the upper alluvial areas tend to have fewer boulders and more sand. The potential for significant scour of the channel

FIGURE 14 View looking east at distributary channels of zone 4 on the western slopes of the Tortolita Mountains north of Tucson, Arizona. The land in about the top quarter of the photograph is in zone 5.

FIGURE 15 View looking downstream from U.S. Highway 80 at small scoured channel of a tributary to the San Pedro River located 0.6 mile south of the filled channel shown in figures 12 and 13.

bed and banks in the pediment area is low. Marked scour along some channels in the upper alluvial plain area can occur, but the general potential for scour is not great. Debris flows, defined here as slurries of sediment and water with a sediment weight-percentage above 80 percent, that are potentially hazardous can occur in zone 5.

The boundary between zones 4 and 5 generally coincides with the boundary between Quaternary and Tertiary valley-fill deposits. In some places, the tributary-defined channels characteristic of zone 5 extend into the Quaternary deposits. The small distributary channels of zone 4 rarely extend upslope in the Tertiary deposits. In some places, the boundary that separates zones 4 and 5 is a transition area several hundred feet wide.

The greatest potential hazard in zone 5 is from flooding in the channels and narrow flood plains that occupy the lowlands between the defined ridges. Marked scouring occurs along some of the channels and flood plains, and floods carry large amounts of sediment. In many channels, the depth of flooding depends on the amount of erosion and deposition that takes place during the flood. The depth of flooding generally does not exceed 10 ft except where channels are obstructed, on the outside of sharp bends, and on the few channels that drain areas of more than about 100 mi^2. The depth of floodwater also increases behind debris jams and manmade obstructions. The degree of potential flood hazard of the larger washes in zone 5 is similar to that in zone 1 but with less potential for scour. The main channel of some washes is deceptively small, and large amounts of floodwater will spread over wide areas adjacent to the channel.

ZONE 6

Mountain areas that include steep, well-drained slopes composed mostly of rock are characteristic of zone 6. Interspersed among the rock surface are scattered thin debris mantles and thin soils. Stream channels are steep, scoured, and rocky. Channels of streams draining basins of a few tenths of a square mile are well defined.

The dominant hazard is along the defined channels where flood velocities are high; velocities in the large channels may be as much as 15 feet per second. Sheetflow accompanied by debris flow may occur along some steep slopes. Peak-discharge rates of as much as 500 cubic feet per second from a 0.1-square-mile area can be expected an average of once every 100 years. A large part of the flood-hazard potential in this zone can be attributed to sudden flooding from summer thunderstorms and the high velocity of flow.

If the potential for debris flows exists, then the hazard associated with a debris flow may be the greatest in this zone. The potential for debris flows is directly related to the amount and size of unconsolidated material on steep, nonvegetated slopes.

TABLE 1 TYPE AND DEGREE OF FLOOD HAZARD FOR ZONES

Type of hazard	Flood-hazard zone					
	[1]1	2	3	4	5	6
Inundation of land along channels	high[2]	moderate	moderate	high[2]	moderate	low
Velocity of floodflow	high	moderate	low	high[2]	high	high
Scour of channel bed	high	moderate	low	moderate	low[3]	low
Lateral bank erosion	high	high[2]	low	high[2]	low	low
Sediment deposition	low[4]	low	high[5]	high[5]	low	low
Debris flows	low	low	low	low	moderate	high

[1] High incidence of bridge failure because of scour of piers, abutments, and roadway approaches.

[2] The assumption on which FEMA guidelines is based may not be applicable for fan surfaces that are relatively inactive.

[3] Moderate in upper alluvial plain areas and in large channels.

[4] Moderate to high in unchanneled reaches.

[5] Conveyance of many culverts and bridges reduced because of sediment deposition.

DISCUSSION AND SUMMARY

Geomorphology plays an important role in determining flood hazard. Although this fact is common knowledge, structures continue to fail or become less effective, at least in part because of flood-plain management regulations that may not be applicable for some zones. The hazards that commonly plague engineering works are the lateral bank erosion in zone 2, the scour of channel beds in zone 1, and the sediment deposition and unpredictable flow paths in zone 4.

The relative degree and type of hazard for the six zones are summarized in table 1.

The zonation is based on distinct geomorphic and hydrologic differences between the zones, but there is some overlap (see fig. 1). Zones 2 and 3, for example, can define the hazard of the same land where there is a potential for lateral movement of the banks of channels in zone 1 and also for sheetflow from local rainfall or from runoff from zones 4 or 5. Alluvial fans have a wide variety of flood characteristics, and thus specific areas can be best described by zones 3, 4, or 5. In general, large areas of fans will exhibit characteristics of a single zone.

This general zonation is not intended to replace the detailed engineering definition of hydrologic and geologic characteristics of a particular site of interest. Rather, the zonation of flood hazards can be useful to practicing engineers for the general identification of the type and degree of flood hazard.

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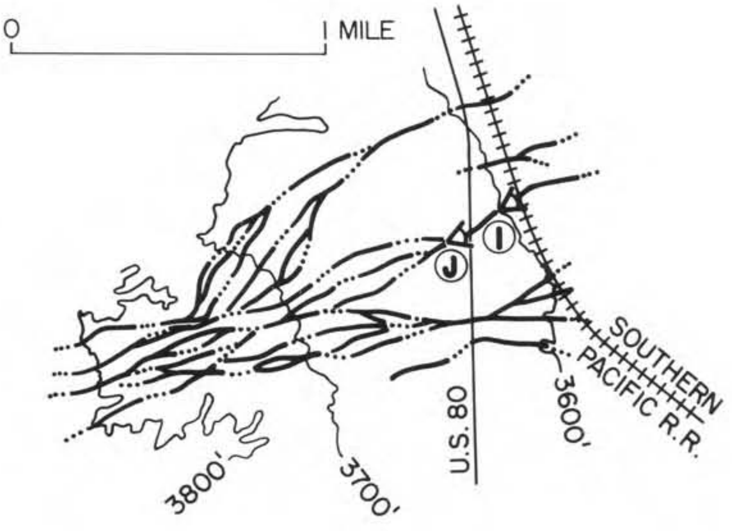
I 10
BENSON
SAN PEDRO R.
ALLUVIAL FAN
S.P.R.R.
U.S. 80
DRAINAGE DIVIDE
COTTONWOOD CANYON WASH
0 1 MILE


0 1 MILE
J
I
SOUTHERN PACIFIC R.R.
U.S. 80
3600'
3700'
3800'

View looking downstream from U. S. Hwy 80 at small channel located 0.6 mile south of Cottonwood Canyon Wash. San Pedro River is about 1 mile beyond this site. There is several feel of head cutting at the exit of this culvert.

Schumm, S. A., 1968. RIVER ADJUSTMENT TO ALTERED HYDROLOGIC REGIMEN-MURRUMBIDGEE RIVER AND PALEOCHANNELS, AUSTRALIA, USGS Professional Paper 598, 65 pp.

Schumm discusses the affects of altering vegetation cover in watersheds and thereby changing tributary runoff and sediment contribution. "For example, the control of tributary runoff and sediment contribution to an alluvial channel will-if both runoff and ·the type of sediment load are significantly altered - induce a long-term adjustment of the river system. The induced changes may be difficult to recognize in a short span of time, but they will, nevertheless, be significant over very long reaches of alluvial rivers, especially in arid, semiarid, and subhumid climatic regions. Depending on the type of sediment load transported by the river, quite different types of adjustment can occur." These photos of channels in south Benson clearly show the variable nature of tributary channel adjustment.

Early accounts of the base flow along the San Pedro River and also the variable channel morphology in the Tres Alamos area also suggest major changes in dimensions, pattern, and shape of the San Pedro River channel in response to man-induced alterations of hydrologic regimen occurred as a result of diversion for irrigation and over grazing of cattle. For example, Parke stated "At the Tres Alamos the stream is about fifteen inches deep and twelve feet wide, and flows with a rapid current over a light, sandy bed, about fifteen feet below its banks, which are nearly vertical. The water here is turbid, and not a stick of timber is seen to mark the meanderings of its bed. In the gorge below, and in some of the meadows, the stream approaches more nearly the surface, and often spreads itself on a wide area, producing a dense growth of cotton-wood, willows and underbrush, which forced us to ascend and cross the terraces. The flow of water, however, is not continuous. One or two localities were observed where it had entirely disappeared, but to rise again a few miles distant, clear and limpid." Tres Alamos is a ghost town. Settled 1874. In 1768 Spanish soldiers from the Presidio de Tucson farmed the Tres Alamos area along the San Pedro River to supply food for the Presidio. Later, in 1830, Mexican farmers settled in the area, establishing more permanent farming operations and transporting their produce through the Redington Pass to Tucson with the protection of soldiers from the Presidio.

Parke, J.G., 1857. Report of Exploration of Railroad Routes. 33rd Congress, 2nd Session, Senate Exhibit Document 78, vol. 7.

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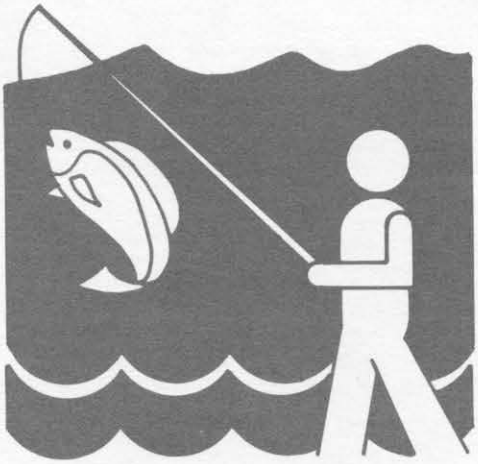
Methods of Assessing Instream Flows for Recreation

COOPERATIVE
INSTREAM FLOW
SERVICE GROUP

INSTREAM FLOW INFORMATION PAPER: NO. 6

FWS/OBS-78/34
JUNE 1978



Cooperating Agencies:

Fish and Wildlife Service
Environmental Protection Agency
Heritage Conservation and Recreation Service
Bureau of Reclamation

U.S. DEPARTMENT OF THE INTERIOR BUREAU OF RECLAMATION

COOPERATIVE INSTREAM FLOW SERVICE GROUP

The Cooperative Instream Flow Service Group was formed in 1976 under the sponsorship of the U.S. Fish and Wildlife Service. Primary funding was provided by the U.S. Environmental Protection Agency. The group operates as a satellite of the Western Energy and Land Use Team. It is a part of the Western Water Allocation Project, Office of Biological Services.

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While the Fish and Wildlife Service is providing the initiative and leadership, the IFG is conceived as a multi-agency, multi-disciplinary program which is to become a "center of activity," providing a focus for the increasing importance of instream flow assessments.

The multi-agency, multi-disciplinary nature of the group is provided through the Intergovernmental Personnel Act transfer of state personnel, and details from other Federal agencies.

Interagency Energy-Environment
Research and Development Program
Office of Research and Development
U.S. Environmental Protection Agency

FWS/OBS-78/34
June 1978

METHODS OF ASSESSING INSTREAM FLOWS FOR RECREATION

Instream Flow Information Paper No. 6

by

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Cooperative Instream Flow Service Group
Western Energy and Land Use Team
Office of Biological Services
Fish and Wildlife Service
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[1] Detailed to the Cooperative Instream Flow Service Group from the Heritage Conservation and Recreation Service.

DISCLAIMER

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ABSTRACT

The Instream Flow Group (IFG) has conducted research into methods of quantifying instream flow needs for fish, wildlife, and recreation. This paper describes two techniques developed by IFG for performing recreational instream flow studies. The single cross section method is relatively simple and provides a base flow figure which will provide for the boating activities which make use of the of river. The incremental method is more sophisticated and may be used to develop recommendations regarding streamflows required for various types of recreation, or to provide a recreation analysis of any streamflow. Streamflow suitability criteria for recreation are presented for both methods.

INTRODUCTION

It has been long recognized that there are many competing demands for the use of stream water. Diverting stream water for irrigation, water supply, and energy developments can deplete streamflows to the point where opportunities for recreation and the associated environmental values of the stream are seriously impaired. Numerous water planning studies, both basin-wide and project oriented, have emphasized the need to quantify the amount of water required to support recreation, fish and wildlife resources, and to maintain aesthetic conditions.

The tools and techniques for estimating streamflows required for recreation and aesthetics, and for insuring reasonable consideration of recreation and aesthetics in the allocation of stream water, are currently undergoing study. Instream flow requirements and values for recreation, in the past, have often been based only upon the amount required to maintain a fishery. However, several studies have indicated that recreation and aesthetic requirements, at times, may not be the same as for a fishery.

This paper presents the techniques of assessing instream flows for recreation. These techniques were developed by the Cooperative Instream Flow Service Group and closely parallel techniques used to assess instream flows for fisheries. The data collection procedures, the physical and hydraulic simulation of the stream, and the computer models which analyze the data are the same for both fisheries and recreation. The major difference between the two techniques is the response of the individual fish or recreationist to various physical parameters of stream flow. These responses to stream flow by different user groups are the criteria which are basic to the methods introduced here.

The first method is called the single cross section approach. This method is useful primarily for identifying flows below which a recreation activity is not feasible and results in a so called "minimum" flow recommendation.

The second method is called the incremental method. With this method the recreation planner is able to analyze various flows and determine the recreation potential of a stream at different flows.

This paper is being distributed with four objectives in mind. These are:

1. To bring the problem of preserving instream flows to the attention of recreation agencies and the research community in order to encourage more research in this vital and neglected area.

2. To discuss the development of the recreation probability-of-use curves and of recreation criteria in general, which are necessary for quantifying instream water requirements for recreation.

3. To obtain review and comment on the recreation criteria and probability-of-use curves, and to request data which may be used to test or improve the criteria or curves.

4. To describe the two approaches for assessing stream flows and discuss how various recreation planning processes can be served by their application.

Both methods of instream flow analysis discussed in this paper utilize computer modeling techniques. Both approaches also require that streamflow data be collected. The single cross section approach, as its name implies, requires that information be collected at only one location on the stream. The incremental method requires that data be collected at multiple locations on the stream. In addition to cross sectional data, data relating the streamflow parameters to recreation potential are necessary. These data are termed recreation criteria.

Recreation criteria for instream flow methodologies are the recreation activity information bases necessary to describe a relationship between the quantity of water flowing in a stream, and the quantity and quality of a particular recreation activity which takes place in the stream.

SINGLE CROSS SECTION METHOD

This method requires that only a single cross sectional measurement be taken across a stream. The product of such an approach is a determination of the lowest flow acceptable for recreation. The approach is based on the assumption that a single cross section, properly located, can define a minimum flow requirement. Such a cross section is located at an area displaying the least depth across the entire stream. When this area provides minimum depths for boat passage, the flow at this level may be defined as a minimum acceptable flow. It is assumed that when sufficient water to support boating is available in these critical areas, other areas will have sufficient water to support most of the other instream recreation activities. This approach is best applied to those streams in which flows are expected to be higher than the minimum most of the time.

Criteria for this approach are set forth in Table 1. Criteria have been developed for boating activities only, but for various types of boating craft. Only minimum criteria are presented because this approach provides information on "minimum flows." Criteria are measured in terms of stream depth and width. Velocity is not considered because a minimum velocity is not considered necessary for this approach.

Table 1. Required stream width and depth for various recreation craft as determined by single cross section method.

Recreation Craft	Required depth (ft)	Required width (ft)
Canoe-kayak	0.5	4
Drift boat, row boat-raft	1.0	6
Tube	1.0	4
Power boat	3.0	6
Sail boat	3.0	25

The criteria of Table 1 are minimal and would not provide a satisfactory experience if the entire river was at this level. However, the cross section measured for this method is the shallowest in the stream reach. Therefore, these minimum conditions will only be encountered for a short time during a boating trip, and the remainder of the trip will be over water of greater depths and widths. An important assumption is that all water greater than the minimum is equally useful for the activity (i.e., more is better until bank-full stage).

A computer program (IFG-1) has been developed which predicts width and depth across the transect of any stage (water surface elevation). The output shows discharge and the width with depth equal to or greater than a specific depth. Different water surface elevations may be put into the computer model which are translated into flow in cubic feet per second. When a flow provides the minimum width and depth necessary for an activity, discharge may be considered minimum. Such a minimum indicates that significant losses, if not elimination of this activity, will occur if minimum flow is not equaled or exceeded.

THE INCREMENTAL METHOD

This method, more sophisticated than the single cross section method, describes a relationship between the amount of water in a reach of stream and the associated recreation potential. The incremental method can describe the potential for any recreation activity at any streamflow. A major difference between the methods is that the single cross section method can only be used to identify low flow and cannot be used to assess the recreation potential at any other flow; the incremental method can be used to assess the potential at other flows or to calculate the change in receation potential caused by a change in stream flow.

The incremental method involves a modeling procedure whereby the surface area of a stretch of stream is calculated. In addition to the total surface area of the reach of stream, the area which has certain depths and velocities is calculated. The usable surface area for each activity is then calculated by use of depth and velocity requirements.

It is necessary to make three assumptions regarding the relationship between the quantity of water and the recreation uses of the water: (1) water depth and water velocity are the two streamflow components which are most important in determining whether or not a certain recreation activity may be safely and pleasurably engaged in[1]; (2) there are

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[1] Other parameters such as water quality and temperature are also very important in determining the amount of instream recreation use but in many cases are not significantly influenced by flow. Width is also important but is considered outside of the computer model (i.e., width is not a part of the calculation of usable surface area).

certain measures of water depth and water velocity which may be considered minimum, maximum, and optimum for an activity; and (3) the measurement of water surface area which meets certain requirements of depth and velocity is a viable method of describing recreation potential for instream recreation uses.

This method is comprised of four components: (1) computer simulation of a stream reach, (2) determination of the combinations of stream depth and velocity, (3) determination of a composite probability-of-use for each combination of depth and velocity, and (4) calculation of a weighted usable surface area.

1. Simulation of the Stream. The stream reach simulation model utilized in this approach uses several cross sectional transects, each of which is subdivided into subsections. For any stage (water surface elevation) the mean depth and velocity of each subsection is calculated. Typically, a transect would be established across a pool, a riffle, and an intermediate area. Together these cross sectional measurements would represent a stream reach which may extend several miles. In Table 2 a 100 foot length of stream is represented.

Table 2. Depth velocity matrix showing total surface area of stream in square feet.

Depth (ft)	Velocity in feet per second				
	<0.5	0.5-1.0	1.0-1.5	>1.5	Total
<1	500	400	100	0	1,000
1-2	600	700	800	300	2,400
2-3	100	300	500	100	1,000
>3	0	0	100	0	100
Total	1,200	1,400	1,500	400	4,500

2. Distribution of Combinations of Depth and Velocity. The output of the stream reach simulation model is in the form of a matrix showing the surface area of a stream having different combinations of depth and velocity. Table 2 illustrates a depth velocity matrix. The outlined number in the upper left matrix cell refers to 500 square feet per 100 feet of stream having a combination of depth less than 1.0 foot and velocity less than 0.5 foot per second. This figure is the sum of the areas within the stream reach with this combination of depth and velocity.

In order to evaluate the effect of these physical changes upon a streams desirability for recreation, it is necessary to develop an information base for each recreation activity. Such an information base should identify a relationship between depth and velocity of the water, and the desirability of such water for each recreation activity. The information base, called recreation criteria, has been developed and is set forth in the following pages.

3. Composite Probabilities-of-Use. Determination of the probability-of-use for an activity on a certain area of water requires multiplying the probability-of-use for the depth by the probability-of-use for the velocity. For example, from Figure 1 the probability-of-use for the depth of 2.6 feet is 0.9. The probability-of-use for the velocity of 6 feet per second is 0.24. The composite probability-of-use for a depth of 2.6 feet <u>and</u> a velocity of 6 feet per second, is 0.216 (0.9 x 0.24). The probability-of-use is also the weighting factor for calculation of the weighted usable surface area.

4. Weighted Usable Surface Area. The weighted usable surface area equates an area of low desirability to an equivalent area of optimal desirability. For example, if 1,000 square feet of surface area had a composite probability-of-use of 0.216 (see above) it would have a weighted usable surface area of 216 square feet (total surface area times composite probability-of-use). These 1,000 square feet of surface area would be considered to have the same recreation potential as 216 square feet of surface area having optimum depths and velocities.

An example of a matrix is shown in Table 3. In each cell of the matrix, the upper number refers to the surface area of a stream having a depth velocity combination as indicated. The numbers in parentheses refer to the weighted usable surface area.

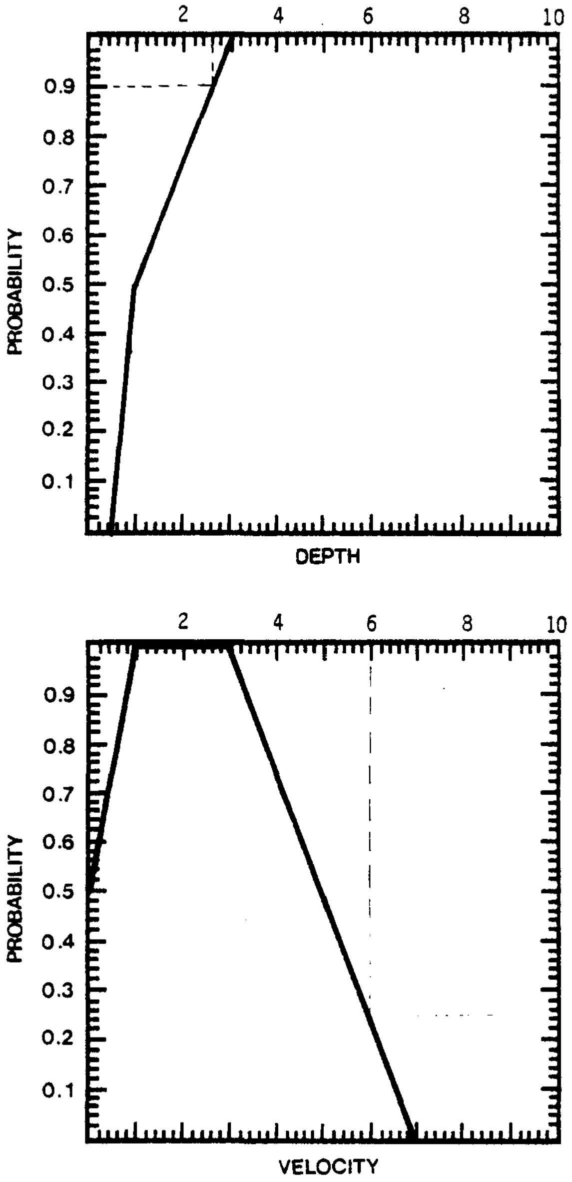

Figure 1. Probability-of-use curve for stream fishing (boat non-power) in relation to depth and velocity.

Table 3. Total surface area of stream and (weighted usable surface area) for a hypothetical recreation activity in square feet.

Depth (ft) and (Probability-of-use)	Velocity in feet per second and (probability-of-use)				
	<0.5 (1.0)	0.5-1.0 (0.8)	1.0-1.5 (0.4)	>1.5 (0)	Total
<1 (0)	500 (0)	400 (0)	100 (0)	0 (0)	1,000 (0)
1-2 (0.3)	600 (180)	700 (168)	800 (96)	300 (0)	2,400 (444)
2-3 (0.8)	100 (80)	300 (192)	500 (160)	100 (0)	1,000 (432)
>3 (1.0)	0 (0)	0 (0)	100 (40)	0 (0)	100 (40)
Totals	1,200 (260)	1,400 (360)	1,500 (296)	400 (0)	4,500 (916)

A separate matrix is required for each recreation activity being considered. A separate matrix is also developed for each of a number of different flows and a different weighted usable surface area is calculated for each flow. Comparison of the matrices provides information on the "best flow" or shows the change in weighted usable surface area due to a change in flow.

RECREATION CRITERIA FOR THE INCREMENTAL METHOD

Recreation activity definitions and a discussion of criteria are presented below.

Minimum and Maximum Criteria

Criteria, as discussed in this section, refer to the parameters of depth and velocity, and deal with the minimum and maximum values. The assumption is made that the recreation activity in question cannot be engaged in outside of the range described by the minimum and maximum values. Optimum values are determined in a somewhat different manner and will be discussed later. Minimum and maximum criteria are of two major types: (1) physical criteria and (2) safety criteria. Regarding physical criteria, recreation activities have certain physical or absolute limits or requirements which must be met (i.e., a boat requires a certain minimum depth of water to float). In the case of safety criteria there are no absolutes; however, it can generally be stated that certain depths or velocities may be unsafe for the average participant. Safety criteria may also be considered a preferred physical limitation.

Optimum Criteria

Minimum and maximum criteria are used to establish the range of depths and velocities which provide a usable surface area for river recreationists. It is also possible to identify a preferred depth or velocity or range of preferred depths and velocities which could be called optimum. Obviously, optimum will not be agreed upon by all recreationists since they represent such a heterogeneous group. However, the total range can be narrowed and a preferred range established. An optimum value of depth or velocity or a preferred range of depths and velocities will be that value or range of values which is usable to the largest number of potential participants.

There are "psychological" criteria that also might be used for selecting optimum depths or velocities. Psychological criteria relate to the quality of the experience. However, in order to evaluate the quality of the experience, one must determine what experience is sought. A number of the recreation activities included in this report have expectations that appear to be unrelated to flow. Therefore, for such activities only the physical and safety criteria need to be considered. Other activities have flow-related expectations and it appears that the experience desired and expected should be a part of the criteria. According to Schreyer and Nelson (1978) the "white water" activities, have an "action-excitement" expectation, and certain types of water are necessary to realize that expectation. Stream depths and/or velocities which produce action-excitement are not easily identified because of the differing skill levels and experience of recreationists. Consequently, psychological criteria, in terms of depth or velocity, are not listed at this time.

The activities which have action and excitement as an expectation are the last four activities listed under boating (below). However, not all of the persons who engage in these activities seek action and excitement. Therefore, a wide range of optimum velocity values is necessary to include the action excitement expectation as well as the other expectations. Each of these four activities may be viewed as two separate activities, one which occurs on tranquil water and one which occurs on non-tranquil water.

Recreation Activities

The stream-oriented recreation activities considered in this report are shown below:

Fishing
Wading
Boat, power
Boat, nonpower

Water Contact
Swimming
Wading
Water skiing

Boating
Sailing
Low power
High power
Canoeing-Kayaking
Rowing-rafting-drifting
Tubing-floating

Definitions

Fishing
Wading: fishing while walking in the stream.
Boat power: fishing from a power boat.
Boat nonpower: fishing from a nonpower boat.

Water Contact
Swimming: propelling oneself through the water with no, or only occasional, contact with the bottom.
Wading: walking in the water, including water play.
Water skiing: being towed behind a boat on skiis.

Boating
Sailing: wind powered boating.
Low power: power boating, motor less than 50 horsepower.
High power: power boating, motor greater than 50 horsepower.
Canoeing-kayaking: using a canoe or kayak in a river.
Rowing-rafting-drifting: using a row boat, raft, or drift boat in a river.
Tubing-floating: floating on a device which is not a full-sized boat or raft. May include inner tubes, small rafts, air mattresses, etc. This activity is also a water contact activity. It is placed here for its similarity to rowing-rafting-drifting.

PROBABILITY-OF-USE CURVES

Development of recreation probability-of-use curves builds upon the recreation criteria discussed in the previous section. Minimum, maximum, and optimum criteria are translated into probablities-of-use and recreation probability curves are developed.

The recreation criteria may be graphed with depth (or velocity) on the X axis and the desirability of certain depths for the recreation activity in question along the Y axis (Figure 2).

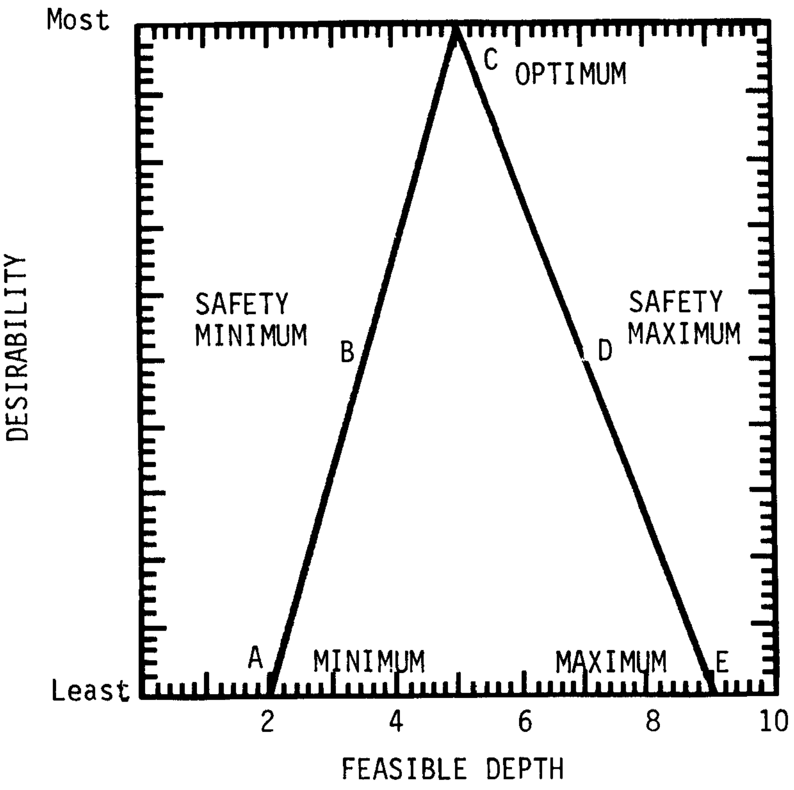

Figure 2. Desirability of stream depth graph for a hypothetical recreation activity.

The physical minimum is shown on the graph as "A" and is the least desirable depth at which the activity is possible. Preferred low flows are the least depth at which the activity can be participated in safely is shown as "B" on the graph. Safety values are somewhat arbitrary because they depend upon experience and skill of the recreationist. In this context, it is assumed that it is an average figure, and that up to 50 percent of the potential participants will find depths between "A" and "B" usable. Point "C" on the graph indicates the most desirable or optimum depth and it is assumed that 100 percent of the potential participants would find such a depth usable. Point "D" indicates the preferred or safety maximum and "E" indicates the physical maximum.

If the Y axis is changed from a desirability scale to a probability scale, with 1.0 on top and 0 on the bottom, the "probability-of-use" may be read off the Y axis.

If Figure 2 represents a probability-of-use curve for an activity in a region where the resource is experiencing capacity use, then the following assumptions can be stated:

1. Areas having depths less than "A" or greater than "E" will have no use.

2. Areas having depths equal to "C" will be experiencing capacity use.

3. Areas having depths equal to "B" and "D" will be experiencing 50 percent of the use of area "C."

Appendix A sets forth the depth and velocity criteria in tabular and graphic forms and defines depths and velocities in terms of desirability as follows:

Optimum	Depth or velocity usable by all; probability-of-use or weighting factor 1.0
Acceptable	Depth or velocity between safety limit and optimum; probability-of-use or weighting factor 0.5-0.99
Marginal	Depth or velocity between physical and safety limits; probability-of-use or weighting factor 0.01-0.49
Unacceptable	Depth or velocity unusable; probability-of-use or weighting factor 0.0

Appendix B shows the probability-of-use curves which are developed from the depth and velocity criteria.

APPLICATION

There are situations where the single cross section method or the incremental method is best suited to do instream flow studies.

The single cross section approach is best suited to situations where:

1. A minimum of time is available.

2. A low flow recommendation is all that is necessary.

3. The low flow recommendation will be exceeded for most of the recreation season.

The incremental method is best suited to situations where:

1. Increments of flow need to be analyzed.

2. The change in streamflow needs to be related to change in recreation potential.

3. The most "exact" answer, available with today's state-of-the-art, is desired.

Opportunities for preserving instream flows for recreation may occur within several programs and processes. Planners did not always take advantage of these opportunities in the past because no method existed by which to quantify the instream flow need.

Opportunities exist within the State water adjudication procedures wherein all water rights will be adjudicated including the Federal reserved rights. When the purpose of the Federal reservation of land includes recreation, the quantity of water necessary to accomplish the purpose must be quantified, and this includes the instream flow required.

Both Federal and State wild and scenic river programs contain language that may be used to preserve instream flows for recreational or aesthetic purposes. The licensing and relicensing procedures of the hydroelectric utility companies call for exhibits to be prepared which describe the recreation resource and the benefits to the public from such a license or project.

Whenever a water project is proposed the impact of the project on recreation is studied. The incremental method will permit the stream portion of such analysis to take its place alongside the reservoir portion.

Use of the incremental method will permit full consideration of recreation by water management agencies as they make decisions about water allocation, conduct hearings for diversion permit requests, or determine low flows.

In general, whenever proposals are made which will change an existing streamflow or flow regime, the impact upon recreation can be determined and be considered in the planning process.

LIMITATIONS

The limitations of the methods discussed in this paper should be understood prior to field testing.

The single cross section is limited to making minimum flow recommendations to accommodate the boating recreation activities. It is less exact than the incremental method and the location of the cross sectional measurement is critical.

The incremental method may be used to describe the impact of a change in flow or used to identify an optimum flow. However, there is no such thing as an optimum flow or flow regime for recreation. Each recreation activity has its own unique flow requirement and frequently flow requirements conflict among activities. For example, a greater flow resulting in higher velocities may benefit the white water boaters, but would all but eliminate fishing while wading. Usually a flow recommendation would be provided in terms of a flow regime. The recommendation of a flow regime would recognize the variable supply of water throughout the year as well as the periods of greatest demand for instream water. A flow regime for recreation would take into account the greater recreation demand during the recreation season, during the weekends, and perhaps even during the daylight hours.

Use of the incremental method can provide only a measure of recreation potential and cannot provide adequate information for developing a recommended flow regime based on the demand for recreation. If such a recommendation is necessary, or if knowledge of a change in recreation use or benefits, due to a change in flow, is desired, a demand-supply study should be undertaken. A demand-supply study would use the output from the incremental method as the supply component.

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1. Schreyer, Richard and Martin L. Nelson. 1978. Westwater and Desolation Canyons: Whitewater River Recreation Study. Institute for the Study of Outdoor Recreation and Tourism. Utah State Univ., Logan, UT. 164 pp.

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1. Lamb, Berton Lee, Editor. *Guidelines for Preparing Expert Testimony in Water Management Decisions Related to Instream Flow Issues*. Fort Collins, Colorado, Cooperative Instream Flow Service Group, July 1977, 30 pages. (NTIS Accession Number: PB 268 597; Library of Congress Catalog Card No. 77-83281).

2. Lamb, Berton Lee, Editor. *Protecting Instream Flows Under Western Water Law: Selected Papers*. Fort Collins, Colorado, Cooperative Instream Flow Service Group, September 1977, 60 pages. (NTIS Accession Number: PB 272 993; Library of Congress Catalog Card No. 77-15286).

3. Bovee, Ken D., and Cochnauer, Tim. *Development and Evaluation of Weighted Criteria , Probability-of-Use Curves for Instream Flow Assessments; Fisheries*. Fort Collins, Colorado, Cooperative Instream Flow Service Group, December 1977, 49 pages. (NTIS Accession Number: PB ; Library of Congress Catalog Card No. -).

4. Bovee, Ken D. *Probability-of-Use Criteria for the Family Salmonidae*. Fort Collins, Colorado, Cooperative Instream Flow Service Group, January 1978, 88 pages. (NTIS Accession Number: PB : Library of Congress Catalog Card No. -).

5. Milhous, Robert R. and Ken D. Bovee. *Hydraulic Simulation in Instream Flow Studies: Theory and Techniques*. Fort Collins, Colorado, Cooperative Instream Flow Service Group, May 1978, pages. (NTIS Accession Number: PB ; Library of Congress Catalog Card No. -).

6. Hyra, Ronald. *Methods of Assessing Instream Flows for Recreation*. Fort Collins, Colorado, Cooperative Instream Flow Service Group, May 1978, 49 pages. (NTIS Accession Number: PB ; Library of Congress Catalog Card No. -).

APPENDIX A

CRITERIA DEVELOPMENT

Sources of Information Used to Develop the Criteria of Appendix A:

1. Christiansen, M.L. 1975. Development of Resource Requirements Determinants for Selected Activities. Watershed Recreation Research Report.

2. Scott, J. and R. Hyra. 1977. Methods for Determining Instream Flow Requirements for Selected Recreational Activities in Small and Medium Sized Streams. Paper presented at AWRA Conference, Tucson, Arizona.

3. Thompson, J. and R. Fletcher. 1972. A Model and Computer Program for Appraising Recreational Water Bodies. Department Forest Sci. Utah State Univ., Logan, Utah, pp. 48.

4. U.S. Bureau of Outdoor Recreation. 1977. Recreation and Instream Flow. Volumes 1 and 2, Jasen M. Cortell and Associates, Waltham, Massachusetts. pp.252.

5. U.S Bureau of Outdoor Recreation. 1977. Resource Requirements for Water Related Recreation. S.E. Regional Office. Draft Report. pp. 15.

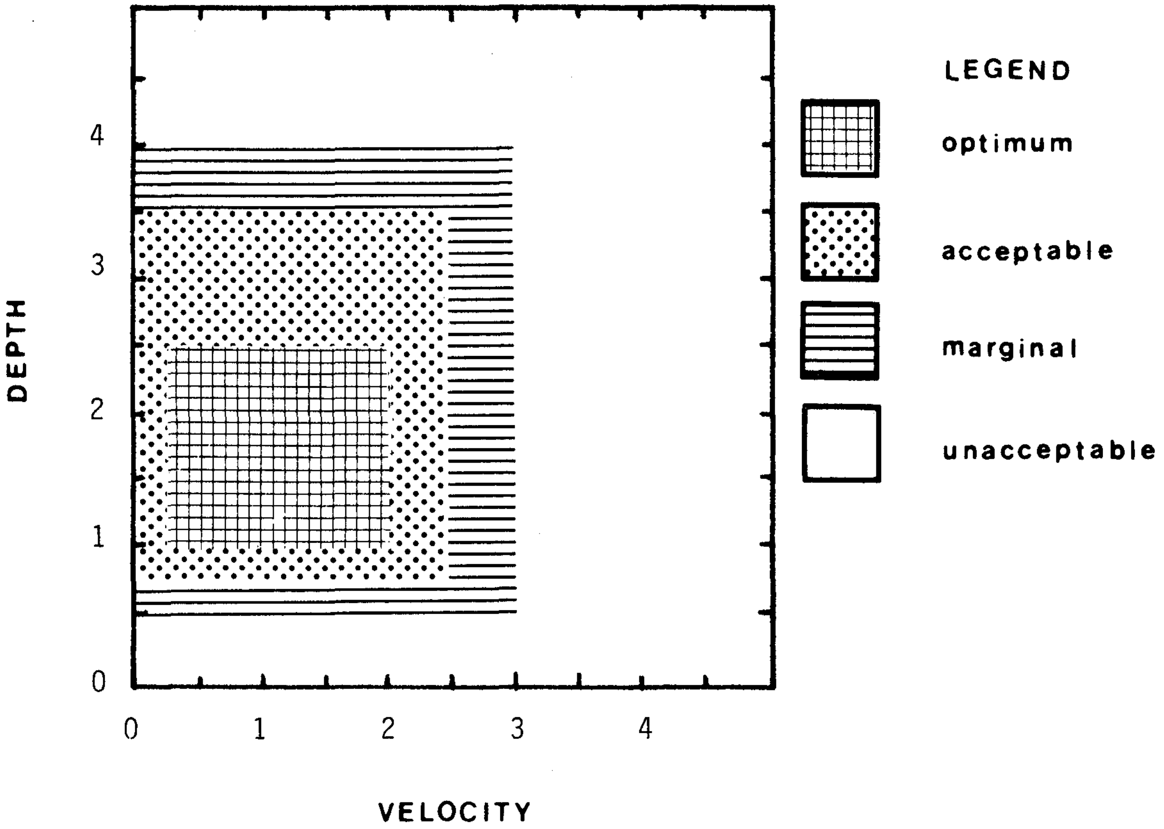
6. U.S. Corps of Engineers. 1963. Channel Improvement for Navigation Snake River Downstream From Weiser, Idaho. Detailed Project Report. pp. 77.

FISHING WADING

CRITERIA

	PHYSICAL	SAFETY	OPTIMUM
DEPTH			1.0-2.5 ft
minimum	0.5 ft	0.75 ft	
maximum	4.0 ft	3.50 ft	
VELOCITY			0.25-2.0 fps
minimum	0.0 fps	0.0 fps	
maximum	3.0 fps	2.5 fps	

COMMENTS: Depth in ft multiplied by velocity in fps should equal 10 or less. Safety depends upon height and weight of individual as well as substrate type.

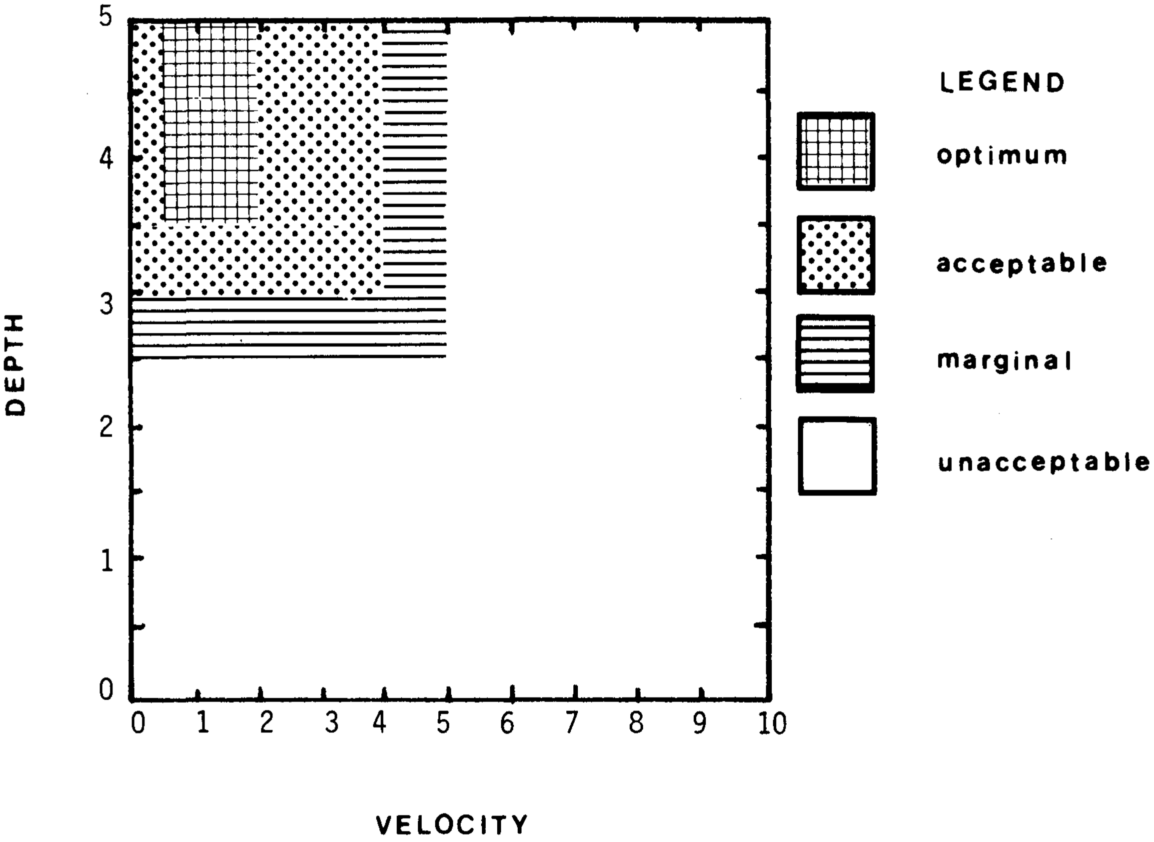


FISHING BOAT POWER

CRITERIA

	PHYSICAL	SAFETY	OPTIMUM
DEPTH			3.5 ft +
minimum	2.5 ft	3.0 ft	
maximum	NA	NA	
VELOCITY			0.5-2.0 fps
minimum	0 fps	0 fps	
maximum	5 fps	4 fps	

COMMENTS: Size of boat and motor important. Generally includes boats of low power.

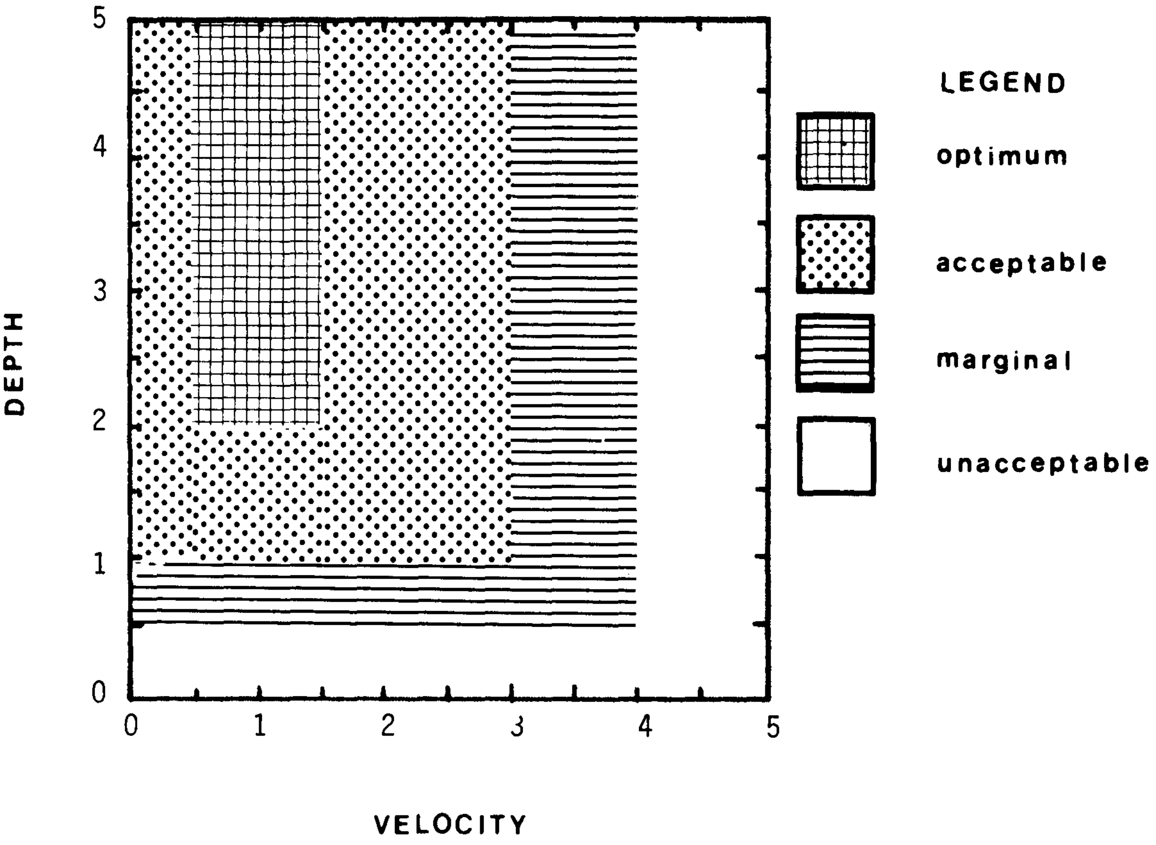


FISHING BOAT NON-POWER

CRITERIA

	PHYSICAL	SAFETY	OPTIMUM
DEPTH			2.0 ft +
minimum	0.5 ft	1.0 ft	
maximum	NA	NA	
VELOCITY			0.5-1.5 fps
minimum	0 fps	0 fps	
maximum	4 fps	3 fps	

COMMENTS: Type boat important.

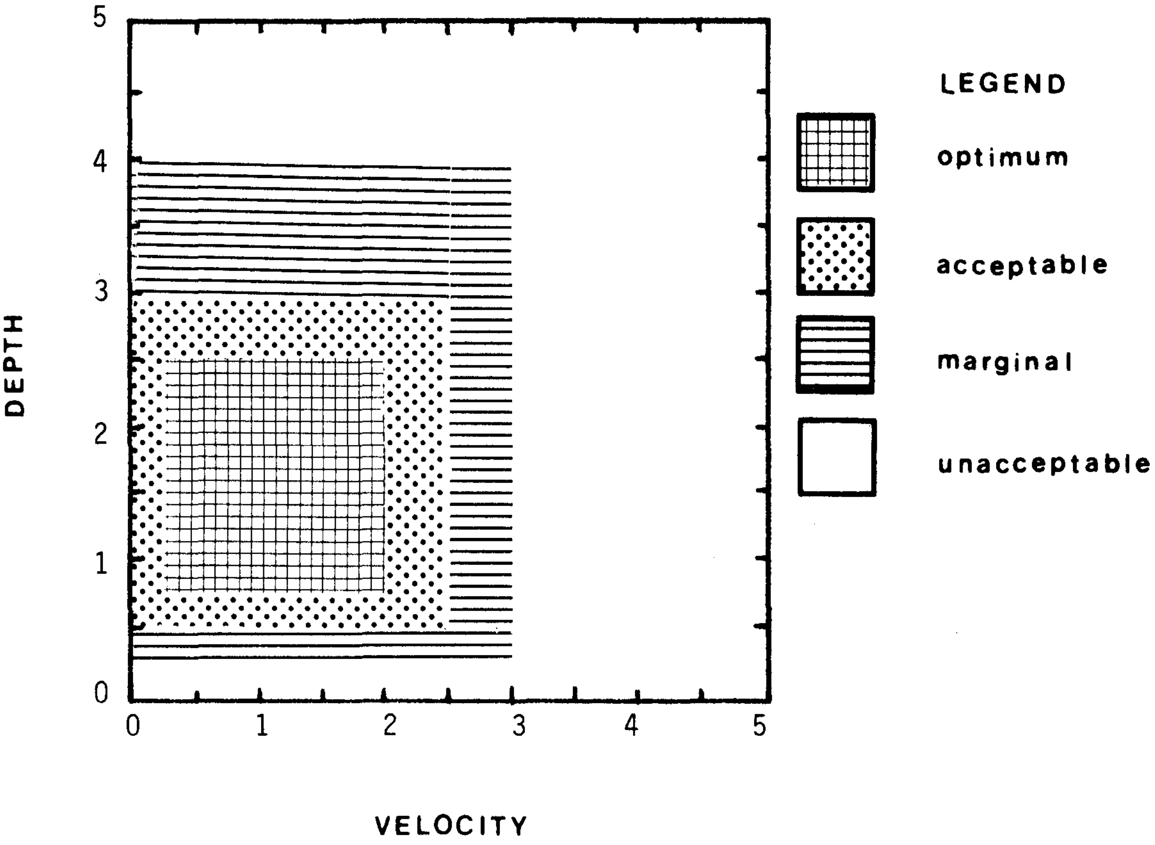


WATER CONTACT WADING

CRITERIA

	PHYSICAL	SAFETY	OPTIMUM
DEPTH			0.75-2.5 ft
minimum	0.25 ft	0.5 ft	
maximum	4.0 ft	3.0 ft	
VELOCITY			0.25-2.0 fps
minimum	0 fps	0 fps	
maximum	3.0 fps	2.5 fps	

COMMENTS: Depth in feet multiplied by velocity in fps should equal 10 or less. Saftey depends upon height and weight of individual as well as substrate type.

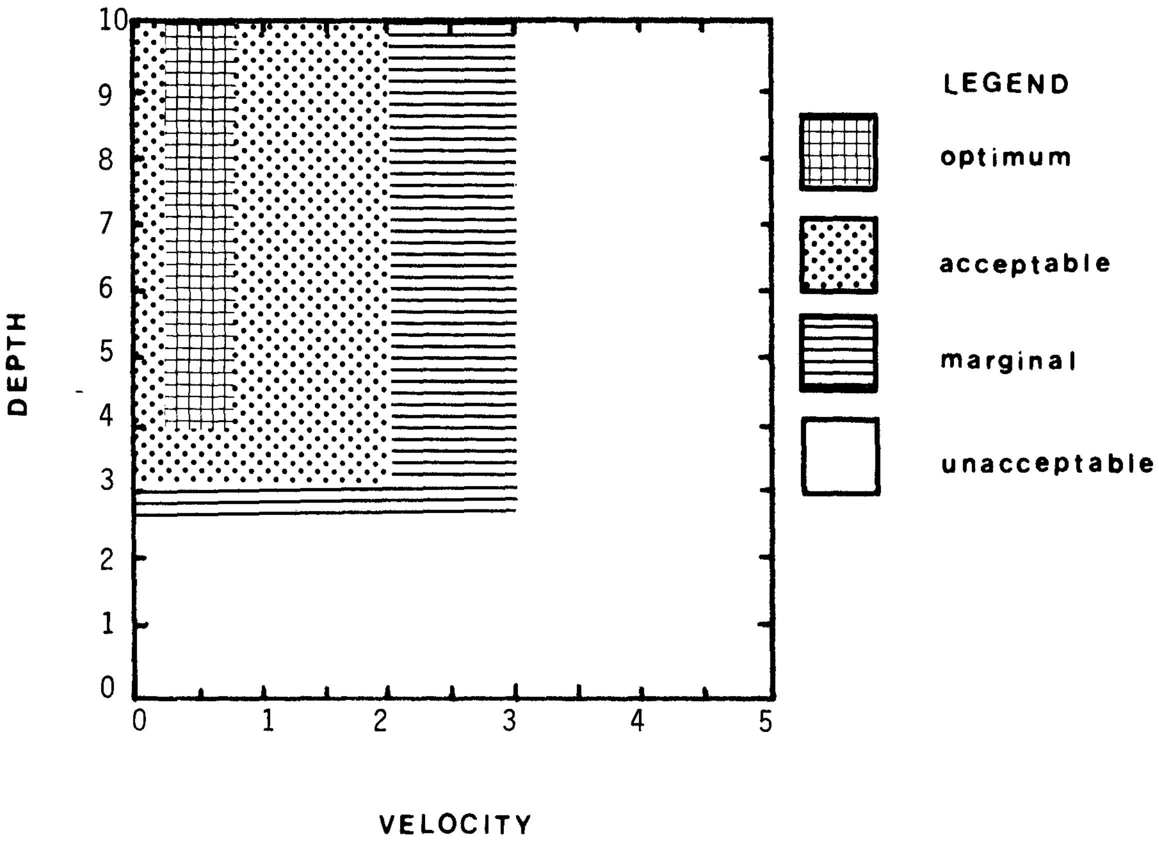


WATER CONTACT SWIMMING

CRITERIA

	PHYSICAL	SAFETY	OPTIMUM
DEPTH			4 ft +
minimum	2.5 ft	3.0 ft	
maximum	NA	NA	
VELOCITY			0.25-0.75 fps
minimum	0 fps	0 fps	
maximum	3.0 fps	2.0 fps	

COMMENTS: Water quality, temperature, slope of beach, visibility and underwater slope important. Depth safety criteria does not permit diving.

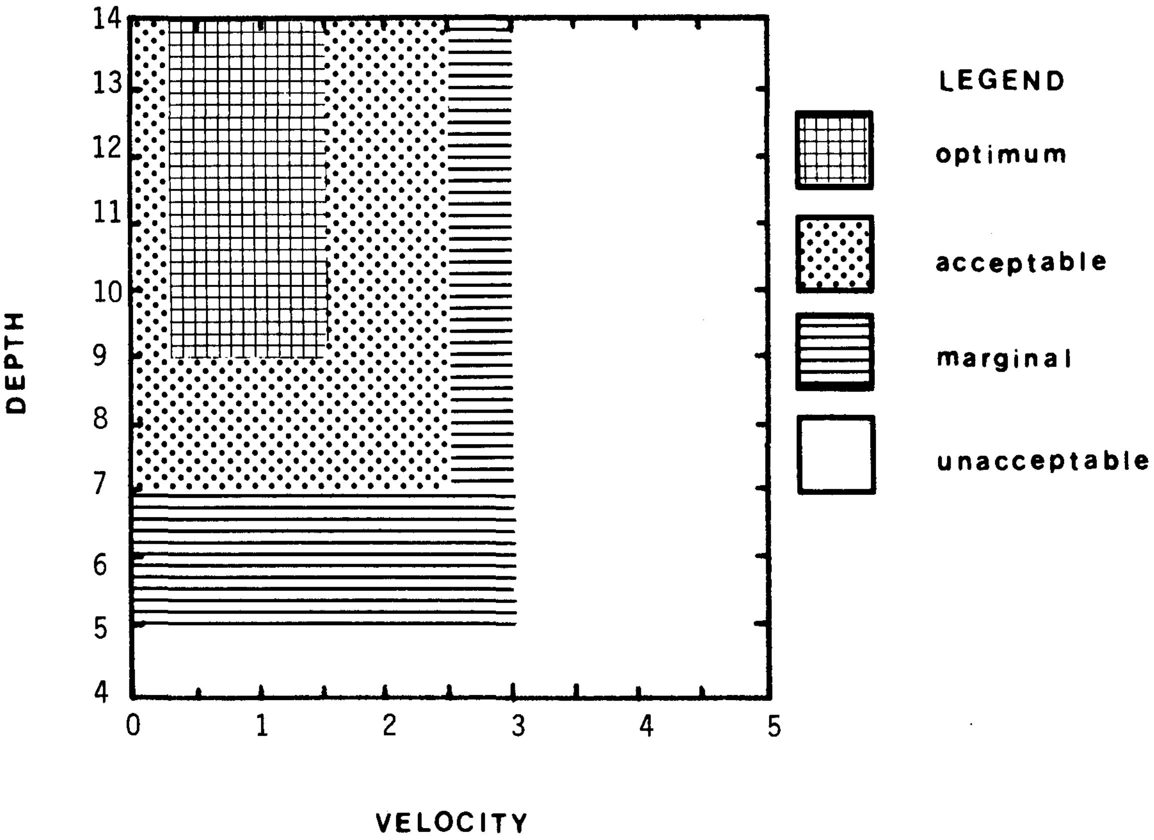


WATER CONTACT WATER SKIING

CRITERIA

	PHYSICAL	SAFETY	OPTIMUM
DEPTH			9 ft +
minimum	5 ft	7 ft	
maximum	NA	NA	
VELOCITY			0.25-1.5 fps
minimum	0 fps	0 fps	
maximum	3.0 fps	2.5 fps	

COMMENTS: Width is critical also.

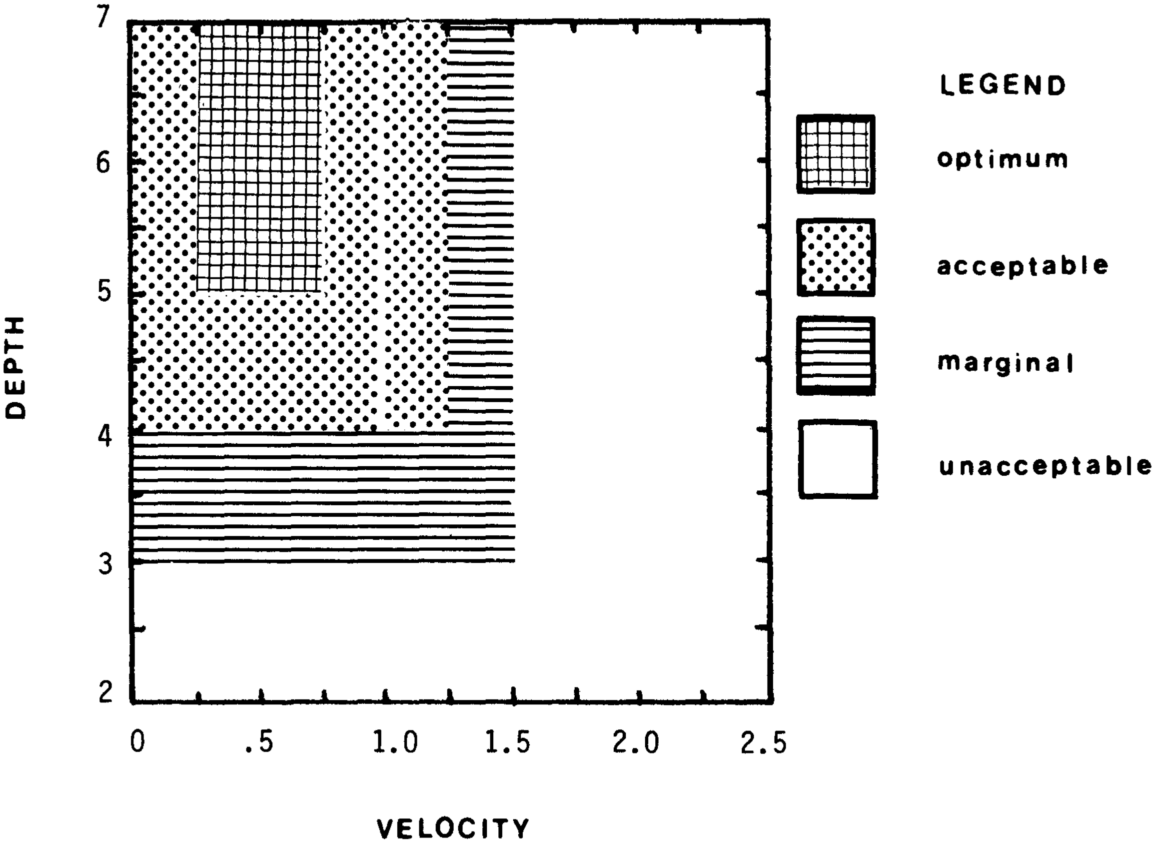


BOATING SAILING

CRITERIA

	PHYSICAL	SAFETY	OPTIMUM
DEPTH			5 ft +
minimum	3 ft	4 ft	
maximum	NA	NA	
VELOCITY			0.25-0.75 fps
minimum	0 fps	0 fps	
maximum	1.5 fps	1.25 fps	

COMMENTS: Keel or centerboard depth is critical.

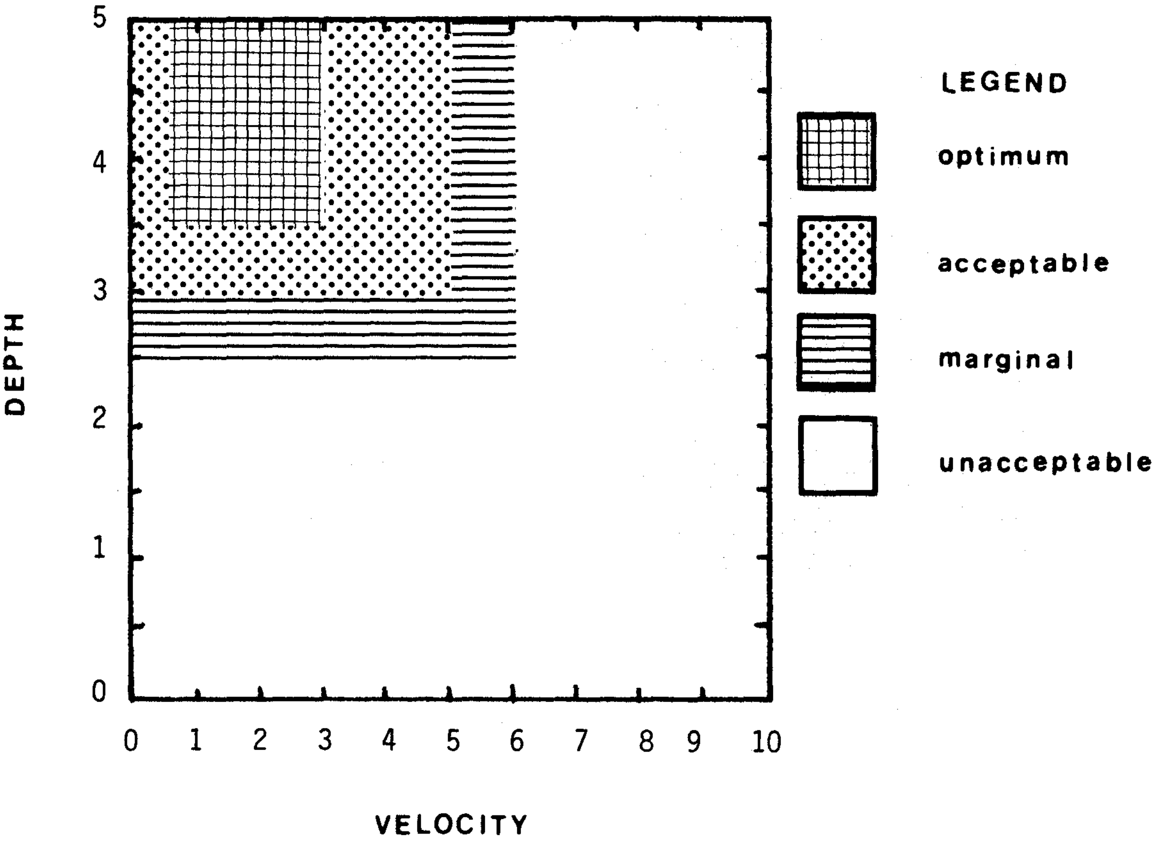


BOATING LOW POWER

CRITERIA

	PHYSICAL	SAFETY	OPTIMUM
DEPTH			3.5 ft +
minimum	2.5 ft	3.0 ft	
maximum			
VELOCITY			0.5-3.0 fps
minimum	0 fps	0 fps	
maximum	7 fps	6 fps	

COMMENTS: Low power boats are less than 50 hp.

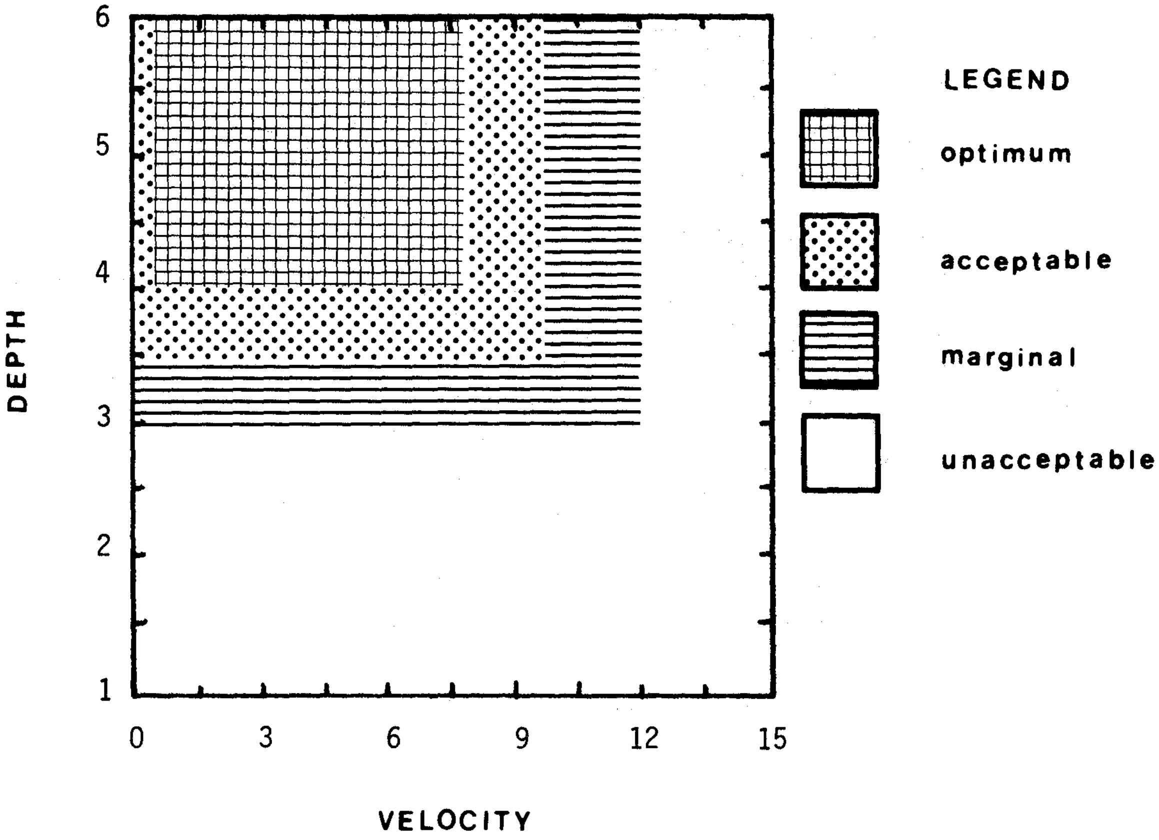


BOATING HIGH POWER

CRITERIA

	PHYSICAL	SAFETY	OPTIMUM
DEPTH			4.0 ft +
minimum	3.0 ft	3.5 ft	
maximum	NA	NA	
VELOCITY			0.5-8.0 fps
minimum	0 fps	0 fps	
maximum	12.0 fps	10.0 fps	

COMMENTS: High power is greater than 50 hp. Jet boats or sleds require only 1.0 ft ± water depth. Higher velocities safe only under certain conditions.

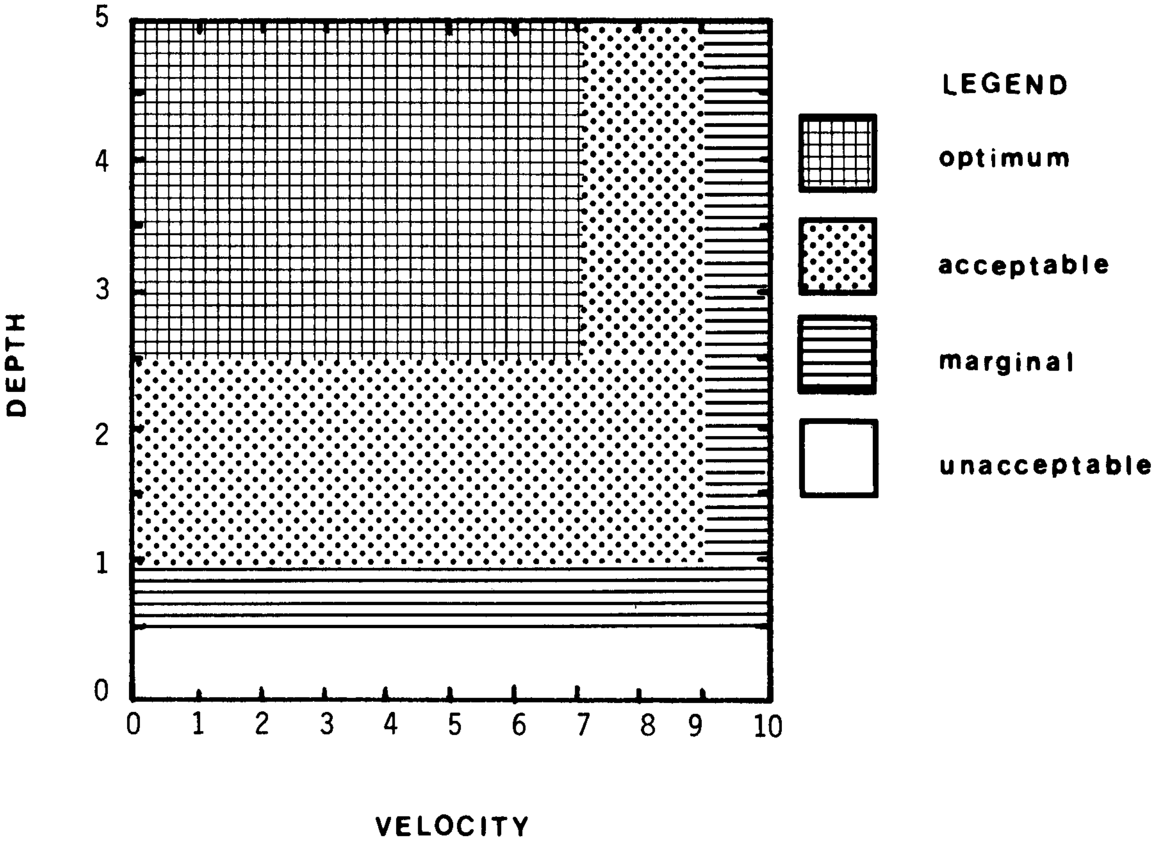


BOATING CANOEING-KAYAKING

CRITERIA

	PHYSICAL	SAFETY	OPTIMUM
DEPTH			2.5 ft +
minimum	0.5 ft	1.0 ft	
maximum	NA	NA	
VELOCITY			0.5-7.0 fps
minimum	0 fps	0 fps	
maximum	10.0 fps	9.0 fps	

COMMENTS: Higher velocities exclude open canoes. Higher velocities safe only under certain conditions.

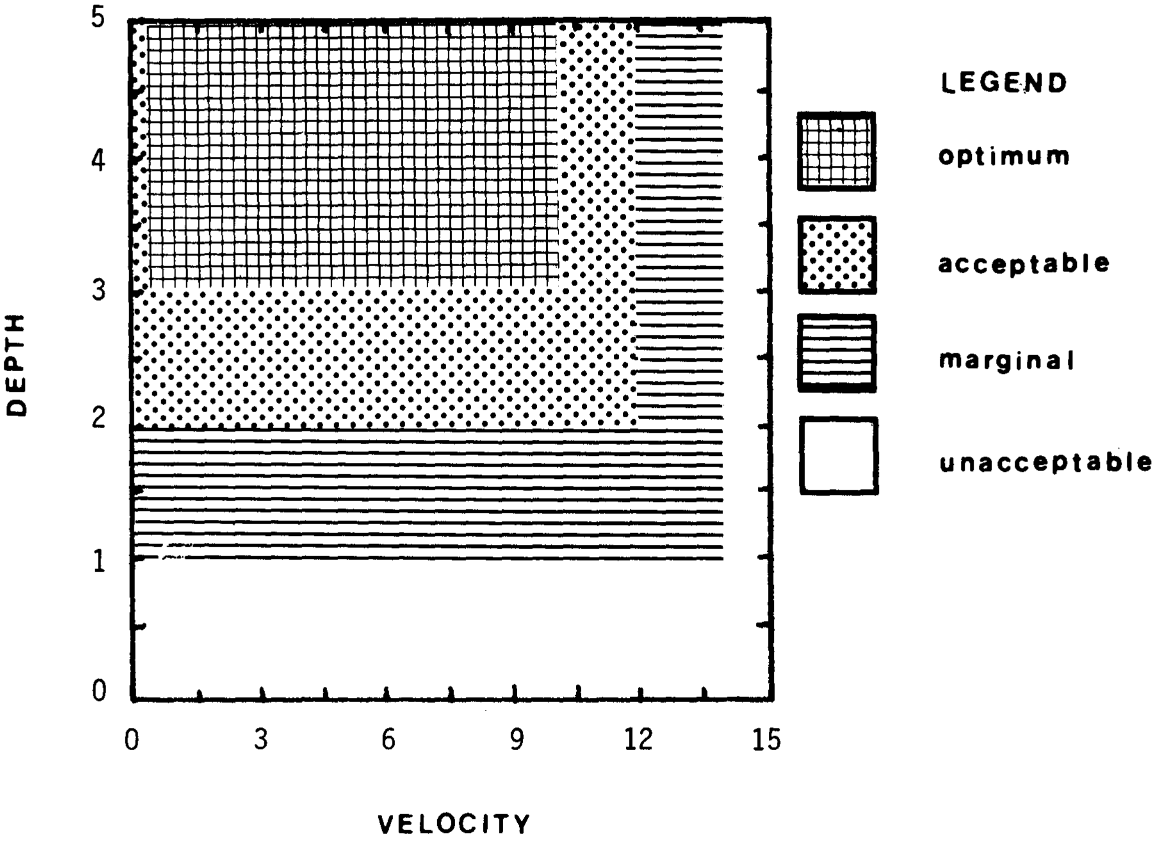


BOATING ROWING-RAFTING-DRIFTING

CRITERIA

	PHYSICAL	SAFETY	OPTIMUM
DEPTH			3.0 ft +
minimum	1.0 ft	2.0 ft	
maximum	NA	NA	
VELOCITY			1.0-10.0 fps
minimum	0 fps	0 fps	
maximum	14.0 fps	12.0 fps	

COMMENTS: Higher velocities require boats/rafts of a type specifically designed for white water. Higher velocities safe only under certain conditions.

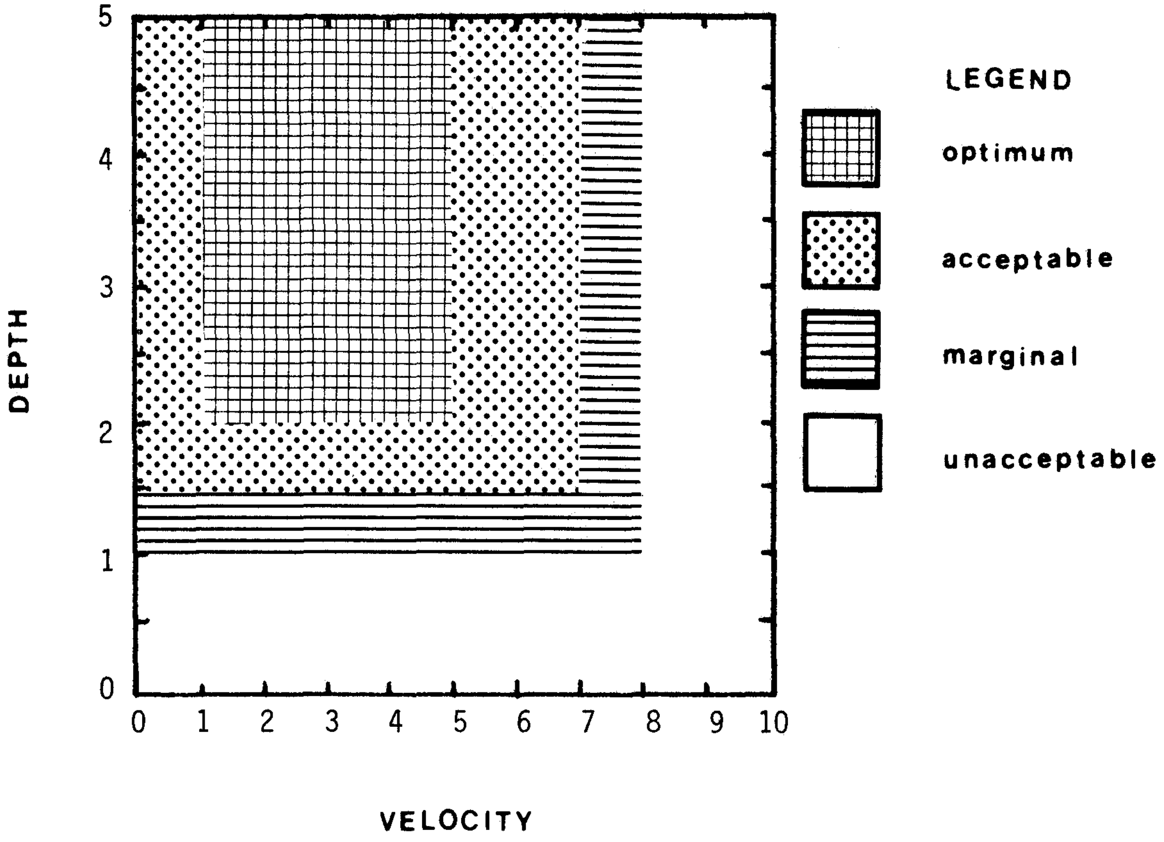


BOATING TUBING-FLOATING

CRITERIA

	PHYSICAL	SAFETY	OPTIMUM
DEPTH			2.0 ft +
minimum	1.0 ft	1.5 ft	
maximum	NA	NA	
VELOCITY			1.0-5.0 fps
minimum	0 fps	0 fps	
maximum	8.0 fps	7.0 fps	

COMMENTS: Higher velocities safe only under certain conditions.

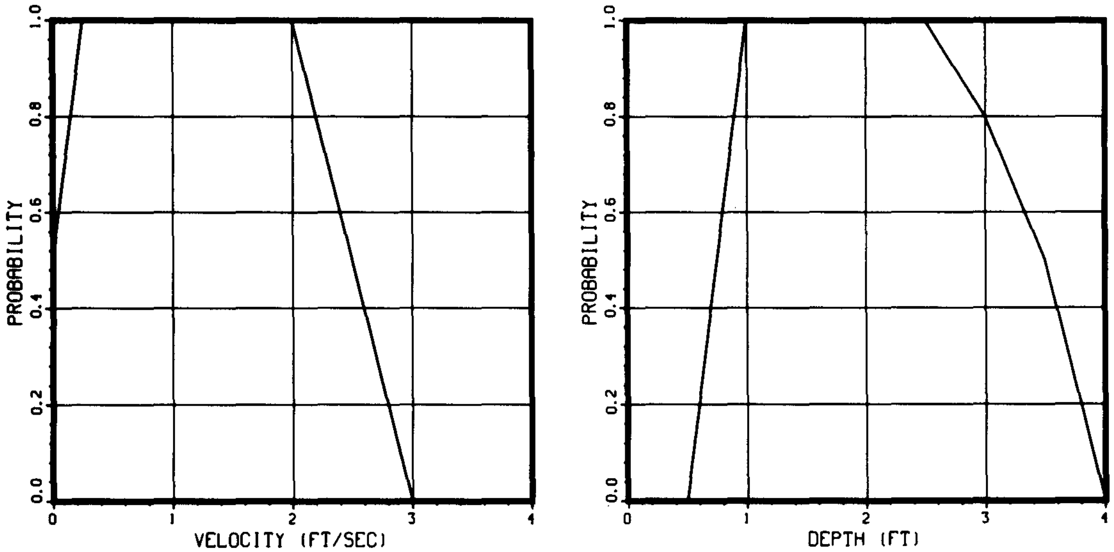


APPENDIX B

PROBABILITY-OF-USE CURVES

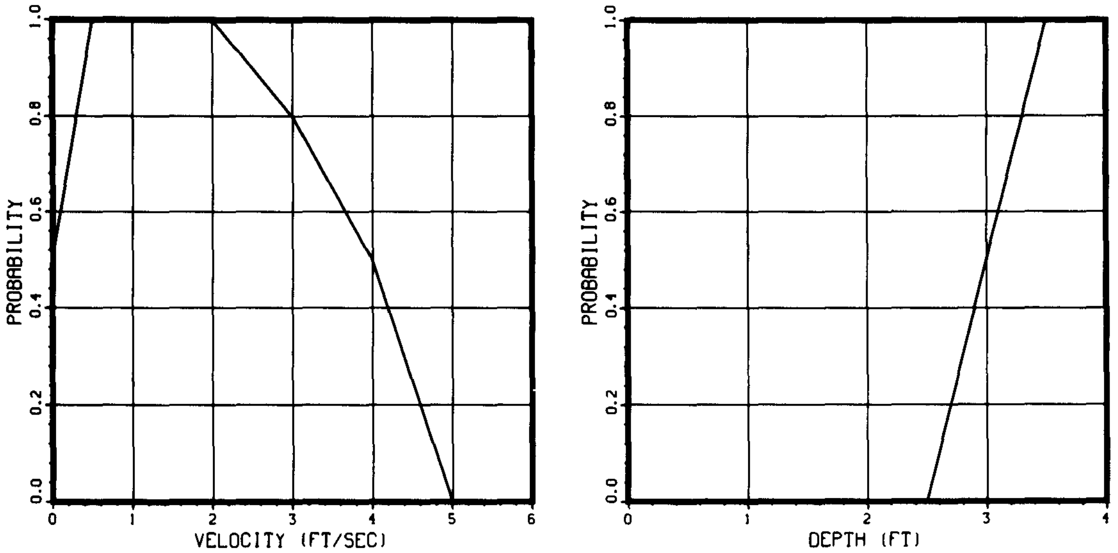
FISHING WADING

700000 78/06/26.



FISHING BOAT POWER

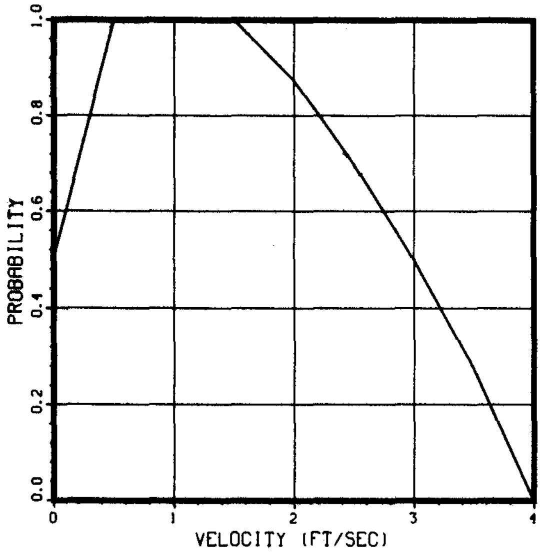
700100 78/06/26.

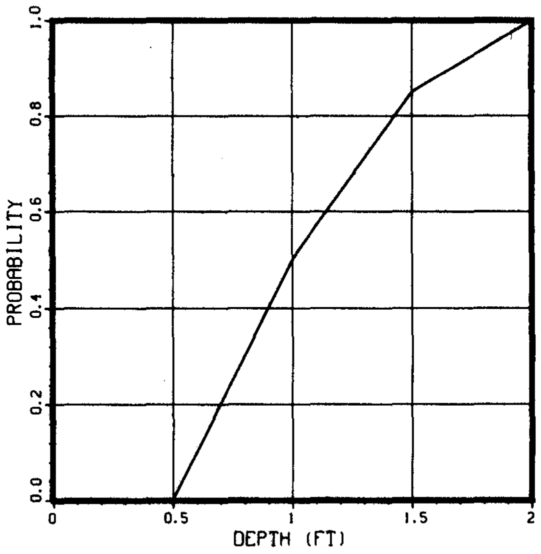


FISHING BOAT NON POWER

700200

78/06/26.

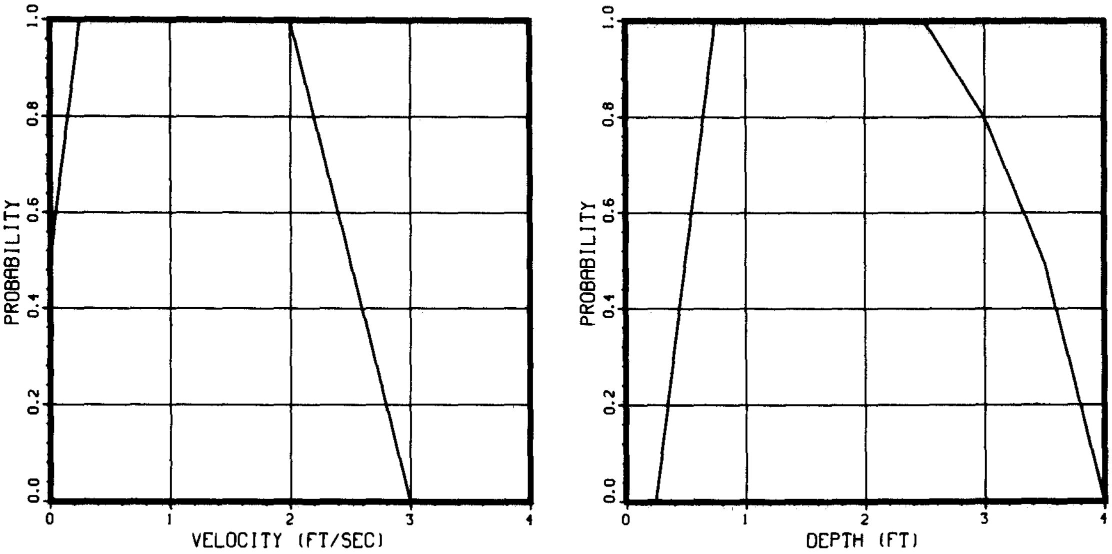




WATER CONTACT WADING

710100

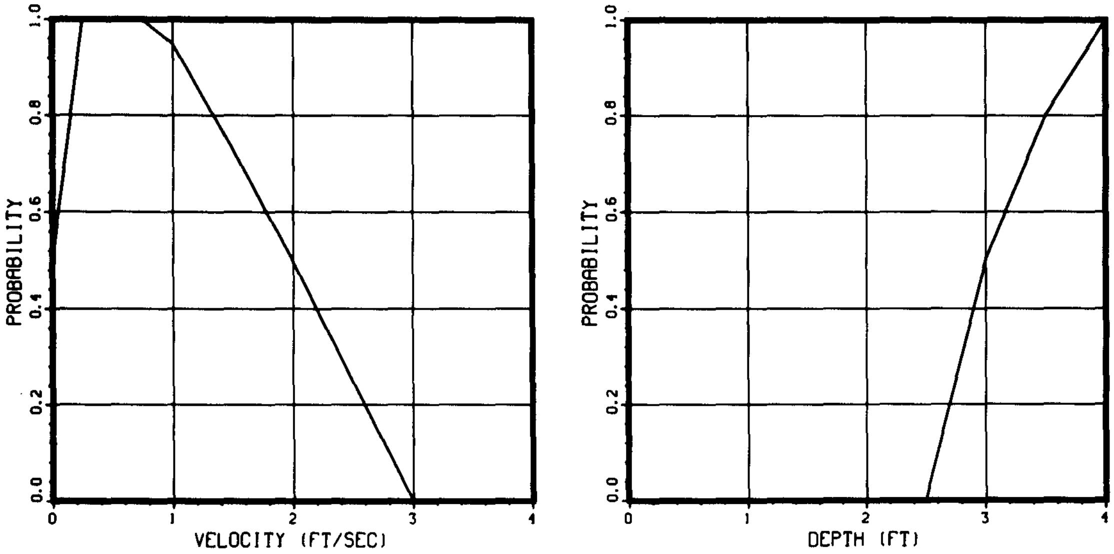
78/06/26.



WATER CONTACT SWIMMING

710000

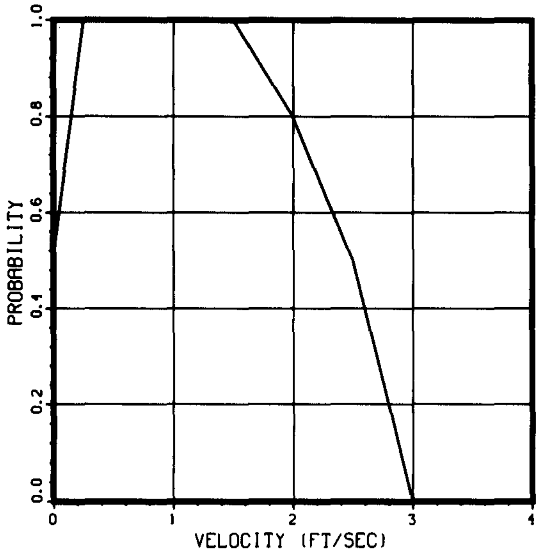
78/06/26.

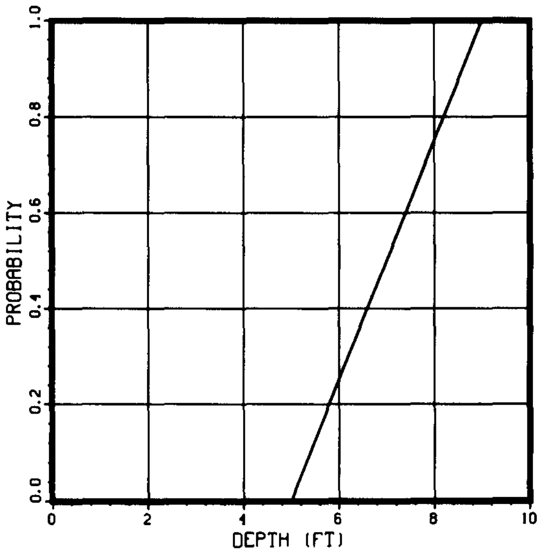


WATER CONTACT WATER SKIING

710200

78/06/26.

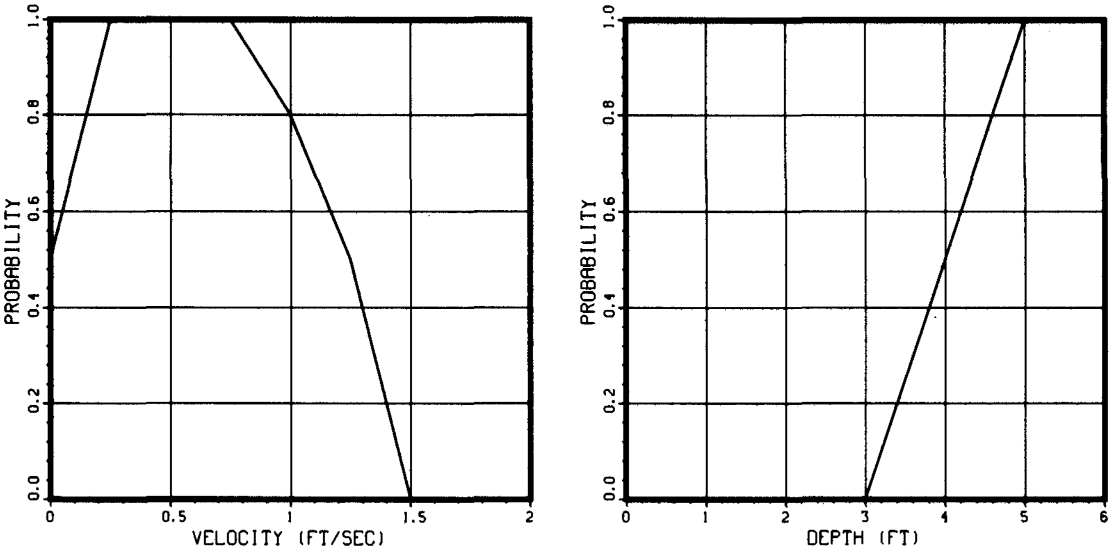




BOATING SAILING

720000

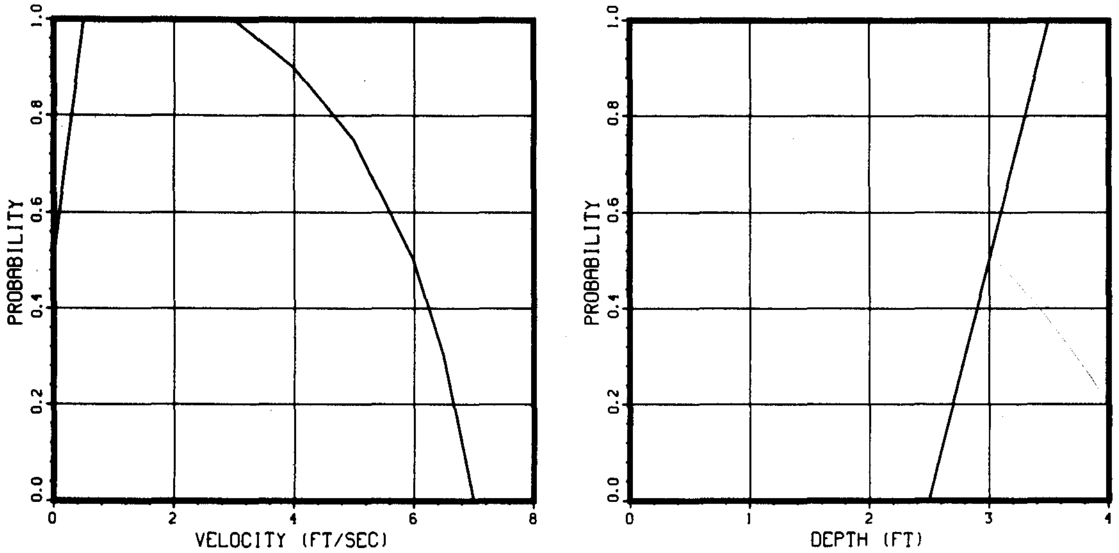
78/06/26.



BOATING LOW POWER

720100

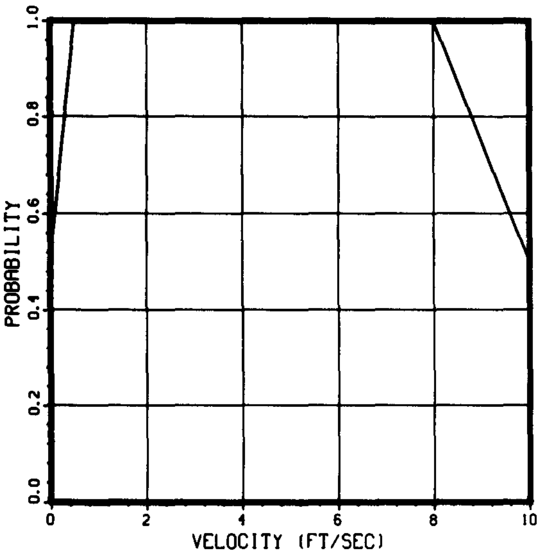
78/06/26.

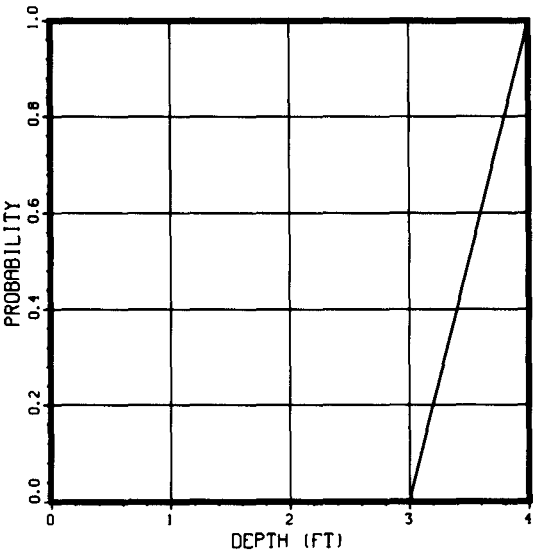


BOATING HIGH POWER

720200

78/06/26.



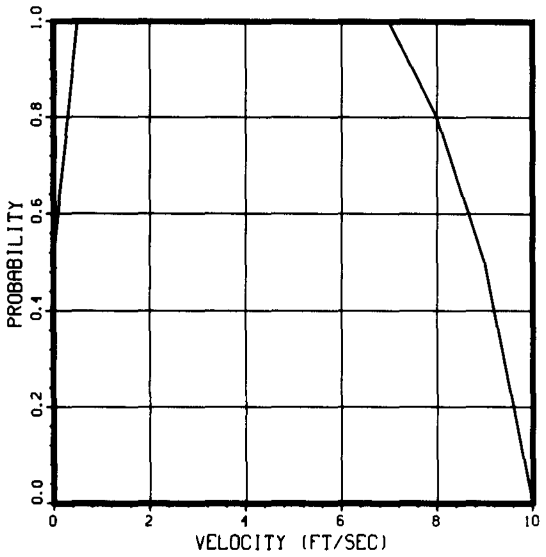


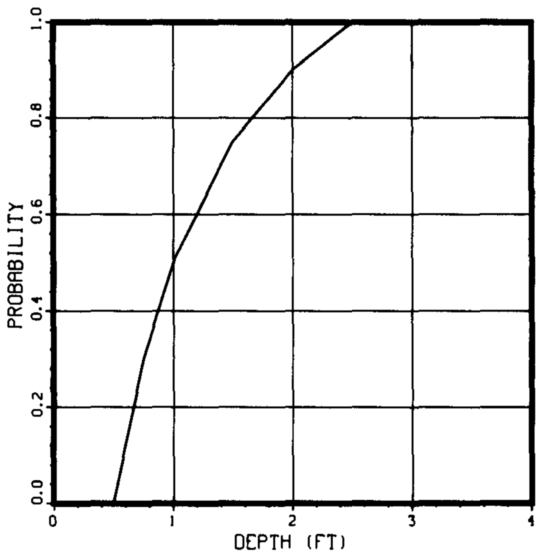
NOTE: Velocity plots have a maximum of 10 fps. The curves for the velocity for this activity reaches a probability of 0.0 at 12 fps.

BOATING CANOEING KAYAKING

720300

78/06/26.





BOATING ROWING RAFTING DRIFTING

720400

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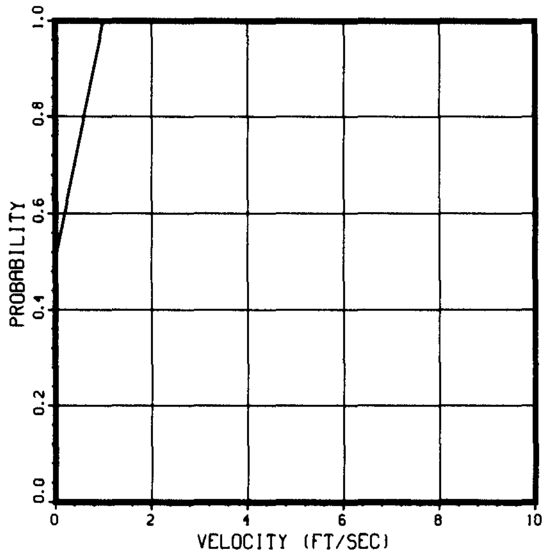

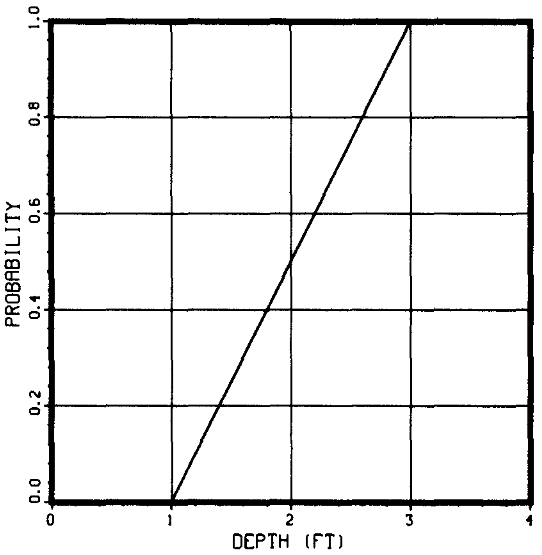

NOTE: Velocity plots have a maximum of 10 fps. The curve for the velocity for this activity is at a probability of 1.0 at 10 fps, a 0.5 probability at 12 fps, and a 0.0 probability at 14 fps.

BOATING TUBING FLOATING

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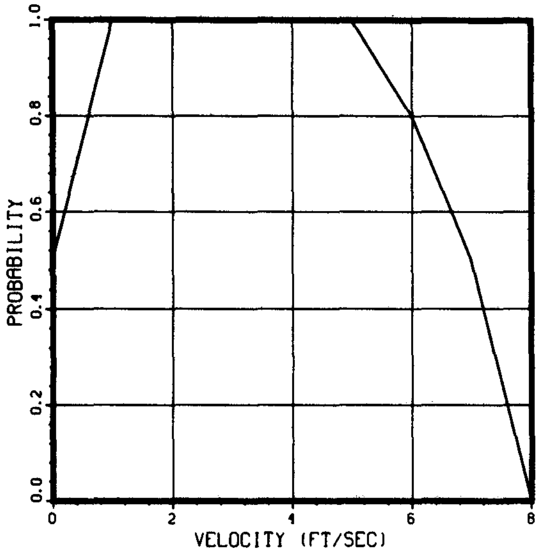

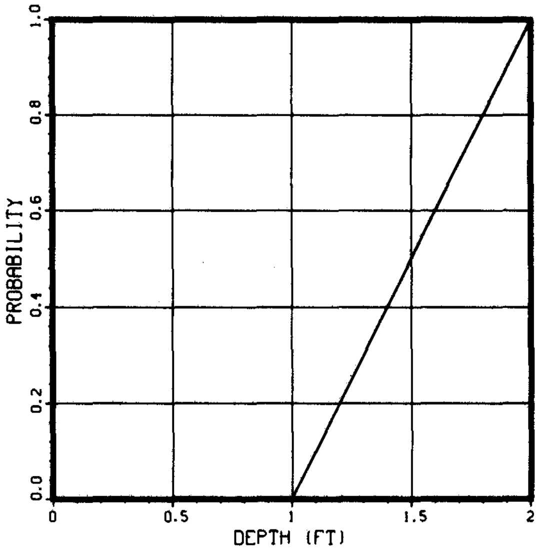

U. S. Department of the Interior

Fish and Wildlife Service

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March 3, 1849

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Recreation and Instream Flow. Volume 1
Flow Requirements, Analysis of Benefits, Legal and Institutional Constraints

Jason M Cortell and Associates, Inc, Waltham, Mass

Prepared for

Bureau of Outdoor Recreation, Washington, D C

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Vol. 1

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Analysis of Benefits
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Submitted to

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Waltham Massachusetts

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SECTION 2

THE RELATIONSHIP OF INSTREAM FLOW TO TYPES OF AQUATIC RECREATION

The first step in establishing the flow-to-activity relationship is the setting of the requirements governing recreation activities. These are of two types. First, there are physical criteria which must be met if an activity is to be possible. These can be expressed in terms of width, depth, and velocity. If these conditions are met in a stream, regardless of absolute discharge, then the activity is possible. A second set of criteria helps to determine the desirability of the stream for the activity. These are site and stretch-specific and may or may not be flow related. Examples of this would be the presence of clear, clean water and sandy beaches for swimming or long stretches of water suitable for boating, rather than only a few hundred feet of such water bounded by major rapids or waterfalls.

The second step in this process is to determine the ability of a given stream to meet these requirements as a function of discharge. It is not possible to say in absolute terms that a discharge of so many cfs (cubic feet per second) is suitable for a certain activity. It is possible, however, to say that a discharge of so many cfs is suitable for particular activities in a particular river.

The final step in the process is an analysis of the expected recreation potential on a particular stream as a function of discharge and, ultimately, the recommendation of a flow level, that will support the widest range of recreational uses. This is accomplished by applying the techniques of hydraulic geometry to the stream in question to determine the relationship between stream flow and physical characteristics (width, depth, and velocity). These may then be compared to the physical criteria required by various recreational activities to determine those that may be supported at various stream flows. The stream is then examined for site and stretch characteristics that might either favor or eliminate activities. A determination can thus be made as to the suite of activities compatible with a particular reach of a stream and a definite flow for that suite of activities can be recommended. This recommendation might be in the form of a single flow which maximized a certain suite of activities at all times, or a set of seasonal, monthly, weekly or even daily flows which offer suitable conditions for different suites of activities at different times of the year (e.g. white water canoeing in the spring and swimming, wading, and fishing in the summer).

2.1 FLOW-RELATED REQUIREMENTS FOR RECREATION

For purposes of river evaluation, what is needed is a set of clearly defined physical parameters relating recreational potential to flow. The criteria presented here are intended to meet this need. The data are drawn from a number of sources (primarily Thompson and Fletcher, 1972 and U.S. Dept. of the Interior, Bureau of Land Management, 1972) and modified or extended in some cases. They provide a clear physical description of those conditions in a stream which will support an activity, those which are optimal for the activity, and those which preclude the activity. The main descriptors will be width, depth, and velocity, since these are the main characteristics of a stream which change in response to changing flow. A summary of these is presented in Table 2. Of secondary importance will be those auxiliary conditions which influence the desirability of the activity, such as sand bottoms for swimming; those which might eliminate a physically possible activity, such as a low-flow die-off of fish; and those which might influence the potential market for an activity, such as the presence of a competing, higher quality resource in the immediate area.

2.1.1 Fishing

Fishing depends upon, first, the survival and catchability of desirable species of fish, and second, the ability of fishermen to pursue and capture them. The first requirement has been studied extensively by fisheries departments throughout the nation. Survival conditions are usually specified in terms of a requisite minimum percentage of Average Annual Flow (AAF) to support spawning, hatching, rearing, and passage at appropriate times of the year.

Catchability may also be flow related. The first requirement is that the simple survival criteria of adults of the target species be met. For trout and many other salmonids, these are met if the water is relatively clean, temperatures are less than 60°F to 65°F, and velocities are low enough that the fish can maintain their position in the stream (4 to 8 feet per second). Smallmouth bass will survive in less clean waters and at temperatures into the 90's but may have more limited capacity to deal with high velocity flow. (Stalnaker, 1975)

The willingness of the fish to bite is the other factor which must be considered in catchability. This is perhaps the least understood area in fisheries. The upper bounds for fish catching can be established rather simply. If velocities exceed 5 to 10 feet per second, even strong salmonids are either swept downstream or retreat to sheltered areas (D.L.Tennant, 1975). This may occur for warm water species at about 2 to 4 feet per second. Depth limits the other end of the flow scale. If depths are reduced below six inches, most fish worth catching

TABLE 2

Summary of Instream Flow Requirements for Recreation

	ACTIVITY	MINIMUM CONDITION	MAXIMUM CONDITION	OPTIMUM CONDITION	COMMENTS
FISHING	**Wading**	W = -- D = -- V = --	W = -- D = 4 ft V = 2.5 ft/sec	W = -- D = <4 ft V = <2.5 ft/sec	All conditions should be checked against fish survival flow.
	Boating-Canoeing	W = 25 ft D = 6 in V = --	W = -- D = -- V = 10 ft/sec	W = >25 ft D = 2-5 ft V = <5 ft/sec	
	Boating-Low Power	W = 25 ft D = 1 ft V = --	W = -- D = -- V = 10 ft/sec	W = >25 ft D = 2-5 ft V = <5 ft/sec	
	Bank	W = -- D = -- V = --	W = D = Flood V =	W = based D = on fish V = catchability	
WATER BOATING	**Rafts & Drift Boats**	W = 50 ft D = 1 ft V = 5 ft/sec (Class I)	W = -- D = -- V = 15 ft/sec (Class V & VI)	W = >100 ft D = 2-5 ft V = 10 ft/sec (Class II,III,IV,V)	In all cases, check against International Classification.
	Canoes & Kayaks	W = 25 ft D = 3-6 in V = 5 ft/sec (Class I)	W = -- D = -- V = 15 ft/sec (Class IV & V)	W = >75 ft D = 2-3 ft V = 10 ft/sec (Class II,III,IV)	
TRANQUIL WATER BOATING	**Canoeing**	W = 25 ft D = 6 in V = --	W = -- D = -- V = 5 ft/sec	W = >75 ft D = 2-5 ft V = <1.5 ft/sec	
	Rowing	W = 25 ft D = 1 ft V = --	W = -- D = -- V = 5 ft/sec	W = >75 ft D = 2-5 ft V = <1.5 ft/sec	
	Sailing	W = 100 ft D = 2 ft V = --	W = -- D = -- V = 1.5 ft/sec	W = >200 ft D = ~5 ft V = ~0 ft/sec	
	Low Power	W = 25 ft D = 2 ft V = --	W = -- D = -- V = 10 ft/sec	W = >100 ft D = ~5 ft V = <5 ft/sec	
	High Power	W = 100 ft D = 5 ft V = --	W = -- D = -- V = 15 ft/sec	W = >300 ft D = 10 ft V = <5 ft/sec	
WATER CONTACT	**Swimming**	W = 25 ft D = 3 ft V = --	W = -- D = -- V = 3 ft/sec	W = >100 ft D = 5 ft V = <1.0 ft/sec	Water temp - max 50-100°F Visibility - Opt=Depth Bacteria max 1000mpn
	Wading	W = -- D = -- V = --	W = -- D = 4 ft V = 2.5 ft/sec	W = -- D = 1-4 ft V = 2-5 ft/sec	Max D x V = 10 Opt D x V = 2-5 + above
	Tubing	W = 25 ft D = 1 ft V = 1 ft/sec	W = -- D = -- V = 10 ft/sec	W = >75 ft D = 2-5 ft V = 5 ft/sec	Same as Swimming
	Water-Skiing	W = 200 ft D = 5 ft V = --	W = -- D = -- V = 3.5 ft/sec	W = >500 ft D = 10 ft V = <2.5 ft/sec	Same as Swimming

Maximum Conditions -

For a normal-sized, adult fisherman in chest waders, Depth = 4 feet, Velocity = 2.5 feet. At any lesser depth, the product of depth (ft.) and velocity (ft/sec) should be less than 10. Where the bottom is uneven, rocky, or slippery, the maximum conditions are shifted downward.

Optimum Conditions -

These are determined by the catchability of the species being pursued. The ability of the fisherman to pursue the fish by wading is assured by any flow yielding less than maximum depths and velocities.

2.1.1.2 Boat Fishing

Some assumptions are required to set flow criteria for boating in pursuit of fish. It is assumed that fishing occurs from a canoe or similar shallow draft craft and that power boats are small fishing boats, equipped with a motor of 15 horsepower or less. Canoes, when unpowered, can negotiate (with great difficulty) water as shallow as 3 inches and can turn around in little more than their own length. A limit of 6 inches is more realistic if hang-ups are to be avoided. Paddling, as opposed to poling, becomes possible at a depth of 2 feet. Safety for a fishing party is optimized if the occupants can "walk out" after capsizing, implying a depth of less than five feet. There is no maximum depth for canoeing, but there are maximum velocities. Competent, but not expert, paddlers can handle a canoe effectively in waters as fast as 6 feet per second; at this velocity, backpaddling is just sufficient to hold the boat steady in the current. Faster water would make manuevering more difficult, and a firm upper boundary is reached at a velocity of 15 feet per second - even strong paddlers could not make sustained headway against such a velocity. A velocity of 10 feet per second would tax many boaters.

Small power boats offer an advantage in that they can make headway against relatively strong currents without exhausting the fisherman. They, too, however, become unmanueverable and find difficulty in upstream progress in currents of 10 feet per second. Depth limits are less generous than for canoes. With a short-shaft motor, depths of less than 2 feet will often cause propeller fouling on bottom growth. With motors up, negotiating water between 6 inches and 1 foot is possible. Turning within one boat length is feasible, but difficult.

The following criteria govern fishing from small non-powered and low-powered fishing craft.

Minimum Conditions -

Depth = 6 inches for canoes, 1 foot for small power boats. There is no lower limit for velocity. Width can be as narrow as one times the length of the craft being used, or, more realistically 25 feet. (In narrower streams, wading or bank fishing would be preferred to boat fishing).

Maximum Conditions -

Velocity = 10 feet per second. There are no width and depth maxima for boating in pursuit of fish. Velocity maxima should be for short distances only.

Optimum Conditions -

Depth = 2 to 5 feet. Velocity less than 5 feet per second. Width greater than 25 feet.

2.1.1.3 Bank Fishing

Bank fishing, to a high degree, is independent of stream flow from the anglers viewpoint. The activity is possible, although perhaps non-productive, at no flow and can be carried out at any flow that does not over-top or make inaccessible the banks of the stream. Optimal bank fishing flow depends upon the catchability of the fish being sought. In the sense of maximizing the chance of capturing a fish, it is the lowest flow that will sustain the population. This low level of flow minimizes the mobility of the fish. Such a condition, however, cannot be recommended since it would quickly lead to destruction of the fisheries resource.

2.1.2 Non-Tranquil Water Boating

Boating in non-tranquil water (white water, wildwater) is an activity of relatively broad aesthetic appeal, but relatively minor numerical participation. The demands placed on a boater by white water are sufficient to discourage many potential participants. None-the-less, much of the literature on water based recreation concerns this activity and its general popularity is growing rapidly.

There are four common forms of white water craft, each with its own advantages, disadvantages, and criteria for use. Perhaps the most common is the open canoe, usually from 15 to 17 feet in length, which is used by both serious and casual white water boaters. Kayaks are among the most popular craft for the veteran white water boater. On larger rivers, or with larger parties, wooden or aluminum drift boats and rafts are the crafts of choice.

In terms of stream flow criteria, canoes and kayaks may be grouped together. Both are small, maneuverable, and capable of upstream and cross-stream maneuvers. The drift boats and rafts are larger, less maneuverable and almost impossible to move upstream in heavy water. They are, however, very stable in heavy water and can carry unskilled passengers; they are used almost exclusively by commercial river guides.

In either class of craft, a certain minimum condition must be met in a stream to provide even a limited white water experience. The exact conditions of gradient and flow that yield white water vary from stream to stream, but a good rule of thumb is that white water streams have a gradient in excess of 10 feet per mile and a flow in excess of 500 cubic feet per second. These conditions will provide Class I white water on the International River Classification scale. This scale recognizes six grades of white water. These may be subjectively described as:

> Class I - Very Easy. Waves are small and regular, passages are clear. Obstacles are sand bars, bridge piers, and riffles.
>
> Class II - Easy. Rapids of medium difficulty with clear, wide passages.
>
> Class III - Medium. Waves are numerous, high, and irregular. Passages are clear but narrow and require expertise in maneuvering. A spraydeck on open boats is useful.
>
> Class IV - Difficult. Long rapids with powerful waves and many obstacles are present. Passages are difficult to see and powerful, precise maneuvering is required. A spraydeck is essential on open boats.
>
> Class V - Very Difficult. Rapids are long and very violent, following each other almost without interruption. The riverbed is extremely obstructed with large drops and violent currents.
>
> Class VI - Extraordinarily Difficult. The difficulties of Class V carried to the extreme of navigability.

For recreational white water boating, only Classes I through IV are of interest. Class I marks the minimum level for a white water experience, Class III is the usual upper bound for open boats, and Class IV is the upper limit for most recreational kayakers. Rafts, drift boats, kayaks, and covered canoes can negotiate Class V waters if they are expertly handled. Class VI waters are stunt waters for expert boaters with maximum safety precautions.

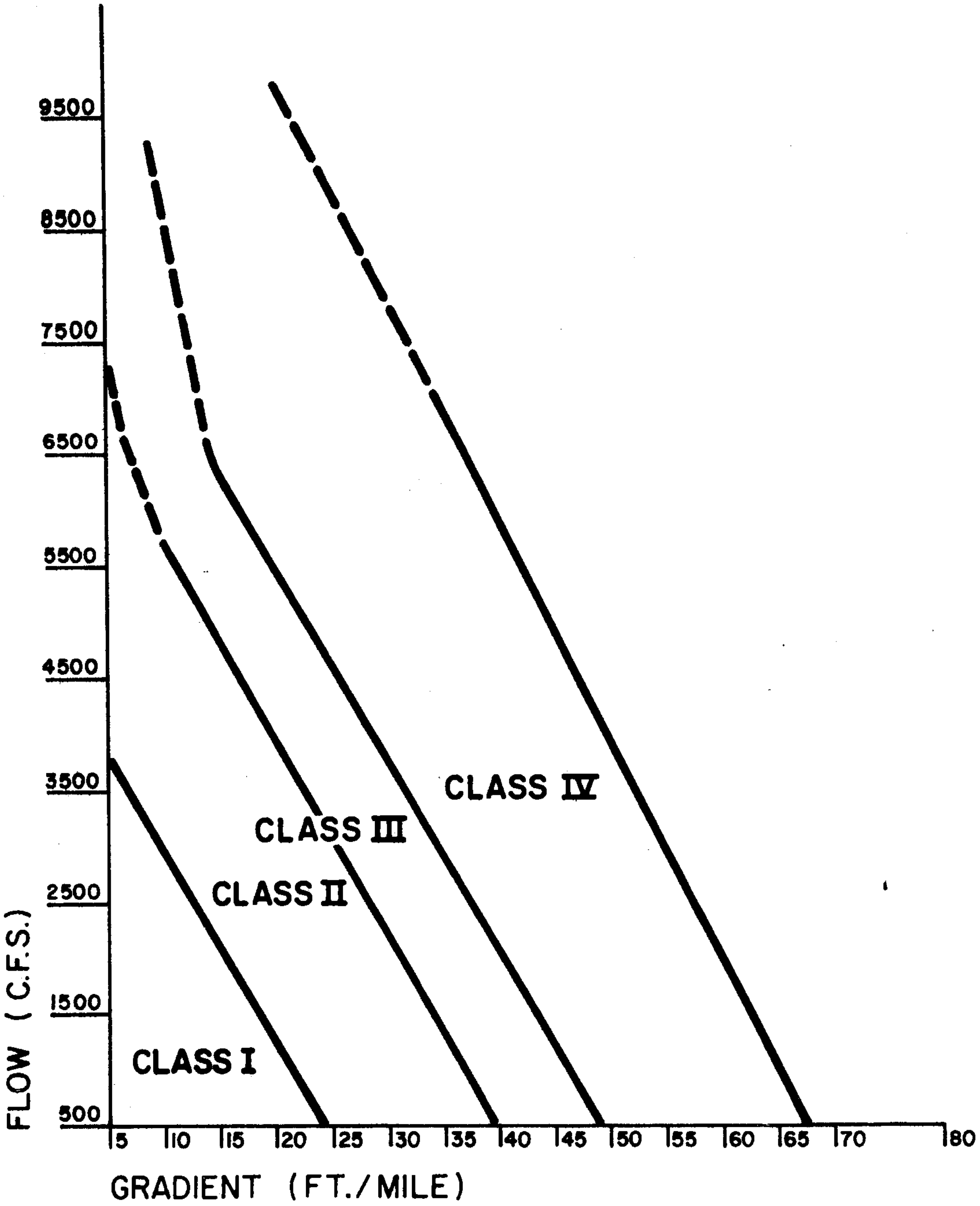
The Class of a stretch of river can be estimated roughly from information on gradient and flow. The following graph applies to stretches of uniform gradient quite well. It does not predict the class of short, steep stretches (See Figure 1).

More precise and less subjective Class determinations can be made if the river can be field inspected. The following chart (Table 3) can be used for this purpose. The stretch of interest is scored in all 11 categories and the scores summed. The total score indicates the International Classification of the stretch.

In addition to providing water of a suitable International Class, a stream must meet other requirements in order to provide a high quality white water experience. These are best described in terms of obstructions and time of travel.

Obstructions must be viewed as detractions from the white water experience. Portaging around a dam is not what is sought by most white water boaters. Thus, careful map, air photo, and field inpsection will be needed to find possible obstructions to boating and to determine if there is sufficient warning of these obstructions to insure against boater injury and suitable portaging areas to allow passage. This must be dealt with on a river-by-river basis, but in general, the more obstructions, the less desirable the water for white water boating.

Time of travel has two influences. First, it may determine the gear and supplies required for a river trip and, second, it may select for or against some forms of boating. The kayaker, for instance, may enjoy running and re-running a short, intense section of a stream with still water above and below. This might not be possible for a group in a drift boat, which is difficult to move upstream and heavy to portage. Thus, short sections of water may be ideal for "practice" and longer runs, of some hours or even days, may be more suitable for float trips or white water expeditions. Garren (1976) has provided some rules of thumb for determining the time of travel for various craft in various river situations. He notes that, if a kayak is assigned a drift time of 1.0, a canoe will require 1.1 times as long to traverse the same distance, a drift boat will require 1.3 times as long, and a rubber raft will require 1.6 times as long. He also presents a generic relationship between river discharge, in cfs, and river velocity in miles per hour. See Figure 2. This, much like the Class derived from the Arighi and Arighi chart, can be greatly refined by the hydrological studies, but the chart is useful for estimating time of travel directly for kayaks. This can be adjusted for other types of craft, if needed, using the multipliers.



ESTIMATING RIVER DIFFICULTY
(Assumes Fairly Even Gradient)

AFTER ARIGHI AND ARIGHI, 1974

Figure 1

Regardless of the approach taken to classification, upper and lower limits on river characteristics can be specified for the two groups of craft type, based on their characteristics.

2.1.2.1 Canoes and Kayaks

Canoes and kayaks are very maneuverable and draw very little water. They can pass over obstacles with as little as 3 inches of water and can be turned in their own length. With small margins for error and to prevent unnecessary bottom dragging, a minimum depth of 6 inches and a minimum width of 25 feet will allow passage. The minimum water velocity to yield Class I white water is about 5 feet per second.

Maxima for these craft are somewhat more difficult to establish. Very wide rivers, especially if they are Class IV or higher, adversely effect safety, but do not physically preclude the activity. Depths, too, cannot alone eliminate the activity, although at very high stage, most of the obstacles that create the white water experience may be so deeply covered as to be unnoticeable. Maximum velocity is in the vicinity of 15 feet per second. Above this speed, even an expert boater or team would be nearly unable to hold position or move upstream.

Optimum flow levels are completely river and boater skill specific. Generally, river conditions yielding Class II and III waters will be optimum for open canoes. The optimum for kayaks and decked canoes, especially for skilled boaters, may include Class IV waters. These optimum conditions will occur on many rivers at a depth of between 2 and 3 feet, with widths on the order of 75 to 100 feet, and velocities of about 10 feet per second.

Thus, the criteria for white water boating are as follows. Note that these are very general and, particularly for the optimum conditions, can only be accurately assessed at streamside or on the water.

Minimum Conditions -

> Width = 25 feet, Depth = 3 to 6 inches, Velocity = 5 feet per second. Conditions should yield Class I (and perhaps some Class II) water in the stream.

Maximum Conditions -

> No firm width and depth maxima can be established. Velocities in excess of 15 feet per second will preclude all but the most skilled and dedicated boaters. Conditions should yield Class IV or V waters over much of the stretch of interest.

Optimum Conditions -

> Width = 75 to 100 feet, Depth = 2 to 3 feet, Velocity = 10 feet per second. Conditions should yield Class II and III waters in the stretch of interest (some Class IV might be desirable for kayakers.) The optimum conditions will require field checking, unless flow related classifications for the stream are available from reliable guidebooks or organizations.

2.1.2.2 Rafts and Drift Boats

The primary differences between these craft and canoes and kayaks are their lack of maneuverability and their ability to negotiate very heavy water. In terms of river characteristics, these craft require more space than do the smaller craft. A minimum width of 50 feet and a minimum depth of 1 foot should insure their passage. As before, a minimum velocity of 5 feet per second will often generate mild white water conditions. The implication of these minima is that rafts and drift boats require larger streams and more water to be used successfully.

Maximum and optimum conditions are very similar to those discussed for canoes and kayaks, except that these boats can sustain Class V waters more readily than can the smaller craft. Numerical maxima are as before, but these conditions can yield a higher Class water in the stream without eliminating the activity.

Minimum Conditions -

> Width = 50 feet, Depth = 1 foot, Velocity = 5 feet per second. Class I or II waters should prevail.

Maximum Conditions -

> No firm width or depth maxima can be established. Velocities greater than 15 feet per second may be limiting. River conditions yielding Class V and VI waters over long stretches will eliminate the activity.

Optimum Conditions -

> Width = 100+ feet, Depth = 2 to 5 feet, Velocity = 10 feet per second. Conditions in the stream should yield Class II to IV waters in the stretch of interest. Some Class V will add to the enjoyment of skilled boaters, but may prove dangerous in the event of capsize.

2.1.3 Tranquil Water Boating

Five separate kinds of activity must be considered in tranquil water boating: canoeing, rowing, sailing, low power boating, and high power boating. These activities share many characteristics with non-tranquil water boating, but exhibit much more stringent limits on maximum conditions. The longitudinal suitability and time of travel considerations given above for white water boating apply in much the same fashion to flat-water boating, except that some short flat water reaches will see very heavy use if access is good. Obstructions to flat water boating include not only the dams and falls which obstruct white water activities, but rapids as well. Ideally, a flat water reach would include no dams, falls, or white water stretches. The flow would be uniform and progress could be made both downstream and upstream without severely taxing the participants. Failing of this, major portage areas should be considered as obstructions. A cut-off length of 1/4 mile for portaging may represent the upper end of desirability for users of light craft, such as canoes. Portaging of power boats is generally out of the question and any portage site must be considered as completely obstructing. Should a river reach prove generally suitable for flat water boating, there are specific criteria governing each of the forms of the activity, set by the nature of the craft.

2.1.3.1 Canoeing

Canoes, as discussed above, can negotiate waters as shallow as 3 to 6 inches, although poling will be more appropriate than paddling. Widths as narrow as the length of the boat can be acceptable, although a practical minimum is about 25 feet. The quality of canoeing improves markedly as depths become greater than 2 feet. At two feet, paddling without striking the bottom is possible. Safety considerations make a depth of 5 feet the upper bound of optimal canoeing; at this depth, most people can wade out in the event of capsize. There is no maximum width or depth which precludes canoeing, but velocities in excess of 5 feet per second impede upstream progress and mark the general lower limit of Class I white water conditions. Thus, the criteria are:

Minimum Conditions -

Width = 25 feet, Depth = 3 to 6 inches, Velocity = 0 feet per second.

Maximum Conditions -

There are no depth or width maxima. Velocities over 5 feet per second change the activity from tranquil water boating to low level white water.

Optimum Conditions -

Width greater than 75 feet, Depth = 2 to 5 feet, velocity less than 1.5 feet per second.

2.1.3.2 Rowing

Rowing for pleasure shares many of the same limits as tranquil water canoeing. The major difference is that rowing requires greater depths to be pleasant. Poling a rowboat would detract from the experience. Therefore, minimum depths should be no less than 1 foot.

Minimum Conditions -

Width = 25 feet, Depth = 1 foot, Velocity = 0 feet per second.

Maximum Conditions -

No width or depth maxima can be established. Velocities should be less than 5 feet per second.

Optimum Conditions -

Width greater than 75 feet, Depth = 2 to 5 feet, Velocity less than 1.5 feet per second.

2.1.3.3 Sailing

Sailing even the smallest craft requires a draft of 2 feet to keep a short dagger board off the bottom. A width minimum of 100 feet would just barely allow a small craft (12 to 13 feet) to tack upstream. Maximum conditions, as for other forms of boating, are not applicable except in terms of velocity. If the wind dies, a sail boat must be considered unpowered, since few sail boats carry oars. Thus, 1.5 feet per second can be taken as the upper velocity limit for river sailing activities. Optimum conditions would include a depth of about five feet, the more width the better, and a velocity as near zero as possible.

Minimum Conditions -

Width = 100 feet, Depth = 2 feet, Velocity = 0 feet per second.

Maximum Conditions -

There are no maximum widths or depths for sailing. Velocities should not exceed 1.5 feet per second as a rule.

Optimum Conditions -

Width greater than 200 feet, Depth = 5 feet, Velocity near 0 feet per second.

2.1.3.4 Low-Power Boating

Small power boats (less than 15 feet and less than 50 horsepower) can be operated in streams as narrow as those used by canoes as long as fouling of their propellers can be avoided. Maximum conditions are velocity limited at about 10 feet per second, since many small power boats cannot exceed this speed (about 7 mph). Optimum conditions are found when widths exceed 100 feet, to allow turns under full power, when depths are at or about 5 feet, and when velocities are less than 5 feet per second.

Minimum Conditions -

Width = 25 feet, Depth = 2 feet, Velocity = 0 feet per second.

Maximum Conditions -

There are no maximum widths or depths. Velocity less than 10 feet per second is required.

Optimum Conditions -

Width greater than 100 feet, Depth = 5 feet, Velocity less than 5 feet per second.

2.1.3.5 High-Power Boating

High-power boats (greater than 15 feet in length and greater than fifty horsepower) are far more restricted in their operation on streams than the other classes of tranquil water boats. In fact, this type of boat is most often found on a lake or reservoir, rather than on a stream. It will be found on wide streams or where large lakes are not available. Minimum width for their operation is 100 feet to allow turning even at fairly low speeds. Depth should be greater than 5 feet in the river channel to avoid propeller drag on acceleration. They can also make greater headway than other craft, and can navigate without undue difficulty against 15 foot per second currents. Optimum conditions are widths in excess of 300 feet, to allow full power turns, depths in excess of 10 feet, and velocities less than 5 feet per second.

Minimum Conditions -

Width = 100 feet, Depth = 5 feet, Velocity = 0 feet per second.

Maximum Conditions -

There are no width and depth maxima. Velocity should be less than 15 feet per second.

Optimum Conditions -

> Width greater than 300 feet, Depth = 10 feet. Velocity less than 5 feet per second.

These conditions are suitable for the majority of high-powered boats. There are, however, local and regional variant forms of high-power boating which may deserve special consideration, for example: jet-boating on larger western rivers and air-boating on southern rivers and swamps. Generally, the conditions for jet boats are similar to those for propeller-driven high-power boats except that operating depths may be as small as the hull draft of the individual craft (about 18 inches) and jet boats may be powered to make upstream progress in heavy white water conditions. Airboats, used mainly in non-riverine areas, are very maneuverable and can move in virtually no water for short distances. Their extremely shallow draft and flat bottoms make depth limits almost meaningless. As is the case with jet boats, however, they should be considered as a specialty craft and treated accordingly.

2.1.4 Water Contact Recreation

Four activities are considered under this general category: swimming, wading, tubing, and water skiing. All share the characteristic of deliberate contact with or immersion in the water without protective clothing. This places some generic limits on the activities based on temperature and water quality. Temperatures below 50°F or above 100°F will eliminate most water contact activities. Visibility should ideally extend to the bottom of the stream for both swimmer safety and for rescue. Total coliform bacteria counts should be below 1000 MPN (most probable number) per 100 ml of water to meet public health standards (FWPCA, 1968). Other than these general criteria, each water contact activity has its own unique set of physical limits.

2.1.4.1 Swimming

Swimming will be considered here as the advanced form, rather than the splash and wade form, treated as wading below. Advanced swimming requires relatively deep water, relatively still water and a width sufficient for several strokes bank to bank. Ideally, it would also occur at an area with a sand bottom and a beach to maximize the enjoyment of the participants. When lake front beaches are rated, a gentle slope of 100 feet out to a depth of 5 feet is considered ideal, but such conditions will seldom be found in a river. A reasonable minimum width for true swimming is 25 feet. Water depths of 3 feet or greater will allow a clean stroke without striking bottom. An optimum swimming depth is about 5 feet, which allows both advanced swimming and resting or wading out. Velocities of 3 feet per second will tax even a very strong swimmer quickly (Thompson and Fletcher, 1972). One foot per second or less is most desirable.

Minimum Conditions -

Width = 25 feet, Depth = 3 feet, Velocity = 0 feet per second.

Maximum Conditions -

There are no width or depth maxima. Velocities should be less than 3 feet per second.

Optimum Conditions -

Width greater than 100 feet, Depth = 5 feet (10 feet if diving is part of the activity), Velocity less than 1 foot per second.

2.1.4.2 Wading

Whether or not one can wade safely in a river at a given place is related to the depth of the water, the velocity of flow, the nature of the bottom, the purpose of the wading activity, and the physical size and strength of the participant. The depth and velocity are usually directly related to discharge; the nature of the local wadable bottom (slope, roughness, for example) may also be related to discharge. These, in turn, tend to predetermine what activities may safely take place and by what kinds of people.

Wading may be a part of the white water boating activity. The wading involved here is, of course, an unwanted incident of the primary recreational activity. However, the fact that one cannot safely wade out of a bad situation was used earlier to set a boundary on optimum boating conditions.

In terms of numbers of participant days, wading by fishermen is probably the most common wading activity found in riverine recreation. In this case, the wading is incidental to the primary purpose, which is catching fish. Thus, this kind of wading activity is longitudinal in nature.

Finally, wading is often engaged in as a substitute for swimming in rivers. In this case, wading, in the form of a special kind of water contact sport, is the primary activity. It tends to be localized in nature, in contrast to wading for fish, in places chosen because they present special opportunities for water play.

In absolutely calm water, with a smooth, firm bottom of sand or gravel, a person can safely wade up to shoulder height, if not encumbered by heavy clothing or other gear, though few would choose to do this. (Such an area would be ideal for swimming, for which wading is but a surrogate activity.) More to the point, these conditions are not commonly found in rivers, where movement of the water is almost always found. In fact, one can set bounds on wading safety, as a first approximation, by considering depth and velocity.

The rough rule of thumb is that any time the product of depth in feet and velocity of the water in feet per second exceeds 10, conditions are unsafe for wading. This assumes a bottom of gentle slope, with no holes, and covered with fine materials (such as sand or gravel) which provide both bottom smoothness and good footing. Where these physical conditions do not obtain, the depth velocity relationships become more restrictive. In essence, wading safety must depend upon physical conditions which are not conducive to losing one's footing and which will not prevent recovery if one does fall down. Waders may not know how to swim. Or they may not be able to swim because of restrictive clothing, as might be the case of the angler in his chest-high "waders."

Figure 3 presents limit curves for wading by age-body build class. In all cases, good bottom conditions are assumed. The upper curve relates primarily to fishermen. The second curve may apply to either fishing or water contact wading. The lower two curves are most pertinent to the latter activity.

The central portions of curves A, B, C, and D represent depth-velocity products of 10, 9, 5, and 2 respectively. As noted on the legend, they are keyed to large men, normal adults and teens, sub-teens, and pre-schoolers. At the high velocity end of the curves, a cut-off has been provided at velocities in the neighborhood of six feet per second. At such velocities any unexpected change in bottom configuration could lead to danger in the event of a loss of balance, even in rather shallow water. Perhaps more important, in the low velocity area the curves have been flattened out to indicate a suggested maximum safe depth for each class of wader. Even at low velocities, recovery without recourse to swimming becomes difficult when the water depth is greater than about two-thirds to three- quarters of body height.

With the caveats on body size and swimming ability in mind, the following general criteria will serve for wading activity by average sized adults and teens.

RIVER STUDIES PROGRAM

1.0 INTRODUCTION

The river studies program was based on a number of propositions. It was assumed that there is a set of physical parameters governing the potential for a specific kind of recreational activity in a riverine setting. These can be expressed in discrete terms, usually a range centered about an optimum. For any river these physical parameters will tend to vary with stream flow. The impact of flow variations on such parameters is to some extent predictable, since it is governed (at least in the gross) by well-known principles of hydrology. Accordingly, it is entirely feasible to develop a set of analytical techniques, based on map studies and analyses of hydrological data, which will permit one to predict what will happen to existing or potential recreation in a river if flow is modified by reduction or augmentation. Field observations may be necessary at known or potential recreation sites, but these will consist primarily of taking a set of simple physical measurements at the site. These measurements when correlated with flow at the time they are taken, will permit extrapolation to parameter changes that will follow from a modification of the observed flow. And, finally, these predicted changes in physical parameters can be related back to recreational potential.

In order to test these hypotheses, a total of seven rivers were studied between October of 1975 and August of 1976. These rivers, shown in Table A-1, were selected to provide a wide variety of test situations and to allow the interactive development of pre-field, field, and post-field analysis techniques of general applicability to the study of the relationships between flow and recreation.

TABLE A-1

RIVER STUDIES SCHEDULE

RIVER	DATES OF VISIT
Chattahoochee (Atlanta, GA)	10/21 - 10/25, 1975
Saco (Bartlett and Conway, NH)	4/22 - 4/26, 1976
Rio Grande (Alburquerque, NM)	5/16-5/19, 5/22-5/23, 1976
Huron (Ann Arbor, MI)	6/24 - 6/27, 1976
North Platte (North Platte, NE)	6/28 - 7/1, 1976
Boise (Boise, ID)	7/29 - 8/2, 1976
Russian (Cloverdale, CA)	8/5 - 8/8, 1976

2.0 RIVER SELECTION

2.1 Criteria

A number of criteria were established to use in screening candidate rivers for inclusion in the field study experimental program.

Recreation: There are a number of kinds of riverine recreation which may be affected by flow. These include: boating in tranquil waters; water contact activities; fishing; water-enhanced activities; and wetland-related activities. A variety of recreational situations was sought.

Location: A distribution over the mainland, contiguous States was desired.

Size: The experimental program required consideration of a range of river sizes.

Physical Characteristics: The field study program needed to encompass a range of river types.

Urban/Rural Location: A variety of settings were sought for the rivers to be studied.

Regulation: The presence of regulating structures was considered desirable.

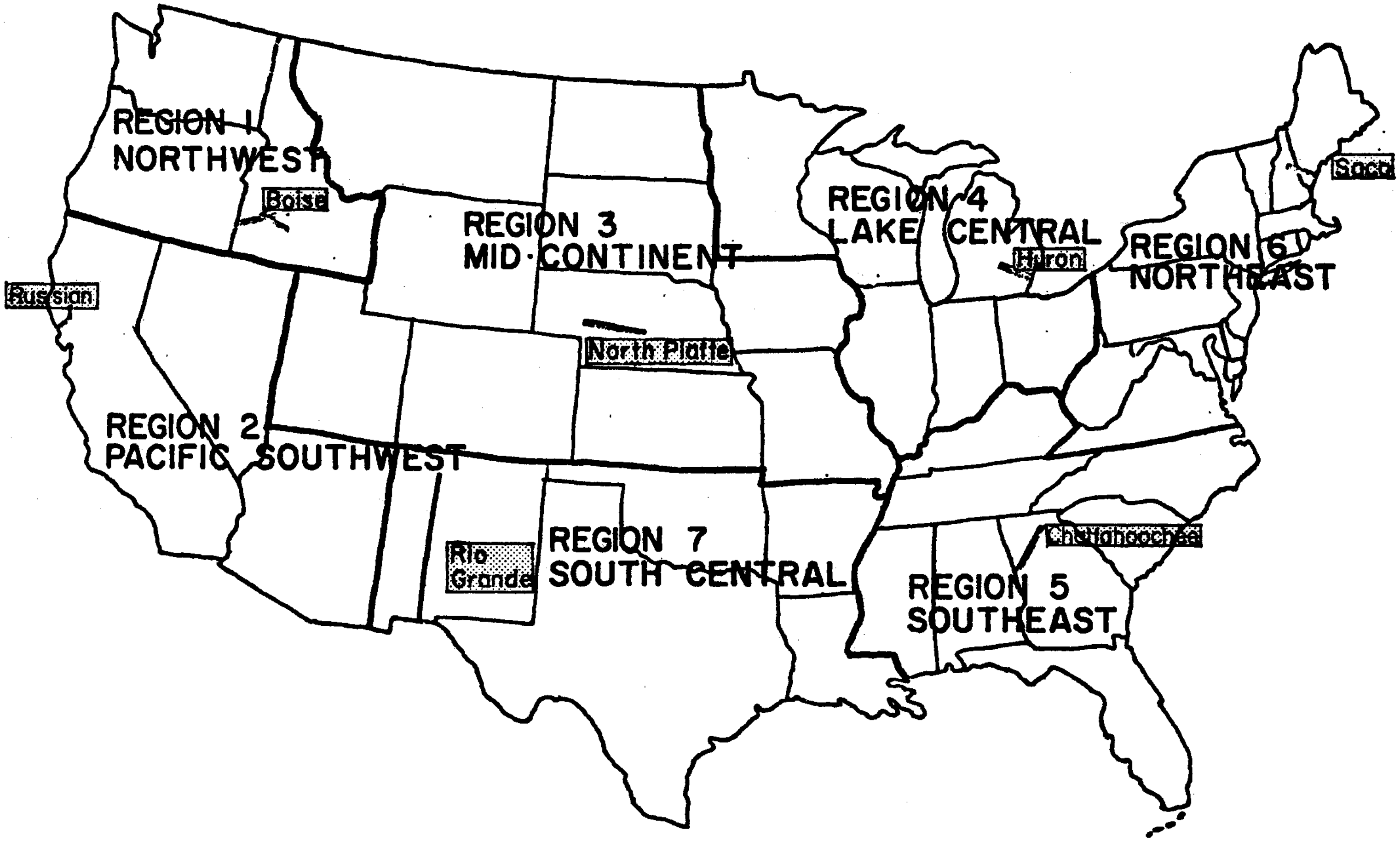
Wild or Scenic River Designation: While such designation was not a bar to selection, it was felt important not to have all test program rivers in this category.

Federal Power Commission Jurisdiction: Relicensing procedures of the Federal Power Commission offer an opportunity to modify future releases to support recreation.

Accessibility: Given limited budgets, easy access to the rivers to be studied was deemed desirable.

2.2 Selection

The seven rivers selected for field study provided a range of types which met the selection criteria. A total of 16 rivers was investigated for possible inclusion in the program. Geographic variability was assured by focussing the selection process on one river in each of the Bureau of Outdoor Recreation Regions (See Figure A-1).



RIVER STUDY LOCATIONS

Figure A-1

2.2.1 Chattahoochee River - Southwest Region

The Chattahoochee River between Buford Dam and Atlanta, Georgia offered a number of attractive characteristics for a study. It was, in fact, chosen as the pilot river, the first river to be studied.

There were a number of special considerations which made the Chattahoochee particularly attractive as a candidate for the pilot river study.

> Time of Year: The logic of the program design and the desires of the sponsoring agency dictated a preliminary field study in 1975. The required "start-up" time precluded any field work during the summer. This indicated a southern river. The weather in October was sufficiently warm to permit efficient conduct of a field program near Atlanta.
>
> Observation of Recreational Activities: Although activity on this part of the Chattahoochee is greater during the summer months, it was still possible to observe active recreation as late as mid-October.
>
> Recreation Potential: Studies by the Atlanta Regional Commission and the Georgia Department of Natural Resources indicated that the full recreational potential of this part of the Chattahoochee was not being used.
>
> Data Base: Access to a good data base on such key factors as flow and recreational use, as well as good mapping, was considered extremely important for the pilot river study. This was available for the Chattahoochee.
>
> Flow Variation: Study of the hydrological data base indicated that it would be possible to observe the effects of wide variations in flow on the river's characteristics within a short period of time. Unannounced changes in release schedules proved to be a disadvantage, however.
>
> Proximity to Regional BOR Office: It was felt that this would be a vital element in the first river study. The Southeast Regional Office of the Bureau of Outdoor Recreation is located in Atlanta. It was able to provide invaluable assistance in pre-trip planning, in effecting coordination with local public and private agencies, and by providing logistic support.

Considering all of these factors, both general and specific, the Chattahoochee was an obvious choice for the pilot river study.

2.2.2 Saco River - Northeast Region

The Saco rises as a white water stream in the White Mountains of New Hampshire and passes through Maine to the coast. Within a distance of 130 miles it undergoes transitions through all river types, from steep mountain rivulet to tidal estuary, through mostly rural areas. There is regulation of some reaches by dam. These are well downstream of the study reach. The river receives very heavy recreational use including white water canoeing, fishing, and water enhanced recreation such as picnicking, hiking, and camping. An intensive field study was planned on the upper reaches during the white water season. The Saco is not under consideration for designation as a wild or scenic river.

2.2.3 Rio Grande River - South Central Region

It was planned to study portions of the Rio Grande in New Mexico between Cochiti Dam north of Alburquerque and Isleta. Between these points the river passes through rural areas dedicated to agriculture, through Indian lands, and through a city. The river is regulated, and water is diverted for irrigation purposes. There are wide variations in flow (and in channel width and depth) on a seasonal basis, with lows occurring during the summer months. There is some canoeing and floating during the spring months, but recreational usage is not high at present. This is attributable to better quality canoeing and related opportunities in mountain streams as well as to poor aesthetic attributes of the river, especially during periods of low flow. Because of the low water temperatures, attributable to bottom flow from Cochiti Dam, there is a trout and bass fishery in the upper portions of the stretch studied, and in irrigation canals fed by the river. The fishery is said to be good in the latter.

2.2.4 Huron River - Lake Central Region

The Huron River rises to the northwest of Detroit, Michigan and passes through Livingston, Washtenaw, and Wayne Counties to enter Lake Erie south of the city. The stretch of interest is about 11 miles long, between Hudson Mills and Delhi Mills in Washtenaw County. The metropolitan area location and the presence of two river oriented parks on this part of the river contribute to heavy use. The area studied is mostly agricultural in nature. There are rapids in Delhi at the Delhi Metropark and at Hudson Mills; these represent an opportunity for canoeists when the water is high and an obstacle when it is not. The river is used for canoeing and some swimming. Water enhanced activities occur at the two parks. There is some opportunity for fishing (panfish) and for wildlife development, including some game as well as nongame animals. Regulation of the river is provided upstream by Portage Lake, the level of which is controlled to provide recreation on the lake. Currently there are no provisions for releases to maintain minimum stream flow, and this has been a matter of controversy in the past. Downstream recreational opportunities can be definitely adversely affected by low flow (impacts on fisheries, impossibility of passage of Delhi rapids, possible impacts on water quality).

2.2.5 North Platte River - Mid Continent Region

The North Platte is an excellent example of a Great Plains river, wide and flat with a braided channel. The reach chosen was that between Hershey Bridge and the diversion dam at North Platte, Nebraska. The river is controlled to provide water for irrigation so extensively that it sometimes nearly dries up in the summer. Riverine recreation is affected adversely by these extreme flow variations and by difficulty of access because of private property holdings along the banks. There is some float-boating and canoeing during spring high water, but participants often encounter fences across the bed which necessitates portage. A Nebraska statute enacted in 1967 does, however, allow persons "in the process of navigating or attempting to navigate with non-powered vessels in any stream or river in this state" to portage or otherwise transport their vessels around obstructions in the stream. During the summer months flows are highly variable; however, when downstream demands for irrigation water are heavy, the releases from the dam at Lake McConaughy allow the river to be used for boating. While Nebraska is primarily an "appropriation law" State, it does recognize certain attributes of "riparian" water law. In the case of the North Platte, both appropriation and riparian doctrines impact unfavorably in riverine recreation. There is some opportunity for hunting of small game and birds in wooded areas and wetlands along the river, although again private property rights tend to limit access. Though not in strong current use for recreation, the North Platte does offer opportunities that are curtailed because of legal and institutional considerations. This factor made it attractive for the purposes of this study.

2.2.6 Boise River - Northwest Region

The Boise River is a prime example of a small, regulated, western river which passes through an urban center and serves as a focus of recreation for metropolitan Boise, Idaho. The stretches of interest were Barber Dam to Boise and from Boise to Caldwell. Upstream, the Lucky Peak Dam, along with 2 other reservoirs, regulates water releases for irrigation and flood control. The river is used for fishing, swimming, tubing, and bankside activities such as hunting in the more rural areas and water-enhanced activities in adjacent urban parklands. Recreational use is highly dependent upon release from Lucky Peak Dam, which is in turn dependent upon needs for irrigation.

During periods of extreme low flows, water quality has deteriorated to the extent that it has been necessary to close the river to use for water contact recreation. There have been a number of studies on this part of the river by other agencies, providing a good ready-made data base against which field techniques and observations could be tested.

2.2.7 Russian River - Pacific Southwest Region

This river, regulated by Coyote Dam, flows through rural areas north of San Francisco. The reach of interest extends 94 miles from Ukiah, California,to the Pacific Ocean. It was planned to concentrate the field studies in the area from Cloverdale to Healdsburg. The upper river is widely used for recreation, including float trips and canoe trips extending over several days. North of Healdsburg there is a great deal of organized commercial recreation as well as public access for boating and swimming. One of the largest canoe rental operations in the entire State of California is maintained on this river with about a thousand craft available for hire during the summer recreation season. The river regulation combines upstream flood control with provision of water for diversion (irrigation). To meet the latter needs, the flow of the river has been augmented by diversion from a power dam on the Eel River, so that augmented flows now existant are considered better than the river's natural historic flows. The river is used for swimming as well as for streamside activities such as picnicking. Some preliminary studies of recreational potential had been carried out by the Southwest Regional Office of BOR.

c.1

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Recreation and Instream Flow. Volume 2. River Evaluation Manual

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Prepared for

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1.0 INTRODUCTION

1.1 Background

The demand for water-based recreation has grown substantially in the past several decades. It has, in fact, grown faster than population. Generically, this has to do with the increase, since the turn of the century, in the amount of leisure time and disposable income available to individuals. Additionally, many water related activities, such as white water canoeing, have undergone growth of boom proportions. This growth has affected both lake and stream-based activities. There are, however, inherent differences between the two types of activities which must be recognized.

Lake activities may be viewed as activity oriented. That is to say that the activity may be successfully and pleasureably carried out on virtually any relatively large body of water. More to the point, lake environments can, and have been, provided by human works (dams). Thus, it is not a supply-limited resource in any immediate sense.

Stream-based activities, on the other hand, are resource oriented. The availability of the activity and its quality may depend on the particular stream in which it occurs. Additionally, free-flowing water is seldom created by human works; indeed the dam that creates a new lake almost always inundates a stretch of free-flowing stream. Thus, instream recreation depends upon a supply-limited, and shrinking, resource. To compound this difficulty, there is intense competition for the waters in a free-flowing stream.

The assessment of such a set of activities is necessary if they are to be preserved. In the past, water has been viewed as a consumable resource with little or no supply limit. This is no longer the case. The need now arises to treat instream water and instream recreation as a nonrenewable resource and to enter into the competition for what free-flowing water remains.

However, before trade-off analysis can begin, the range of possible activities must be determined. Different riverine recreational activities impose different physical requirements.

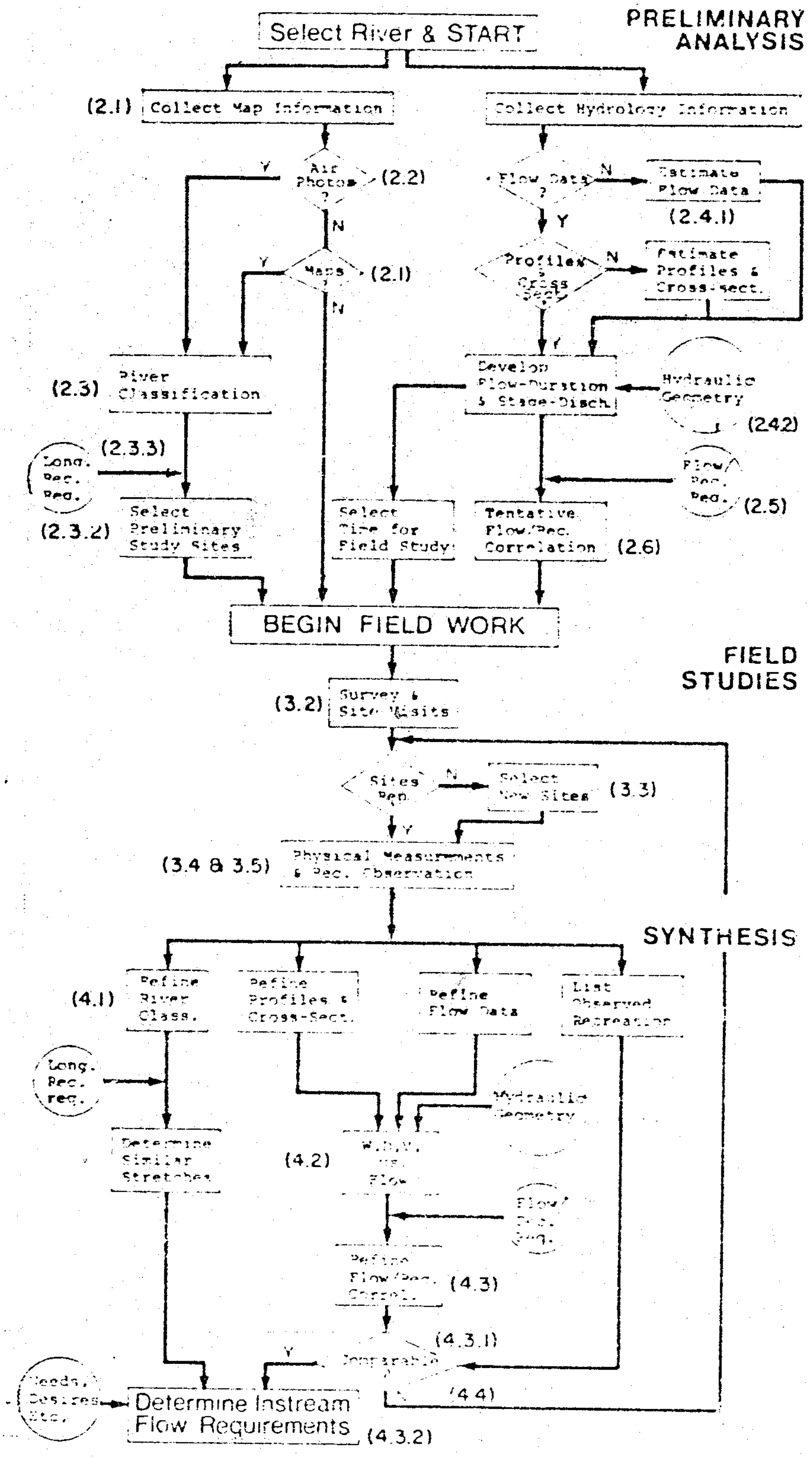
1.2 Scope of the Manual

This Manual serves as a practical guide to the evaluation of the physical relationships between recreational potential and flow level (discharge) on a river. While numerous factors impact on recreational potential, those most closely affected by variations in flow at a given place on a river are width, depth, and velocity. The method presented here concentrates upon relating changes in these parameters, whether observed or predicted, to recreational potential. Figure 1 is a flow chart of this procedure. The basic approach is synthetic in nature to the extent possible. That is, it relies upon preliminary analysis of data, on limited field studies, and on post-field analysis to yield predictions about conditions on the river, in relation to their effect on recreational opportunities. It does not require access to data on or observation of actual recreational experiences, though these can be helpful when they can be provided. It will probably in many cases require field measurements at more than a single flow, but it does not depend upon the availability of controlled releases from a dam or on measurements at a large number of discrete flows. Should an investigator feel, however, that controlled release experiments would be of value, Appendix A provides guidance on carrying them out. These approaches might be of particular use on remote, controlled streams where a second field visit is not feasible.

Section 2, Preliminary Analysis, describes the steps to be taken at the outset of the study of a specified river. This includes: the acquisition and use of maps and aerial photographs; the classification of the reaches of interest according to basic morphological form; the collection and analysis of hydrological data; the specification of criteria governing various types of flow-related riverine recreation; the correlation of the above data to permit tentative predictions as to discharge-recreation relationships on specific stretches or at specific sites on the river; and, finally, the applicability of available data on actual recreational usage of the area. The output of this entire process of preliminary analysis is the preliminary selection of sites for field study and the identification of the optimum expected flow under which to conduct the field study part of the effort.

Section 3, Field Studies, presents the tasks to be accomplished in conducting direct analysis of actual conditions on the river. Topics covered include: selection of dates for the visit, in relation to the previously identified desired flow; reconnaissance of the reach of interest to check stretch and site locations against those derived from map and photo studies; final selection of observation site; physical measurements; and observation of on-going recreation, if any. The field study process provides specific physical information on sites of interest at a given flow and provides the basis for later predictions as to changes in site conditions with variations in discharge.

Section 4, Synthesis, involves the development of predictions as to recreational potential as a function of discharge. The steps required to accomplish this include: analysis of data gathered during the field studies; correlation of the physical measurements and observations with hydrological data; development of rough predictions of changes in physical parameters such as width, depth, or velocity with a variation in flow; pre-



Note: Bracketed Figures Refer to

Flow Chart
RIVER STUDY PROCEDURE

diction of recreation potential at non-observed flow; and the checking of these predictions by a limited set of observations at flows different from that observed at the time of the primary field study. At the conclusion of this portion of the effort it should be possible to relate recreation potential to flow in the portions of the river that have been studied and, thus, to permit specification of flows for different recreational pursuits. This information, in conjunction with analysis of the recreational "market" or demand, of the available supply, and of the value associated with various recreational activities, will provide the basis for developing recommendations about the preservation or provision of instream flows for recreation.

1.3 Considerations for Planners and Policymakers

The following situations cover a broad range of possiblities. They share one common and important element, however. In each case, future recreational potential at some recommended flow may be more important than existing recreational activity on the river. This is as true for the non-regulated as for the regulated cases. While ultimate judgments and decisions must rest on a full evaluation of the social and economic benefits attributable to provision of flow-dependent and recreational opportunities, the initial determination of the requisite discharge depends upon an evaluation of the physical capacity of the river to support recreation and to meet the necessary flow related recreation criteria at specified flow.

1.3.1 Preservation

In some cases, the question may be one of preserving an existing natural flow. This would be important in considering the designation of a river under the provisions of the Wild and Scenic Rivers Act, for example. It could also be important in evaluating the long term impact of a proposed impoundment or large diversion which would radically affect natural flow conditions.

1.3.2 New or Proposed Designs

It may be possible to use a proposed new structure to provide instream recreational benefits greater than those found under existing conditions. This can be accomplished by releases to support recreation which would not be possible lacking regulation of the stream. The Duck River and Bear Creek projects of the Tennessee Valley Authority have such capabilities built in. The additional benefits from augmented instream flow (canoeing and fishery improvement, for example) serve the dual function of helping to justify the project economically and of mitigating unfavorable environmental effects of an impoundment.

1.3.3 Retention and Timed Release

Recreational oportunities on a stream may be enhanced by temporary retention and timed release of water from flood control structures. This is sometimes done on flood control dams which were initially designed to operate in a pass-through mode, with retention only to prevent imminent flood hazard. Modified scheduling of retention and release at such installations can provide an extended white water season and can improve fish habitat and, thereby, fishing opportunity.

1.3.4 Recapture

Even where existing flows are highly regulated and discharges governed by other needs, such as power generation and irrigation, it may be possible to recapture some flow for recreational purposes. This could take the form of acquisition of storage rights behind an irrigation dam as has been done by the Idaho Fish and Game Department at Lucky Peak Dam on the Boise River. It might take the form of acquisition of water rights by State agencies through the appropriation process to maintain instream values. A start was made in this direction by the State of Idaho at Malad Canyon where a flow was "appropriated", not for the normal diversion and consumptive use, but to maintain the aesthetic qualities of a river inside a state park. It could take the form of an alteration of generating schedules and resultant discharges at power dams. Licensing or relicensing of power projects operated under Federal Power Commission regulations may afford an opportunity to insure that impacts on instream recreation below the structure be provided for in release requirements.

The only method for dealing with these effects is a radical departure from the criteria approach used for all of the in-the-water activities. Careful map study and limited field reconnaissance will allow the identification of wetland resources along and near the stream of interest and of the possibility of adverse effects from flow variation.

Water-enhanced activities are also not amenable to simple criteria setting. The aesthetic attraction of water operates at all flows from a trickle to a torrent. Even dry stream beds may be favored hiking places, both for ease of passage and for the water-carved forms sometimes seen.

Thus, these two groups of activities are not included in the criteria system developed above for the on-the-water activities. The recreation planner must be sensitive to these uses, but only the terrestrial ecologist and the aesthetic analyst can make meaningful determination of the influence of absolute flow or flow regime on these resources in specific situations.

2.6 Tentative Flow-Recreation Correlation

A preliminary estimate of the possibility, extent, and quality of available recreation resources on the study stream can be made by comparing the hydraulic geometry information developed in Section 2.4 with the recreation requirements presented in Section 2.5 The planner should assemble the following data elements.

1. Study area map with stretch classifications marked
2. Typical cross-sections for the stretches of interest
3. Stage-discharge, stage-width, and stage-velocity curves for those typical cross sections,
4. Annual and monthly average flow data for the stretches, with maxima and minima, if available,
5. The tabulated width, depth, and velocity criteria for recreation activities (from Section 2.5).

2.6.1 Hydraulic Geometry Correlations

A first level correlation is made in three steps. First, the AAF, monthly average flow, and monthly minimum and maximum flows are tabulated. These are compared to the stage-discharge, stage-width, and stage-velocity curves to determine the average annual width, depth, and velocity; the average monthly width, depth, and velocity; the maximum monthly width, depth, and velocity; and the minimum monthly width, depth and velocity. Finally, these are compared to the recreation criteria to determine possible recreation activities. Of particular importance at this level will be comparison to minimum and maximum recreation criteria. This yields a multiplicity of lists of possible recreation activities under different flow conditions, by month.

Another approach to this first level correlation can be made by simply noting the range of flows with a reasonable chance of occurrence. Several points within this range can then be selected and widths, depths, and velocities determined for these. Then, at each of the selected flows, a list of possible recreation activities can be prepared. This format has a useful side benefit. If the lists are compared in order of increasing flow, several observations can be made.

First, there will be a limited suite of activities available at very low flows. These might include swimming, wading, canoeing (flat water), rowing, and bank fishing in many streams. Second, at some level of flow above this minimum, a larger number of activities will become available. Depth and velocity increases might make possible tubing, sailing, and low power boating without eliminating any of the previous suite of activities. At some flow above this value, tradeoffs will occur. Some activities will be added and others will be deleted. For example, in many streams, the flow necessary to permit high power boating might violate depth and velocity maxima for swimming or wading. At a somewhat higher flow still, entire suites of activities will be replaced by others. The clearest example of this is the 5 foot per second velocity. When this level is reached, the non-power tranquil water boating activities will generally be replaced by the non-tranquil water boating activities and all of the water contact activities except tubing may be lost. At even higher flows, velocities in excess of 10 feet per second will limit low-power boats and tubing, leaving only the white water boaters and bank fishermen. Finally, velocities over 15 feet per second may eliminate even the white water boaters.

2.6.2 Map Correlations

The second level of recreation correlation is solely map dependent. Even though the analysis at typical cross-sections may show that a large number of activities are possible in terms of width, depth, and velocity, many activities are also governed by longitudinal considerations. This is where the earlier classification and air-photo interpretation comes into play.

Let us suppose that a stretch is found to be suitable for any of the various boating activities. This stretch should then be checked on the maps. If it is very short, its desirability for boating activities will be seriously reduced. For example, a short stretch of flat water bounded by two major rapids may not be suitable for tranquil water boating activities. On the other hand, a longer stretch, including both of the rapids and the quiet stretch may make a very desirable tubing area or non-tranquil water boating area.

2.6.3 Auxiliary Requirements

Site-specific considerations come into play in dealing with the water contact activities. For most of these, a sandy bottom and some beach area is preferable to a muddy or gravelly bottom and "fall-in" banks. If these latter conditions are found, the activity may not be practical, even though it is technically feasible.

Guidance in these types of auxiliary considerations is given in Section 2.4, where site-specific and reach specific requirements are determined from air photos, and in Section 2.5, where auxiliary conditions for the various suites of activities are discussed.

The final result of this task will be a listing of possible recreation activities at various flow levels, amended to reflect longitudinal and site-specific requirements.

2.7 Use of Available Recreation Data

Often there will be available to the planner reports, studies, user surveys, or like information on the numbers of people engaging in specific recreational activities at sites or along stretches of the river to be evaluated. Where such information is available, especially when it is keyed to specific dates, the usage can be correlated to hydrological records. This will permit at least a rough estimate of recreation potential, at specific places, at specific flows. Since such data rarely include much information of an hydrological nature, they rarely will provide much insight on specific river conditions such as width, depth, or velocity. That recreation is taking place implies that these parameters are within acceptable limits, but often little more.

2.7.1 White Water User Data

One possible exception to this general rule relates to boating, especially on white water. In some instances recreational information is available tieing recreationists' evaluation of their experience to flow, using home made staff gages or painted gage

3.0 FIELD STUDIES

Preliminary analysis only begins the river evaluation process. Field visits are necessary to test preliminary hypotheses. Several important steps are required for the field studies aspect of river evaluation.

3.1 Timing

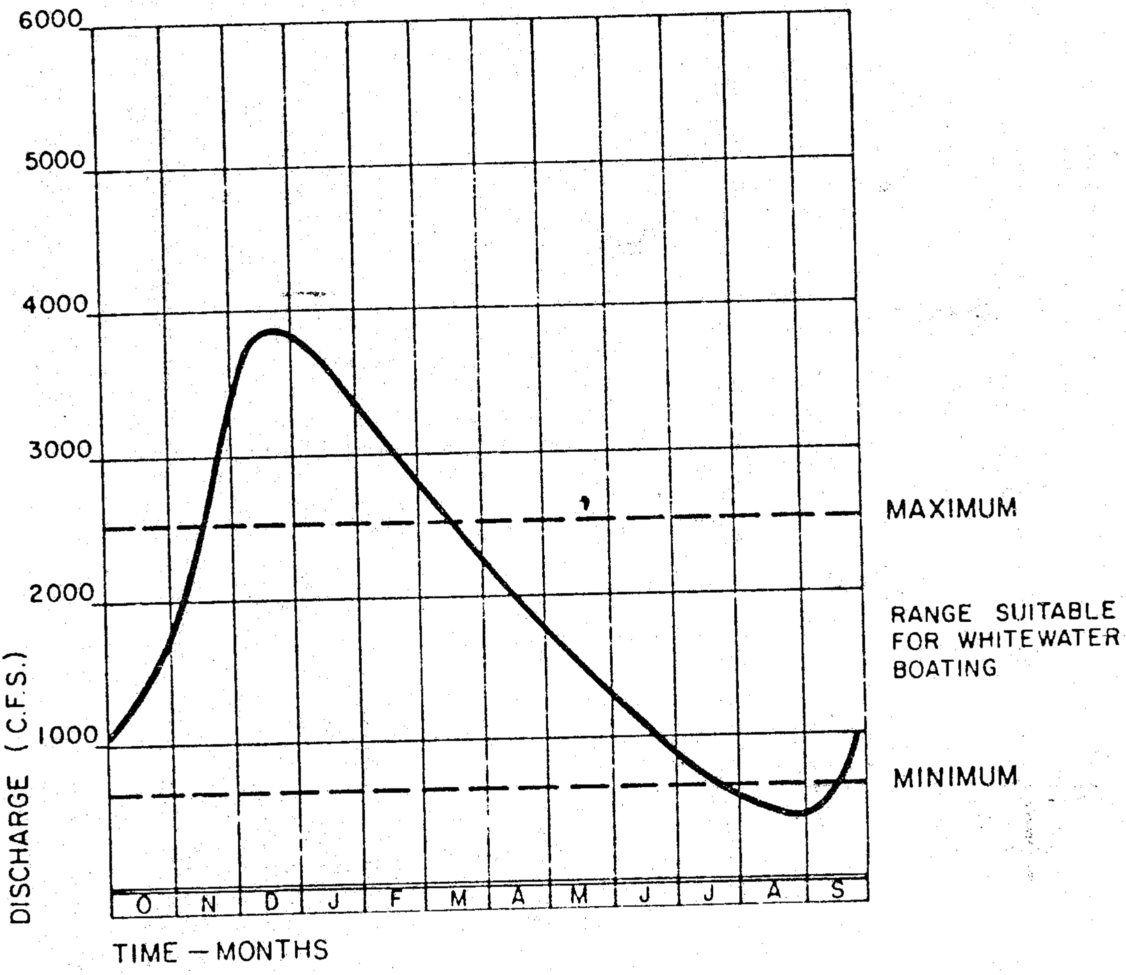
Timing of the field work is an important consideration. This should generally be chosen to provide a flow on the river which is considered to be at or below optimum for the kinds of recreational activity which appear from preliminary analysis to be of prime interest.

Where winters are severe it is desirable to avoid periods of very low temperature. River flow may be affected by ice at such times. Perhaps more to the point, conduct of field work on rivers is uncomfortable and may be hazardous when both air and water temperatures are low. In addition, all other things being equal, it is desirable to select times for the field visit which are appropriate to recreational usage in terms of weather.

Where a river is actively in use for recreation, the best choice of date for the trip may lie in the active recreation season. This affords an opportunity to combine theoretical studies of relationships between flow and recreation with actual observation of on-going activity. However, it will not always be possible to observe the flow of chief interest at such times. Ultimately, the timing of the trip should be governed by the expectation of finding a discharge close to that identified as more or less optimum for some dominant recreational use or some set of recreational uses. Often such flows will not coincide with the peak recreation season. This is especially true for many regulated rivers where flows during the summer months reflect irrigation requirements rather than the needs of recreation.

3.1.1 Identification of Dates for Flow of Interest

In the case of white water rivers, outfitters and canoeing organizations are usually very knowledgeable about the relationship between recreation potential and river stage. Canoeing guides frequently publish such information in written descriptions, tables, or graphs for specific rivers. Figure 11 illustrates this kind of presentation. When it is desired to study a river which is regularly used by white water enthusiasts the best course is to establish and maintain contact with the experts on the state of the water. This usually will provide sufficient information to permit scheduling a trip to the area about a week in advance and still obtain a flow in the range of interest.



SUITABLE FLOWS BY SEASON

(AFTER GARREN, 1976)

Figure 11

For many other kinds of recreation, however, the field visits may or may not coincide with peak recreational use, for various reasons. This being so, the period of expected flow at the desired level should govern selection of field dates. The objective should be to look for a flow on the low side of the expected optimum for the activity or activities expected to be of greatest importance as a result of the preliminary analysis phase of the work. In general, the lower the stage of the river, the easier it is to conduct the measurement program, especially in the case of running cross-sections.

3.1.2 Flow Data Analysis

During the course of an average year, most rivers, even most regulated rivers, exhibit rather wide ranges of average daily flow. The difference from high to low flow may cover several orders of magnitude. Moreover, save for the rare event, discharge patterns tend to be more or less consistent on a seasonal basis from year to year. Thus, if one chose the proper dates one might be able to examine any flow from, say, 200 to 30,000 cfs on a given river in the course of a year.

In the case of the natural stream which is adequately gaged there are usually available long term records of average flow by day, by month, and by year. These data can be plotted to reveal seasonal patterns. Usually, monthly averages will be sufficient for this purpose. However, in some cases where seasonal variation trends are sharp, it may be desirable to plot the pattern of daily averages for that season.

Most regulated streams will not exhibit ranges in flow as wide as those on a natural river. However, such streams are almost always gaged, which makes it possible to obtain and plot the patterns of flow distribution.

If the stream is ungaged, it is possible to approximate the discharge by calculating run-off from the watershed on the basis of meterological records of precipitation. The data can be plotted to some degree of accuracy in terms of seasonal or monthly averages. However, this method is usually not amenable to the determination of average daily flow, except perhaps on very small watersheds.

The analysis of flow data should permit identification of the best likely period in which to conduct the field trip within a matter of a few weeks, unless the year is atypical. The final selection of field trip dates should be made after consultation with USGS personnel or others who visit the reach of interest and are aware of the river stage and its relation to discharge. Where such information is lacking completely, it may be necessary to compare weather patterns (temperature and precipitation) with the norms for the average year and try to pick a period which should provide something approaching the desired flow under average conditions, modified if necessary to account for deviations from the norm in the weather.

3.1.3 Potential Conflicts with Active Recreation

An important consideration on some rivers may be the avoidance of certain recreation periods. An example of this would be the weekend of a white water race. Under these circumstances, cross-section measurements might range from impolitic to impossible. Basically, any event or condition which draws an unusual number of users to a river makes the actual field work difficult. One method of avoiding such conflicts and taking advantage of the circumstance is to plan the field effort for the week days just before the preclusive event or condition and to remain for the weekend to observe the activity and interview the participants.

3.2 Reconnaissance

Once in the field, the general reach of concern having been determined, a reconnaissance survey is the first step. Where the reach is long or access difficult, this is sometimes best accomplished from the air. Windscreen observations from an automobile provide a fairly rapid means for covering a reach of reasonable length if access is good. In some cases, actual transit of the river by canoe or other water craft may be desirable. The purpose of the reconnaissance is to develop a better "feel" for the river than can be obtained from simple analysis of maps, photos, and hydrological data. It permits the final selection of specific reaches and sites to be examined in detail.

3.2.1 Aerial Survey

In cases where the study reach is very long or where roadway access is difficult, aerial survey offers a large information return for little time investment. Aerial survey is best carried out by helicopter or in small, top-winged, low-speed aircraft. This allows slow, low flying and provides for unobstructed photography. Air reconnaissance gives the survey team an opportunity to see the entire reach in a short period of time, to take oblique aerial photographs, and to examine the reach for obstacles and opportunities which might have been missed in the map and aerial photo studies prior to field trip. This can be particularly useful in finding access routes to remote rivers. The routes may often take the form of small dirt roads or logging roads not visible on maps or high altitude air photos.

3.2.2 Windscreen Survey

An alternate to or supplement to air reconnaissance is a windscreen survey where roadway access to the river is good. This has the advantage of not requiring an aircraft, but it will seldom allow a view of all of the study reach. The intent is the same as aerial survey - to find obstacles and opportunities overlooked in remote studies. Additionally, site visits can be made part of the windscreen survey when preliminary sites are readily accessible from roads. A limited amount of bank side hiking can extend the coverage of a windscreen tour considerably.

3.2.3 On-the-Water Survey

If time will allow, an on-the-water survey can be a useful adjunct to an air or windscreen survey and may be required on rivers with little or no roadway access. In this case, on-the-water survey will be the most feasible method of visiting the preliminary study sites to gather information for final site selection. On truly inaccessible streams, it may be necessary to perform physical measurements on too many rather than too few of the preliminary sites to avoid the necessity of repeating the trip. In any event, the on-the-water survey is the most complete and accurate form of survey, since all of the photo stretch classifications can be field verified and amended, if required, before detailed studies are undertaken. The craft of choice for this task is usually an open canoe, either with or without a small outboard motor. Such a craft can negotiate very shallow water and, well handled, can be used in moderate (Class II or II-1/2) white water.

3.2.4 Initial Site Visits

Regardless of the method of reconnaissance chosen, visits to all preliminary study sites must be made. At each site, a field data sheet (see 3.4) can be used to record estimated and measured physical characteristics of selected sites and to record photos of the rejected sites. It is also possible that the preliminary reconnaissance will have revealed some sites of strong potential for study which were not discovered in the pre-field map and air photo studies. These should also be visited so that the final site selection will yield the most representative and useful set of field study sites.

3.3 Site Selection

3.3.1 Recreational Criteria Affecting Site Selection

Some categories of sites at which detailed measurements and observations are to be taken should be pre-selected prior to start of the field study. These might include sites which are representative of similarly classified stretches and sites which are expected to provide unusually suitable conditions for one or more recreation activities. Further subdivision of potential sites is often necessary to ensure adequate documentation of flow conditions along a river reach.

Instream recreational activities can be categorized generally as those centered about a suitable site and those requiring longitudinal suitability. In the one case, minimum flow requirements must be met at the specific location; in the other, minimum flows must prevail throughout the stretch. It is not always possible to identify all areas along a stretch which may present physically limiting factors from remote data alone; however, using a combination of air photos and field checking should make it possible to locate at least the critical areas. These would include such features as: dams, falls and rapids, very wide sections where depths are uniformly below the average for the rest of the stretch, and areas where extensive instream vegetation may interfere with passage. Failure to locate such areas, and to take account of the limiting conditions they present, may lead to error in recommendations based on remote information alone.

Complete width, depth, and velocity measurements at such areas may not always be feasible. For example, in a large riffle area with an average depth of less than six to eight inches it is easy to measure width and depth. But it is extremely difficult to take accurate velocity measurements because of the shallow water. For such a site, discharge information may be imputed by comparison with a site more amenable to measurement in the vicinity, either downstream or upstream.

3.3.2 Physical Site Criteria

The preselection process should have narrowed the areas to be considered for final site selection. However, field checking is often essential to complete the site selection process. Some conditions may not be found if remote data are relied on solely.

For activities, such as most non-tranquil water boating, where minimum depths are extremely critical, the location of physically limiting areas must be accomplished in the field.

When small dams or diversions have been emplaced since the most recent aerial photography, these must be identified either through a field check or through communication with people having knowledge of local conditions.

If no aerial photography is available, sites selected on the basis of map study alone must be verified by field investigation as a rule.

If extraordinary runoff events have occurred since the most recent aerial photographs were taken, major channel shifting may have occurred. While such changes may not require reclassification of the stretch, it may be necessary to shift field study sites to new locations at some distance from places identified during the preselection process.

When two sites appear on the basis of remote data to be similar in terms of classification it is wise to field check them to determine whether or not both must be studied. While no two sites are exactly alike, if the two are sufficiently similar that it appears that recreational activities will be affected in essentially the same manner by changes in flow, then a single site may be chosen for detailed study. If doubt exists, however, both sites may be studied.

Alternative sites may be required if access is difficult or land ownership is unclear. However, when a particular site is deemed necessary for a complete analysis, permission to enter should be obtained prior to departure for the field.

3.3.3 Number of Field Sites Required

The number of sites to be investigated may be influenced by many factors. These include the length and heterogeneity of the river reach, the difficulty of running sections because of river conditions, problems of access, the season of the year, available manpower, and budget. Because there are so many variables, it is not possible to stipulate precisely the number of sites which should be studied in detail.

If one assumes that about a week (5-7 days) is available for field work on a river reach, some rough estimates of the work can be made. If access is possible from roads or by hiking from a road, reconnaissance should take no more than a day for most investigations. If access must be by water, reconnaissance and field surveys are combined. Two people can run a cross-section on a wadeable river 300 feet wide in no more than 1.5 to 2 hours; this time includes completion of the field analysis form and establishing photo points. However, access time must be added. If one assumes no equipment failures, moderate to easy access, and depth and current conditions amenable to wading, a crew can study five sites per day.

If a river is essentially homogeneous in channel pattern, a small number of sites will provide adequate coverage of stretches of interest. However, consider a reach which is classified as 80% braided and 20% straight. This does not imply a like distribution of field investigation sites. If many of the braided stretches are quite similar in nature, it may not be necessary to sample each of them. On the other hand, if the straight stretches offer a number of potentially limiting or hazardous areas, they may require intensive sampling. As a rule, however, the number of sites will tend to be larger in those stretches representing the greater length of the total reach; but the site distribution will not necessarily follow the relative length distributions exactly.

Finally, it should be noted that the number of sites to be studied varies with the purposes of the river investigation as well as with the river conditions and other factors considered above. In some cases a "rough cut" may be all that is required; in others, a rather precise determination of flows may be called for. The latter will entail a much more extensive field program than will the former case. Accordingly, the number of sites to be studied must be determined by the study team after due account is taken of all the variables which must be considered.

3.4 Physical Measurements

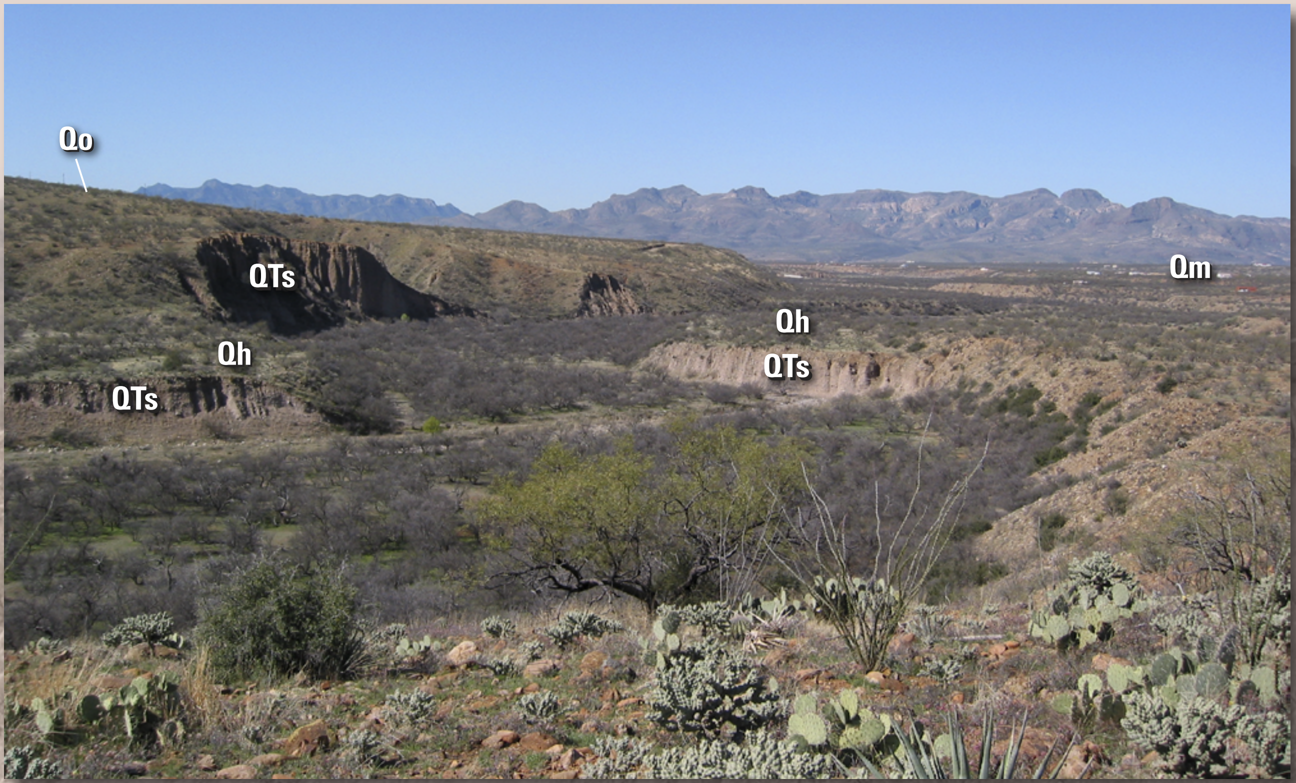
When study sites have been definitely established, a suite of physical measurements are taken, including the development of cross-sections and velocity profiles. Along with measurements of width, depth, and velocity, observations of special conditions affecting recreation potential should be recorded. Liberal use of a camera provides a permanent record which can be of invaluable assistance later in analysis of field data. When a tour of the river is chosen as the means for conducting the reconnaissance, the measurements may be taken at appropriate places during the tour.

3.4.1 Equipment

The following items are necessary to carry out field measurements on wadeable streams or rivers. In the case of rivers which are not wadeable, provisions to carry out measurements from boats, bridges, or cableways must be made.

1. Data Forms:
    a. Field Survey Forms,
    b. Cross-section tabulation forms (on Field Survey Form).
2. Maps - preferably mounted on cardboard strips.
3. Air Photos - black line prints of originals joined together and mounted on cardboard, with a plastic or acetate overlay case.

Processes of Terrace Formation on the Piedmont of the Santa Cruz River Valley During Quaternary Time, Green Valley-Tubac Area, Southeastern Arizona



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Cover. Stepped terraces of Josephine Canyon Wash, looking downstream (west). Qh, Holocene terrace; Qm, middle Pleistocene terrace; Qo, early Pleistocene terrace; QTs, early Pleistocene to Pliocene alluvium. Early Pleistocene terraces on south (left) side of stream are graded to San Cayetano Mountains.

Processes of Terrace Formation on the Piedmont of the Santa Cruz River Valley During Quaternary Time, Green Valley-Tubac Area, Southeastern Arizona

By David A. Lindsey and Bradley S. Van Gosen

A description of terrace gravel on the piedmont of southeastern Arizona and what it reveals about the origin of terraces

Scientific Investigations Report 2010–5028

U.S. Department of the Interior
U.S. Geological Survey

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KEN SALAZAR, Secretary

U.S. Geological Survey
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Processes of Terrace Formation on the Piedmont of the Santa Cruz River Valley During Quaternary Time, Green Valley-Tubac Area, Southeastern Arizona

By David A. Lindsey and Bradley S. Van Gosen

Abstract

In this report we describe a series of stepped Quaternary terraces on some piedmont tributaries of the Santa Cruz River valley in southeastern Arizona. These terraces began to form in early Pleistocene time, after major basin-and-range faulting ceased, with lateral planation of basin fill and deposition of thin fans of alluvium. At the end of this cycle of erosion and deposition, tributaries of the Santa Cruz River began the process of dissection and terrace formation that continues to the present. Vertical cutting alternated with periods of equilibrium, during which streams cut laterally and left thin deposits of channel fill.

The distribution of terraces was mapped and compiled with adjacent mapping to produce a regional picture of piedmont stream history in the middle part of the Santa Cruz River valley. For selected tributaries, the thickness of terrace fill was measured, particle size and lithology of gravel were determined, and sedimentary features were photographed and described. Mapping of terrace stratigraphy revealed that on two tributaries, Madera Canyon Wash and Montosa Canyon Wash, stream piracy has played an important role in piedmont landscape development. On two other tributaries, Cottonwood Canyon Wash and Josephine Canyon Wash, rapid downcutting preempted piracy.

Two types of terraces are recognized: erosional and depositional. Gravel in thin erosional terraces has Trask sorting coefficients and sedimentary structures typical of streamflood deposits, replete with bar-and-swale surface topography on young terraces. Erosional-terrace fill represents the channel fill of the stream that cuts the terrace; the thickness of the fill indicates the depth of channel scour. In contrast to erosional terraces, depositional terraces show evidence of repeated deposition and net aggradation, as indicated by their thickness (as much as 20+ m) and weakly bedded structure. Depositional terraces are common below mountain-front canyon mouths where streams drop their load in response to abrupt flattening of gradients and expansion of channel banks, and they extend down the piedmont along Josephine Canyon Wash. Gravel in depositional terraces also has sorting coefficients typical of streamflood deposits. Sedimentary features in both types of terraces are consistent with deposition by flash floods in ephemeral streams, suggesting the climate was arid. Bedding and clast armor are weakly developed, clast clusters and imbrication are common, and crossbedding is generally absent. Debris-flow deposits, even near the mountain front, are surprisingly rare.

On the tectonically stable piedmont of southeastern Arizona, stream piracy and climate change are the most likely agents of terrace formation. Both piracy and climate change can cause rapid changes in discharge and sediment supply, which initiate cycles of incision, lateral cutting, and aggradation. Increased stream discharge initiates downcutting, but increased sediment supply interrupts downcutting and causes streams to cut laterally and aggrade. At times, on Madera Canyon Wash and Montosa Canyon Wash, stream piracy affected stream discharge and sediment supply, but on Cottonwood Canyon Wash and Josephine Canyon Wash, only climate change could have initiated terrace cutting. Terraces probably formed during extended arid intervals when sparse vegetation and flashy stream discharge combined to increase sediment supply. In most cases, sediment supply was sufficient to promote lateral cutting but not long-term aggradation. Thus, most streams formed erosional terraces. The middle Pleistocene Josephine Canyon Wash formed a depositional terrace because it had a source of abundant unconsolidated sediment.

Introduction

Since the end of basin-and-range faulting and basin filling in Pliocene time (Menges and McFadden, 1981), streams emerging from the mountains have cut landscapes of canyons and stepped terraces in the piedmont of southeastern Arizona. Periods of downcutting (canyon incision) alternated with lateral cutting (terrace formation) and, occasionally, deposition of terrace fill, but the mechanisms for this alternation are obscure. Climate change and tectonism both cause terraces to form (Bull, 1991; Leopold and others, 1964), but we know only the general outlines of Quaternary climate history and tectonism of the region. The relative age of some terraces has been determined by studies of weathering and soil development (for example, Helmick, 1986), and more recently the distribution and relative age of piedmont terraces in many areas have been mapped by staff of the Arizona Geological Survey. Sedimentologic descriptions of terrace deposits were lacking, so depositional processes were not well known.

Here we bring together results of geologic mapping and sedimentologic study of piedmont terraces in southeastern Arizona to interpret the processes that formed these terraces. We use the distribution and morphology of terraces and the lithology of terrace gravel to identify cases of stream piracy, and we use the sedimentologic features of terrace gravel to interpret depositional processes. Much of the data on terrace geomorphology was gathered while mapping part of the Mount Hopkins and San Cayetano Mountains 7.5′ quadrangles (Lindsey and Van Gosen, 2006). This map and maps of surrounding quadrangles made by staff of the Arizona Geological Survey (Pearthree and Youberg, 2000; Spencer and others, 2003; and Youberg and Helmick, 2001), show the distribution of terraces formed during Pleistocene and Holocene time (fig. 1).

On the arid piedmont of southeastern Arizona, sand and gravel are deposited during brief, intense storms that trigger floods and landslides (Field, 1994; Klawon and Pearthree, 2000; Pearthree and Youberg, 2006). In ephemeral streams, a variety of fluid flows, ranging from debris flow to channel flow to sheet wash, can leave behind sand and gravel deposits ranging from poorly sorted and unstratified to well-sorted and stratified (Blair and McPherson, 1994; Costa, 1988; Lindsey and Melick, 2002). Cooler, wetter conditions than today may have prevailed in southeastern Arizona during late Pleistocene time (Davis, 1999; Thompson and others, 2003), allowing some piedmont streams to flow continuously. Deposits of perennial streams differ from those of ephemeral streams. In perennial streams, like those of the semiarid Colorado piedmont, storm-generated streamfloods deposit well-stratified and cross-stratified sand and gravel in channel and bank-attached bars (Lindsey and others, 2005). In this report, sedimentary features (fill thickness, particle size, sorting, and sedimentary structures) are used to assess continuity of streamflow and alluvial depositional processes on the Arizona piedmont.

Alluvial History

The alluvial history of the Santa Cruz River valley, like that of most other basins in southern Arizona and New Mexico, can be divided into two phases: (1) Miocene and Pliocene basin filling and (2) late Pliocene to Holocene erosion (Connell and others, 2005; Menges and McFadden, 1981; Menges and Pearthree, 1989). During phase 1, basin-and-range faulting formed a string of basins in the upper Santa Cruz River valley that defined the future course of the river (Gettings and Houser, 1997). Piedmont alluvial fans deposited poorly sorted sand and gravel of the Miocene and Pliocene Nogales Formation (Simons, 1974) and other units assigned to the lower part of the basin fill (Gettings and Houser, 1997). Basin-and-range faulting in southeastern Arizona had largely ended by Pliocene time, as indicated by the relatively undeformed upper part of the basin fill (Menges and Pearthree, 1989). The Santa Cruz River basin was probably closed downstream near Tucson, Ariz., as indicated by playa deposits in the subsurface (Houser and others, 2004). Phase 2 most likely began with integration of the Santa Cruz River basin into the Gila River drainage in late Pliocene or early Pleistocene time (Connell and others, 2005; Menges and Pearthree, 1989). Tributary streams of the Santa Cruz River began to dissect basin fill and cut pediments capped by coarse gravel. Phase 2 was accompanied by only minor faulting where, for example, faults displace early and middle Pleistocene age terrace deposits near Cottonwood Canyon Wash (Lindsey and Van Gosen, 2006) and terraces of early to late Pleistocene age north of Madera Canyon Wash (Pearthree and Youberg, 2000).

Pleistocene and Holocene alluvial deposits in the valley of the Santa Cruz River (Youberg and Helmick, 2001) consist of (1) river alluvium, deposited by the Santa Cruz River, and (2) piedmont alluvium, deposited by tributary streams draining the adjacent mountain ranges (fig. 1). As the master stream, the Santa Cruz River defines base level for its tributary streams. The extent of piedmont deposits in the Santa Cruz River valley has been influenced by rates of deposition and by local structural features. In response to uplift of the Santa Rita Mountains and extensive development of alluvial fans on the eastern side of the Santa Cruz River valley during phase 1, the river flows nearer the west side than the east side of the valley (fig. 1). South of Madera Canyon Wash, the valley is confined to a narrow faulted basin between the Tumacacori and Santa Rita Mountains (Gettings and Houser, 1997).

In the Santa Cruz River valley, the oldest records of phase 2 piedmont erosion are early Pleistocene pediments capped by thin gravel deposits. In the study area, the gravels seldom exceed 20 m in thickness and rest on older basin fill and bedrock. In map view (figs. 1 and 2), these deposits form distinctive bird-foot outlines that extend out from the mouths of mountain canyons. They are interpreted as dissected alluvial fans; the bird-foot pattern represents inverted radiating channels. The channels are preserved as inverted topography because they are filled with coarse gravel that resisted erosion (Ritter, 1987). For comparison, on the Colorado piedmont north of Denver, Colo., the Rocky Flats fan provides a good example of the early stages of dissection; the inverted channels in this fan have been documented by numerous boreholes (Knepper, 2005; Lindsey and others, 2005). On the Arizona piedmont east of Green Valley and Tubac, Ariz., the distinctive bird-foot map pattern is evident at the mouths of Madera Canyon, Montosa Canyon, and Josephine Canyon. Other thin dissected fans have been described from southeastern Arizona as “red-soil fans” (Melton, 1965), after their characteristic soil color, and “pediment fans” (Menges and McFadden, 1981), after their occurrence on erosional surfaces cut on bedrock. All of these fans are thinner and perhaps coarser grained and better sorted than alluvial fans deposited in tectonically active

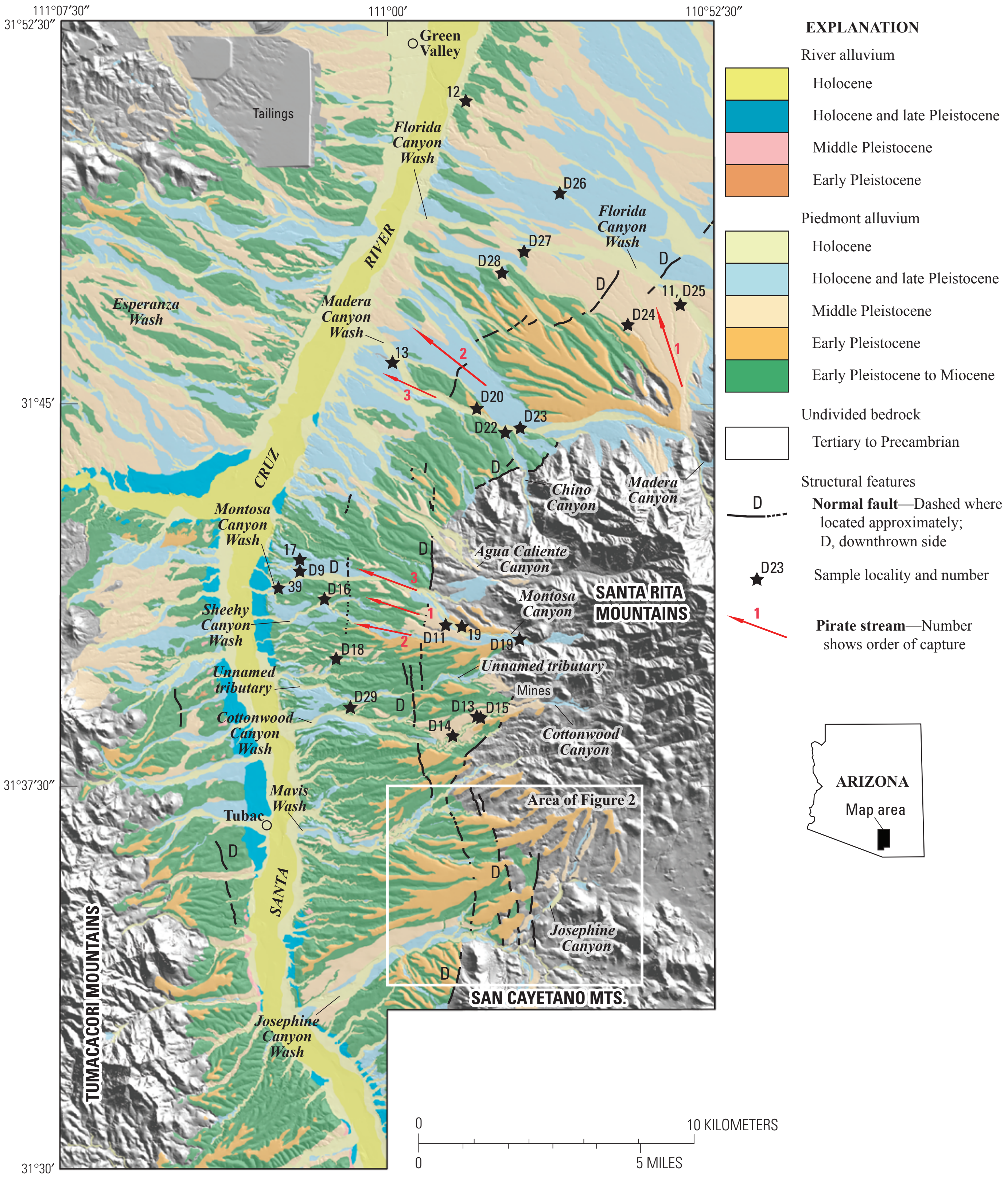


Figure 1. Generalized geology of upper Tertiary and Quaternary alluvium of the Santa Cruz River valley, Green Valley-Tubac area, Arizona (compiled from Lindsey and Van Gosen, 2006; Pearthree and Youberg, 2000; Spencer and others, 2003; and Youberg and Helmick, 2001); also shown are sample locations for this study, and area of figure 2. Individual samples (A, B, and so forth) in close vicinity are not shown. Shaded relief base by D.H. Knepper, Jr.

basins. Indeed, in this report we show that they are texturally similar to younger stream-terrace gravels.

During Pleistocene time, piedmont tributaries, such as Madera Canyon Wash, shifted course on the piedmont as they cut valleys in bedrock and basin fill. Changes in channel course were probably triggered by avulsion during storms and floods, but headward erosion of small tributaries set the stage for beheading and diversion. Stream capture is evident on Madera Canyon Wash and Montosa Canyon Wash. Study of geologic maps (Lindsey and Van Gosen, 2006; Pearthree and Youberg, 2000; Youberg and Helmick, 2001) readily reveals the probable sequence of stream piracy (fig. 1). The scenario of headward erosion and stream piracy outlined here differs from erosion on active alluvial fans, where streams exiting the mouths of mountain canyons cut channels into upper fan surfaces and transfer sediment onto lower fan surfaces (for example, Bull, 1964). Such fanhead trenches are recent features of active fan construction and are not to be confused with post-fan incision described here.

After deposition of basin fill during phase 1, the mountain front retreated as the predecessor of Madera Canyon Wash cut a surface on basin fill and granite and, in early Pleistocene time, deposited a thin (<20 m) gravel fan (fig. 1). Since then, piedmont streams adjacent to the Madera Canyon fan have captured and diverted the early Pleistocene Madera Canyon Wash. In middle Pleistocene time, Madera Canyon Wash flowed north from its mouth to join Florida Canyon Wash; the combined stream flowed northwest to join the Santa Cruz River. Capture was probably by a small tributary of Florida Canyon Wash that eroded southward along the base of the mountain front. During late Pleistocene time, a headward-eroding tributary of Chino Canyon Wash captured Madera Canyon Wash and diverted it along the south side of the early Pleistocene fan. Finally, during late Pleistocene or Holocene time, the lower part of Madera Canyon Wash was captured by a small tributary of the Santa Cruz River. Each of these events in the drainage history can be identified from the distribution of alluvial terraces (fig. 1).

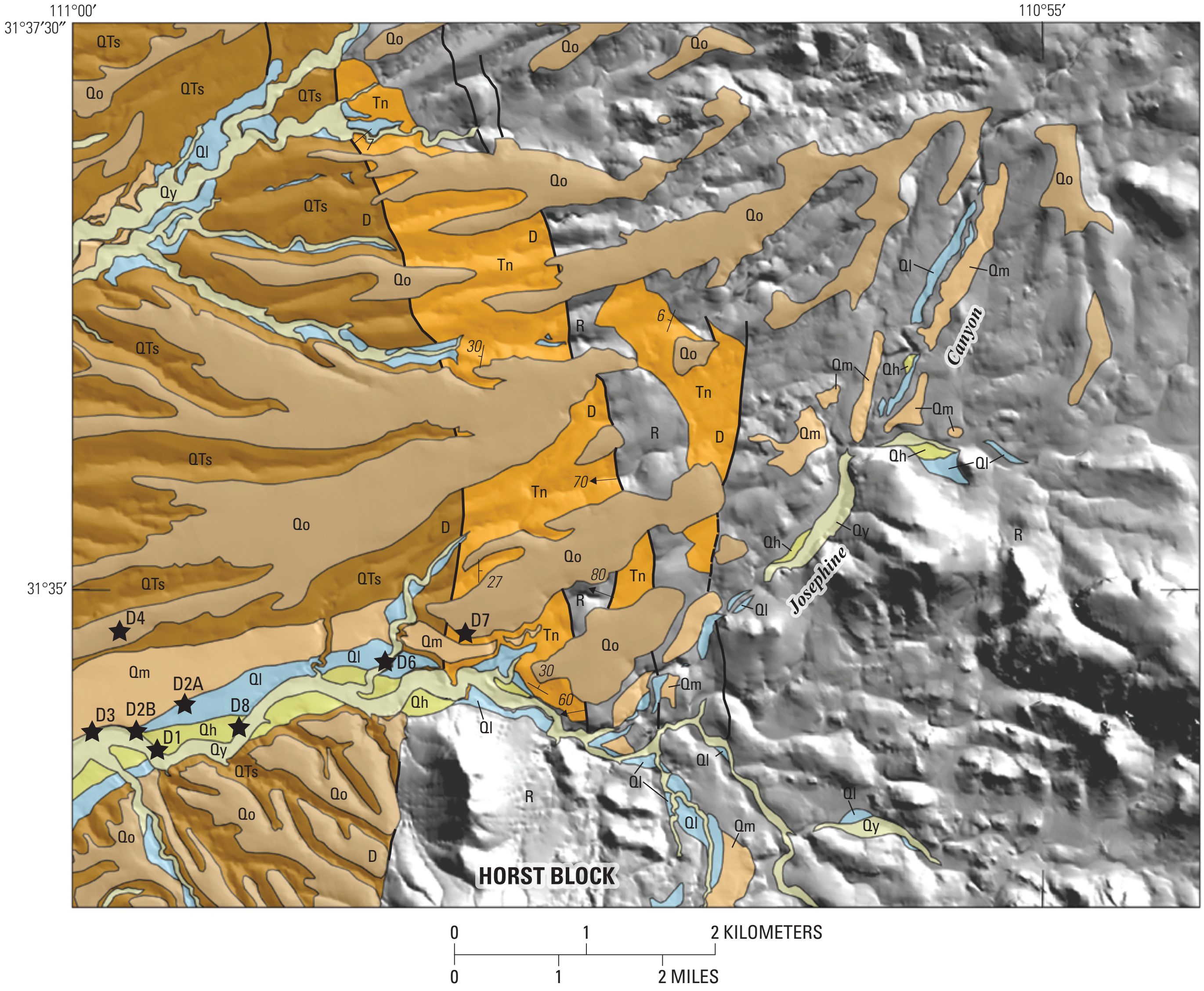
Montosa Canyon Wash also cut a surface on basin fill and bedrock (including volcanic rocks) and, in early Pleistocene time, deposited a thin gravel fan (fig. 1). Like the early Pleistocene alluvium of the Madera Canyon fan, this deposit spreads radially from the canyon mouth, and also like the Madera Canyon fan, this deposit is not more than 10–20 m thick. The northern part of the early Pleistocene fan of Montosa Canyon Wash was dissected by a new, downcutting channel in middle Pleistocene time, which left a wide terrace fill on the order of 5 m thick. Headward-cutting Sheehy Canyon Wash appears to have captured the mountain reach of Montosa Canyon Wash in late Pleistocene time, only to lose it to a tributary that follows the piedmont course of Montosa Canyon Wash today. These events are recorded by the distribution of middle and late Pleistocene terrace deposits. Of interest also is the headcut of an unnamed tributary of the Santa Cruz River, which is now within 1 km southwest of Montosa Canyon Wash where it enters the piedmont. Perhaps the unnamed tributary will become the next piedmont course of Montosa Canyon Wash.

During middle Pleistocene time, the unnamed tributary drained some hills of carbonate rock (near “mines” in the southeast part of fig. 1), as indicated by a thin dissected pediment in its headwaters. A middle Pleistocene terrace near the tributary’s lower end (at sample locality D29, fig. 1) contains carbonate clasts that probably came from the area of the mines. The ancestral middle Pleistocene tributary flowed toward, and may have even joined, the downstream end of Cottonwood Canyon Wash.

In contrast to Madera Canyon and Montosa Canyon Washes, Cottonwood Canyon Wash appears to have followed the same course since middle Pleistocene time (fig. 1). Terraces of middle and late Pleistocene age occur along an approximately 25-m-deep canyon where downcutting proceeded faster than in adjacent tributaries. The mountain catchment basin of Cottonwood Canyon Wash has approximately the same bedrock geology, relief, and area as the basins of Madera Canyon Wash and Montosa Canyon Wash, but its bedrock is not as extensively faulted and fractured (table 1).

Josephine Canyon Wash (fig. 2) appears to follow the model of Cottonwood Canyon Wash—a permanent channel location since middle Pleistocene time and deep incision, especially in the lower (foothills) catchment. In addition, Josephine Canyon Wash has a larger upper (mountain) catchment basin than the others (table 1). The catchment basin is composed of two parts: an upper, mountain terrane of volcanic and plutonic rocks, and a lower, foothills terrain, still rugged but at lower elevation, composed of Tertiary volcanic and volcaniclastic sedimentary rocks (Drewes, 1971). Like Madera Canyon and Montosa Canyon Washes, Josephine Canyon Wash also spread a thin gravel fan over basin fill and bedrock during early Pleistocene time. The Josephine Canyon Wash fan extended upstream across the lower catchment basin with its apex immediately below the upper basin (fig. 2). Thus, the effective mountain catchment basin for the fan was 40 km^2. When the Josephine Canyon Wash fan was dissected in middle Pleistocene time, it provided the large volume of sediment that is now stored downstream in the depositional terrace (Qm, fig. 2) along the north side of present-day Josephine Canyon Wash. At points overlooking Josephine Canyon, middle Pleistocene terrace alluvium is as much as 18 m thick. During middle Pleistocene time, the wash followed a course immediately north of its present course.

The large depositional terrace of middle Pleistocene age that borders the north side of Josephine Canyon Wash was followed by formation of two lower erosional terraces of late Pleistocene and Holocene age (fig. 2). The bedrock horst of the San Cayetano Mountains may have been responsible for stabilizing the course of Josephine Canyon Wash during middle Pleistocene and later time. The high westernmost part of the San Cayetano Mountains is fault bounded (Lindsey and Van Gosen, 2006). The western fault boundary is readily visible and offsets early Pleistocene gravel that extends up to the mountain front. Although no northern boundary fault is



EXPLANATION

Qy	Undifferentiated Holocene alluvium
Qh	Holocene alluvium
Ql	Late Pleistocene alluvium
Qm	Middle Pleistocene alluvium
Qo	Early Pleistocene alluvium
QTs	Early Pleistocene to Pliocene alluvium
Tn	Pliocene and Miocene Nogales Formation
R	Tertiary to Precambrian undivided bedrock

Structural features

70 ↓ D **Normal fault**—Dashed where located approximately; D, downthrown side; arrow and number, dip

7 Strike and dip of beds

★ D7 Sample locality and number

Figure 2. Details of upper Tertiary and Quaternary alluvium in the upper part of Josephine Canyon (from Lindsey and Van Gosen, 2006) and sample locations, Josephine Canyon Wash, Arizona. Shown separately are Miocene and Pliocene Nogales Formation (basin fill) and Holocene terrace deposits. Shaded relief base by D.H. Knepper, Jr.

Table 1. Comparison of mountain bedrock catchment basins: Madera Canyon Wash, Montosa Canyon Wash, Cottonwood Canyon Wash, and Josephine Canyon Wash, west slope of the Santa Rita Mountains, southeastern Arizona. All values are approximate.

[volc, volcanic rocks; plu, plutonic rocks, mainly granitic; sed, sedimentary rocks (estimated from Drewes, 1971)]

	Madera Canyon Wash	Montosa Canyon Wash	Cottonwood Canyon Wash	Josephine Canyon Wash
Mountain catchment area in km^2	19	9	14	100[1]
Maximum relief and (elevation) in m	1,540 (2,880)	1,320 (2,600)	1,320 (2,600)	1,780 (2,880)
Bedrock geology	volc=plu>>sed	plu>volc>sed	volc>plu>>sed	volc>plu>sed
Faulted structure	strong	strong	minor	moderate[2]

[1] Lower (foothills) catchment, 60 km^2; upper (mountain) catchment, 40 km^2.

[2] Faulted below Salerno fault; not faulted above fault (Drewes, 1971).

visible at the surface, it must underlie the young terrace gravel of the wash. The northward continuation of the west boundary fault is concealed where it is overlain by early Pleistocene fan gravel, indicating that the area located north of the wash had not been tectonically active while the San Cayetano Mountains horst continued to rise.

Terrace Classification and Formation

Terraces may be classified as erosional, in which the surface is underlain by thin lags of channel bedload, or as depositional, in which the surface is underlain by thick alluvial fill of channel and overbank deposits (Encyclopedia Britannica, 2010). Sometimes erosional terraces are called “strath terraces” or “degradational terraces,” and depositional terraces are called “fill terraces” or “aggradational terraces” (Bull, 1991). These terms can be confusing, in that erosional terraces represent periods of near-equilibrium—not downcutting—when streams cut laterally and leave behind a lag of channel gravel. The thickness of gravel deposits represents the depth of scour. The process of lateral cutting by migration of the stream channel is well illustrated on the middle reaches of Josephine Canyon Wash (fig. 3*A*). There, concave banks of meander bends undercut cliffs of soft gravel deposits of early Pleistocene and Pliocene age, whereas gravel accumulates along convex banks of meander bends. The wash is dry most of the time, but erosion and deposition occur during bankfull and higher flow. The gravel floodplain grows primarily by lateral accretion of bars to the bank. The floodplain surface has been stabilized by trees, shrubs, and grasses; only light scour and deposition of overbank fines occur during high flow. Bar and swale structure (Bull, 1991), visible on the Holocene terrace of Josephine Canyon Wash as well as the floodplain, may reflect an earlier braided channel or indicate continuing light scour and deposition on the floodplain surface.

Terrace formation is the product of alternate states of stream equilibrium and disequilibrium. Equilibrium is represented by no net channel incision or deposition, whereas disequilibrium is represented by degradation (downcutting) or aggradation (filling). Channel incision can be initiated if base level falls, one stream captures another, or the climate changes. Each period of incision is followed by lateral cutting of floodplains as the stream returns to equilibrium. Likewise, sediment may accumulate (aggrade) in channels and on floodplains if base level rises, a stream is beheaded, or the climate changes. Channel incision is well illustrated by the upper reaches of Josephine Canyon Wash (fig. 3*B*). There, the stream is actively downcutting into volcanic bedrock. During the late Pleistocene, the meandering stream cut laterally, forming a strath on bedrock. This stream was at near-equilibrium, like the middle reach is today. Meanders from the time of strath formation are now entrenched in bedrock; they reveal the planform of the former channel and the means by which it cut the strath. In contrast, channel filling is the dominant process on downstream reaches of Josephine Canyon Wash. Downstream, aggradation is revealed by a braided stream pattern where the stream is no longer able to transport its sediment load. Depositional terraces are often the product of braided streams.

Like Josephine Canyon Wash, most streams studied on the piedmont of the Santa Cruz River valley show the progression from degradation (incision upstream), equilibrium (meandering middle reach), to aggradation (braided downstream reach). Thus, both equilibrium and disequilibrium occur at the same time on different reaches (Bull, 1991; Schumm, 1993). As the incision-equilibrium-deposition cycle is repeated, terraces are formed when the floodplain is abandoned by renewed downcutting. Channel incision (or deposition) is only one possible response to change. Streams also adjust their gradient by changes in channel form (planform); channel form may be braided, meandering, or straight (Schumm, 1977, 1993). Often, as in the case of streams in the study area, these responses occur together.

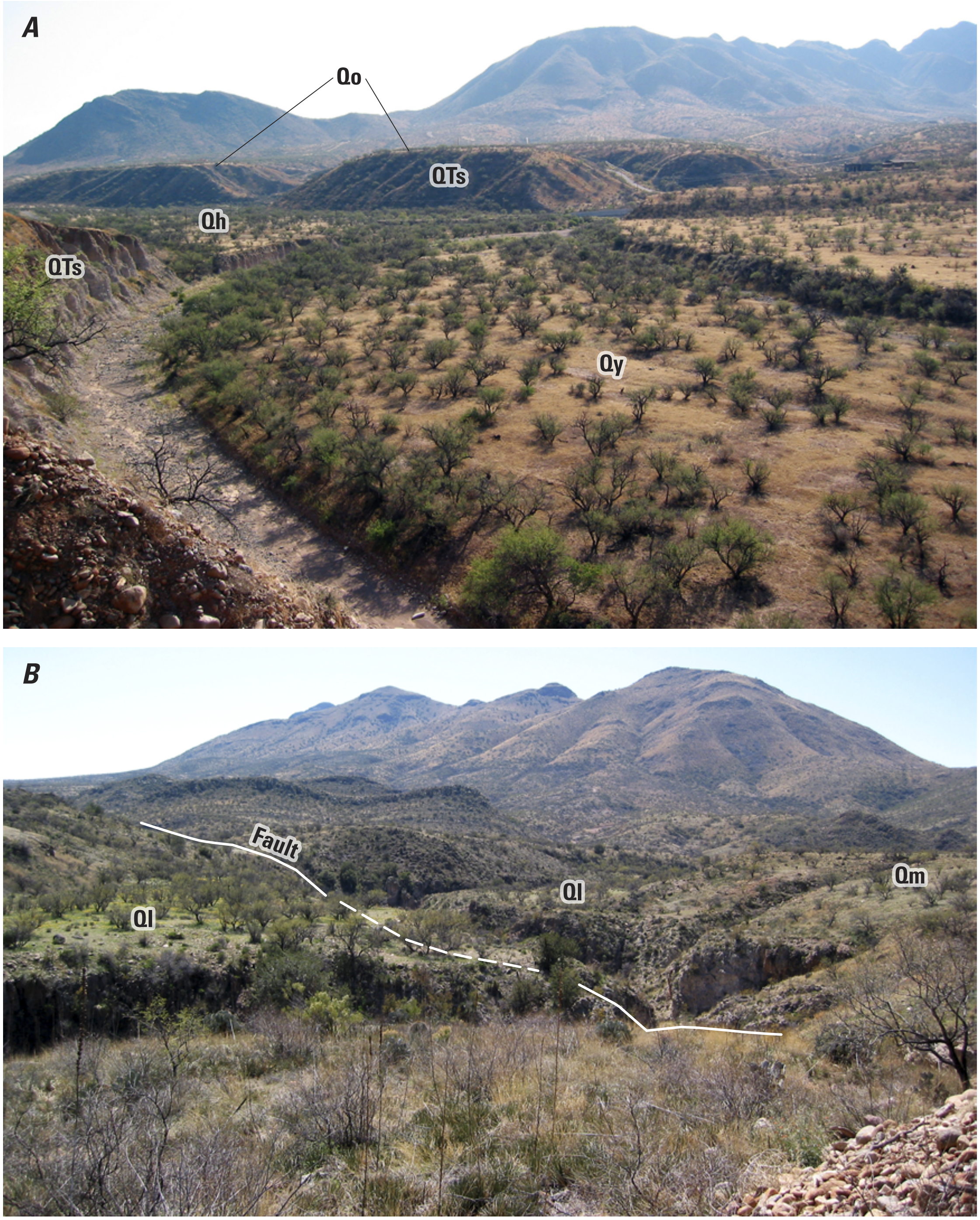


Figure 3. Formation of erosional terraces on Josephine Canyon Wash. *A*, View upstream (east) of the near-equilibrium middle reach (stream power/resisting power =1). The channel is undercutting outcrops (left side of photograph) of Pliocene to early Pleistocene alluvium (QTs) in concave meander bank. Modern floodplain (Qy) gravel accretes to convex meander bank in foreground. Vegetated floodplain surface shows bar and swale topography (Bull, 1991). Stepped terraces in background are of Holocene (Qh) and early Pleistocene (Qo) age; bedrock horst of the San Cayetano Mountains on skyline. *B*, View downstream (southwest) of the degradational upper reach (stream power/resisting power >1). The channel is confined to entrenched meanders in volcanic rocks as it continues to downcut. Meanders are probably inherited from the time when the late Pleistocene strath terrace (Ql) was cut. A normal fault crosses stream at the stream bend in the foreground, but does not offset the terrace, and continues in the bedrock saddle in the middle distance on left; high terrace on right side of photograph is of middle Pleistocene age (Qm); San Cayetano Mountains on skyline.

Degradation and aggradation can be understood by reference to Lane's (1955) equation for channel equilibrium:

$$Q_S \times D_{50} \propto Q_W \times S$$

where

Q_S is sediment discharge (supply or load),
D_{50} is median particle size,
Q_W is stream discharge (streamflow), and
S is channel slope.

When all four variables are in balance, the stream is in equilibrium, but when one or more variables change, the stream is in disequilibrium until other variables compensate. Depending on the direction of change, disequilibrium is revealed by degradation (incision, vertical cutting) or by aggradation (deposition). Equilibrium is indicated by lateral cutting. Channel incision is favored when stream power ($Q_W \times S$) exceeds resisting power ($Q_S \times D_{50}$); aggradation is favored when resisting power exceeds stream power (Bull, 1991). As illustrated for Josephine Canyon Wash, the downstream progression of stream power/resisting power of >1, =1, and <1 can be related to the progression from incision (>1, for upper reaches including tributaries) through equilibrium (=1, for middle reaches) to aggradation (<1, for lower reaches of the trunk stream).

Both theory and experiment indicate that the fundamental cause of lateral cutting of terrace surfaces is probably increased sediment supply (sediment discharge), although streamflow (stream discharge) plays a secondary role (Hancock and Anderson, 2002). Sediment supply and stream discharge are subject to rapid change and thus are the principal causes of disequilibrium. When sediment supply increases, streams deposit alluvium on their valley floors and cut laterally. The alluvial cover protects the valley floor from downcutting. When sediment supply wanes or streamflow increases, streams resume downcutting, leaving a terrace above the new channel.

As the master stream, the Santa Cruz River defines base level for its piedmont tributaries. During periods of downcutting by the river, base level drops, slopes increase at the foot of the piedmont, and tributary streams cut headward. During periods of river-valley filling, base level rises, and tributaries cut laterally, then aggrade (Schumm, 1993). In this scenario, the history of piedmont incision and terrace formation is linked to the base-level control of the Santa Cruz River. Base level of the Santa Cruz River may have dropped 50–80 m since middle Pleistocene time, based on the elevation of terrace remnants mapped on the west side of the river near Tubac (fig. 1) (Helmick, 1986; Youberg and Helmick, 2001). Between 8 and 5.6 ka, in Holocene time, the river alternated between downcutting and filling with little or no net decline in base level; this time period is interpreted to reflect arroyo cutting as desert vegetation replaced woodlands when the climate became warm and dry (Waters and Haynes, 2001). The effect of base-level change also depends upon the rate of change: slow changes would allow the river and its tributaries to remain in equilibrium through minor adjustments, such as changes in channel sinuosity (Schumm, 1993).

Faults that cross tributaries can create local base levels and alter stream slope. Rapid change, such as surface offset along faults that cross tributaries, creates knickpoints in the stream profile and has the potential to initiate incision upstream and aggradation downstream. However, at many places in the study area, faults mapped in basin fill have not moved since middle Pleistocene time, and in the area between Mavis Wash and Josephine Canyon Wash, there has been no fault movement since early Pleistocene time (figs. 1 and 2). Mapped evidence for late Pleistocene surface rupture is mostly north of Madera Canyon Wash. These constraints on the time of fault movement indicate tectonic stability during much of Pleistocene time, allowing hundreds of thousands of years for lateral cutting and for scarp retreat to the present mountain front.

Erosional embayments, pediments, and thin fans at canyon mouths also indicate tectonic stability (Bull, 1984). Except at the mouth of Chino Canyon, faults are not located at the mountain front, but instead are on the piedmont a few kilometers downstream (west) of the front. With the exception of Chino Canyon, the present mountain front is not a major fault boundary and is not straight, but instead consists of erosional embayments centered on canyon mouths. Rock-cut surfaces (pediments) beneath early Pleistocene gravels are observed on granite (Madera Canyon Wash) and volcanic rock (Montosa Canyon Wash) as well as on Nogales Formation (Josephine Canyon Wash, fig. 2). All of the surfaces cut on hard rock are on the upthrown sides of major valley fault systems and must represent a long expanse of time (fig. 1). These surfaces existed by early Pleistocene time, when thin fans were deposited at canyon mouths.

Profiles of ephemeral streams in southeastern Arizona reflect adjustment to tectonic stability during Quaternary time. These streams have concave-up profiles in mountain segments and nearly flat profiles in piedmont segments; they are adjusted to hydrologic factors, not base level (Cherkauer, 1972). Gradient, drainage area, and particle size follow channel profiles; all of these correlate with stream discharge. Steep mountain segments gather most of the stream discharge. Discharge increases very little or even diminishes downstream on narrow, elongate piedmont segments, as infiltration and evaporation remove as much discharge as is received from direct precipitation and overland flow (Cherkauer, 1972).

Under the stream-piracy scenario, a major wash emerging from the mountains may be captured by a minor wash within the basin, with opportunities for incision and aggradation on both streams (Ritter, 1987). Stream capture can also reorganize mountain catchment basins (Bull, 2009). In both basin and montane settings, a key factor is the relative elevation of the two streams; the capturing stream occupies a lower level than the stream it captures. On the piedmont, stream capture commonly takes place on the upper surfaces of alluvial fans, where a small wash located on the fan cuts headward and captures the main wash draining the mountain catchment basin (Denny, 1967). As illustrated on the piedmont of the Santa Cruz River valley, the stage is set for stream piracy by headward-cutting washes on the flanks of early Pleistocene fans. The actual capture probably takes place by avulsion rather than headward erosion (Miller, 1959), when the higher, main wash overflows its banks and spills into the lower, small wash during an extreme event, such as a cloudburst.

Incision and aggradation after stream piracy can be profound (Bull, 2009). Capturing streams gain discharge and sediment supply; increased discharge results in incision and rapid headward erosion of the channel; whereas downstream, sediment will begin to accumulate. As incision wanes, aggradation proceeds upstream. Likewise, a stream beheaded by capture loses discharge and will begin to aggrade until its slope is sufficient to transport all of the available sediment.

Stream piracy has played an important role in dissection and terrace formation on the piedmont landscape of the Santa Cruz River valley since early Pleistocene time. Headward erosion by small washes on the upper piedmont diverted Madera Canyon Wash and Montosa Canyon Wash in middle and late Pleistocene time. Piracy and diversion of main washes to adjacent small washes terminated lateral cutting on the pirated stream. The valley of the pirated stream remained abandoned until some remnant or tributary of the pirated stream cut sufficiently headward to occupy it. In contrast, the pirate wash gained discharge and continued downcutting until increased sediment supply and decreased slope reestablished equilibrium, at which time it began to cut laterally and widen its valley. Washes that cut deeper canyons than Madera Canyon and Montosa Canyon, including Cottonwood Canyon Wash and Josephine Canyon Wash, do not show a record of stream piracy. Thus, terraces along Cottonwood Canyon and Josephine Canyon Washes did not form in response to stream piracy.

A hot, dry interglacial climate with monsoonal storm patterns, like those of today, and sparse desert vegetation might provide the conditions necessary to initiate erosion cycles that lead to lateral cutting of some reaches while degradation proceeds upstream and aggradation takes place downstream. Previous studies have linked aggradation in the lower Colorado River to interglacial periods, including the Holocene (Bull, 1991), when dry climate, sparse vegetation, and cloudbursts would have combined to increase sediment supply. However, short-term climate fluctuations within interglacial periods (see for example, Waters and Haynes, 2001) may complicate broad correlation of terrace formation with interglacials. A corollary of aggradation on the piedmont during dry periods is that stream incision is most likely to occur during cool, wet periods when vegetation was denser than the present, leading to higher stream discharge and lower sediment supply than the present (stream power/resisting power >1).

Terrace Deposits

Except near the mountain front, middle Pleistocene and younger terraces in the study area are mostly erosional; terrace surfaces are underlain by thin (commonly, 2–3 m) lag gravels (figs. 4*A*, 4*B*, and 4*C*). In contrast, fans of early Pleistocene age and a depositional terrace of middle Pleistocene age on Josephine Canyon Wash (figs. 5*A* and 5*B*) have thicknesses of 10–20 m. Near the mountain front, where abrupt changes in channel profile and dimensions cause streams to deposit their sediment load, terraces tend to be depositional. Older terrace gravel, of middle and early Pleistocene age, is deeply weathered, with the zone of red oxidation and rock disintegration extending into bedrock (fig. 4*C*). On the terrace surface, original channel topography is muted or absent. In contrast, younger (late Pleistocene and Holocene) terrace tops preserve bar-and-swale features (Bull, 1991).

Gravel in both erosional and depositional terraces of the study area always shows evidence of particle sorting and rearrangement by flowing water (figs. 4*B* and 6*A*, 6*B*, and 6*C*). In addition to weak layering in the form of lenses of varying particle size, common features include outsize clasts (such as boulders stranded by waning flow or lodged in finer sediment), clast clusters (clasts that lodge against one another during transport), and imbricate clusters (clasts resting on scour surfaces and rotated toward the upstream direction) (see Lindsey and others, 2005, for descriptions and references to these features in gravel deposits). These features are present in flash-flood deposits of perennial streams, but other evidence for perennial flow, such as clast-armor layers, downstream fining of gravel lenses, and crossbedding—all associated with gravel bars in perennial streams—is generally absent. Both layering and clast armor are absent or only weakly developed in gravel deposits of ephemeral streams in arid regions (Hassan, 2005; Laronne and others, 1994). The weak development of layering in most gravel deposits of piedmont tributary terraces of the Green Valley-Tubac area, and the absence of structures diagnostic of perennial streams, favors deposition in ephemeral streams with intermittent, flashy stream discharge.

Proximal deposits, that is, deposits formed near the mountain front, show evidence of both turbulent streamflood and debris-flow deposition in many regions (see for example, Bull, 1972; Costa, 1988; Blair and McPherson, 1994). Most proximal deposits studied here are of streamflood origin, but debris-flow origin cannot be excluded, because individual deposits may be transitional and criteria for distinction are not always clear. Proximal streamflood deposits below the mouth of Montosa Canyon are coarse and appear poorly sorted to the eye, but they contain crude stratification, lenses of imbricate clasts, possible horizons of clast armor, isolated large boulders, and clast clusters (figs. 6*A*, 6*B*, and 6*C*). All of these features are characteristic of streamfloods, and most or all can form during catastrophic floods (debris floods of Hungr, 2005;

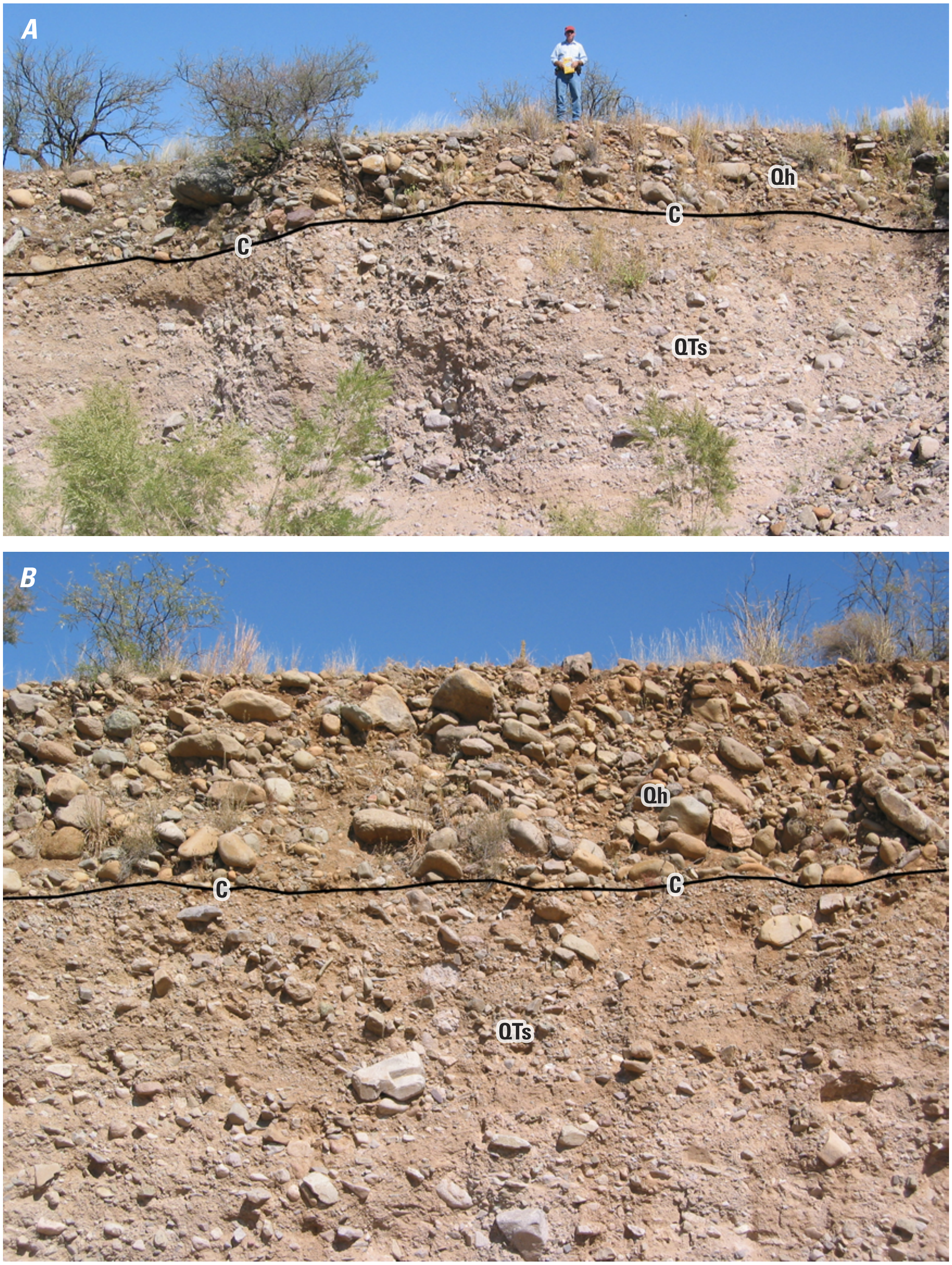


Figure 4. Erosional terraces. *A*, Erosional terrace of Holocene age (Qh) with thin gravel resting on Pliocene to early Pleistocene alluvium (QTs), north side Josephine Canyon Wash, sample locality D1 (fig. 2); C, units Qh-QTs contact. QTs outcrop in stream bank is too narrow to show on figure 2. *B*, Close view of figure 4*A*. Imbrication of large clasts is typical of streamflood deposits. Thin (2–3 m) terrace gravel deposits such as these represent the depth of scour and fill of former stream channels. *C*, Erosional terrace of middle Pleistocene age overlying basin fill (QTs), north side of Cottonwood Canyon Wash, sample locality D13 (fig. 1), showing weathered, clast-supported gravel, 3 m thick. Middle Pleistocene and older terrace deposits are deeply weathered, reddish in color, and surfaces are smooth.

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hyperconcentrated flows of Pierson, 2005). Stratification may be largely a product of aggradation, where successive floods have stacked layers on top of one another. Reverse grading and rafted clasts, a characteristic of debris flows where the largest boulders are concentrated near flow tops and fronts (see for example, Hungr, 2005), were observed only in early Pleistocene proximal deposits at Montosa Canyon Wash (fig. 6*B*). There, however, identification of rafted clasts on old terrace surfaces is uncertain because large boulders can be exposed by weathering and erosion of fine sediment. A single exposure of poorly sorted middle Pleistocene gravel, containing abundant interstitial sand and silt, in the banks of Florida Canyon Wash resembles a debris flow (fig. 6*D*), but interpretation is clouded by presence of faint stratification, imbrication in clast clusters, and a low Trask sorting coefficient.

Figure 5. Middle Pleistocene depositional terrace on Josephine Canyon Wash. *A*, Thick depositional terrace of middle Pleistocene age overlying Pliocene to early Pleistocene alluvium (QTs), north side Josephine Canyon Wash, sample locality D3 (fig. 2). Terrace gravel (Qm) is approximately 18 m thick. View is west, downstream. Unit QTs outcrop at base of cliff is too narrow to show on figure 2. *B*, Close view of figure 5*A* showing weak stratification and unconformable surface cut on Pliocene to early Pleistocene alluvium (QTs) (sample locality D3, fig. 2).

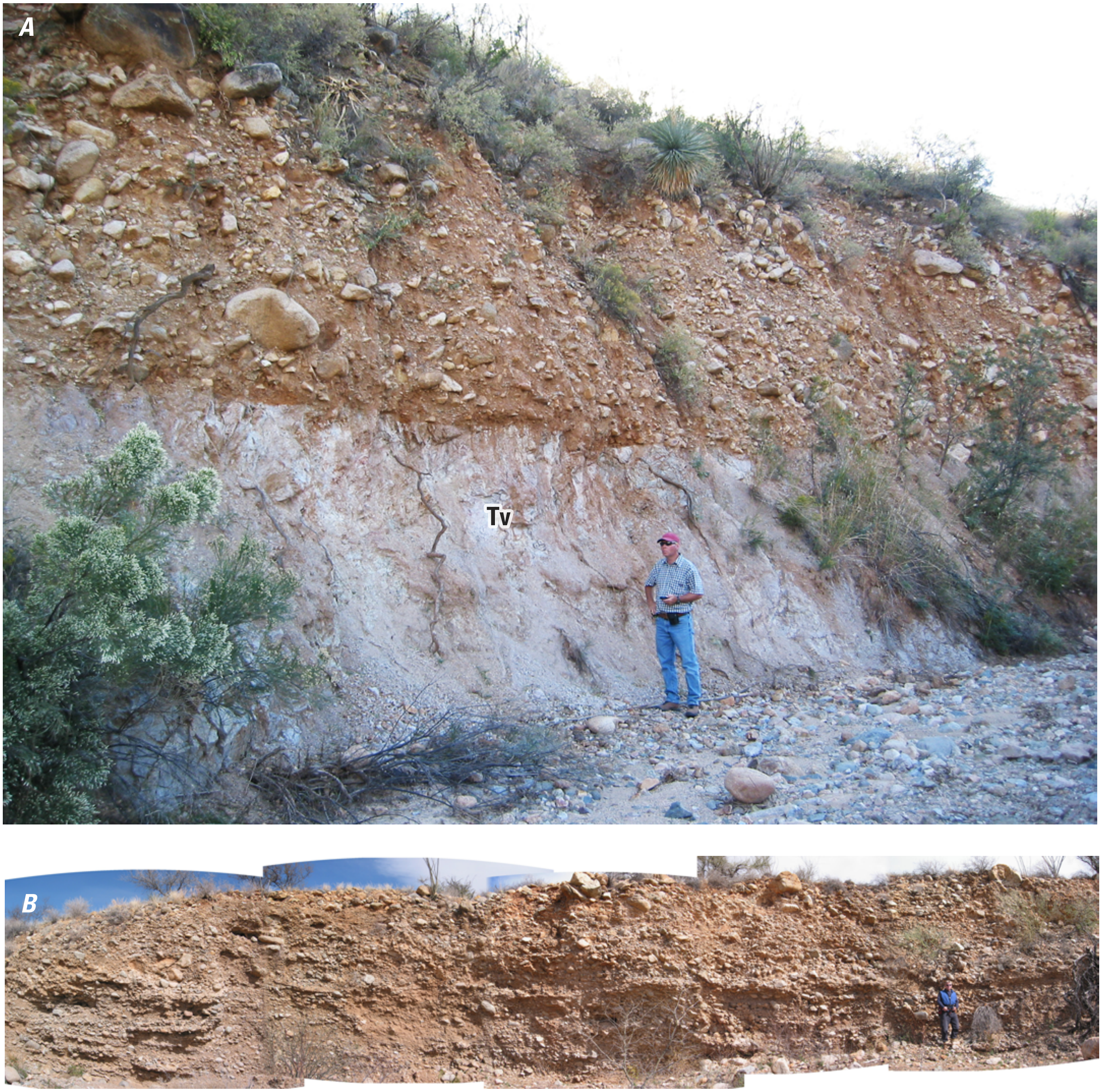

Figure 6. Sedimentary features in depositional terraces near the mountain front. *A*, Coarse terrace gravel of late Pleistocene age at the head of Montosa Canyon Wash, sample locality D19 (fig. 1), located near point where wash leaves the mountains at Whipple Observatory headquarters. Gravel was deposited on a smooth surface cut on volcanic rock (Tv). Note outsize boulders, upper left, and weak stratification. *B*, Panoramic view of fan gravel of early Pleistocene age on Montosa Canyon Wash, sample locality 19, about 1 km west of the mountain front. Stratified gravel deposited by repeated streamfloods. Large boulders on weathered surface may be remnants of a debris flow deposit, or may have been weathered out of coarse streamflood deposits. *C*, Close view, right side of figure 6*B*, showing stratification, imbrication (I), clast armor (A), outsize clasts (O), and clast clusters (CC) typical of streamflood deposits. Streamflow direction right to left. *D*, Middle Pleistocene terrace gravel interpreted as possible debris-flow deposit based on unsorted appearance, Florida Canyon Wash (sample locality 11, D25, fig. 1). However, the Trask sorting coefficient is in the range of streamflood deposits reported by Costa (1988). Also, note faint stratification, left center, and isolated imbricate cobble cluster between pack and boot, indicative of sorting. Photograph by Roger Melick.

Figure 6. Photographs of sedimentary features in depositional terraces near the mountain front. *A*, Coarse terrace gravel of late Pleistocene age at the head of Montosa Canyon Wash, sample locality D19 (fig. 1), located near point where wash leaves the mountains at Whipple Observatory headquarters. Gravel was deposited on a smooth surface cut on volcanic rock (Tv). Note outsize boulders, upper left, and weak stratification. *B*, Panoramic view of fan gravel of early Pleistocene age on Montosa Canyon Wash, sample locality 19, about 1 km west of the mountain front. Stratified gravel deposited by repeated streamfloods. Large boulders on weathered surface may be remnants of a debris flow deposit, or may have been weathered out of coarse streamflood deposits. *C*, Close view, right side of figure 6*B*, showing stratification, imbrication (I), clast armor (A), outsize clasts (O), and clast clusters (CC) typical of streamflood deposits. Streamflow direction right to left. *D*, Middle Pleistocene terrace gravel interpreted as possible debris-flow deposit based on unsorted appearance, Florida Canyon Wash (sample locality 11, D25, fig. 1). However, the Trask sorting coefficient is in the range of streamflood deposits reported by Costa (1988). Also, note faint stratification, left center, and isolated imbricate cobble cluster between pack and boot, indicative of sorting. Photograph by Roger Melick.—Continued

Gravel Lithology

Gravel lithology reflects the lithologic terrane of the catchment basin. As gravel is reworked downstream, it is redeposited with some modification of lithologic proportions, but the reworked gravel still reflects the distinctive lithologic composition of the catchment basin. Gravel lithology was determined by pebble counts below the catchment basins of Madera Canyon, Montosa Canyon, Cottonwood Canyon, and Josephine Canyon (fig. 7). Gravel on the piedmont below the mouth of Madera Canyon also contains contributions from Florida Canyon and Chino Canyon Washes that requires separate consideration (fig. 8). For this report, new data (appendix A, tables A1–A5) were combined with data from an earlier study (Lindsey and Melick, 2002). Details of methods and data are given in appendix A.

Granitic and volcanic rocks are abundant in terrace gravel from all four catchment basins, but the gravel of each basin is distinctive (fig. 7). Pebble counts show that gravel from Madera Canyon is distinguished by clasts of abundant granitic rocks and crystal-poor ignimbrite. Montosa Canyon gravel has conspicuous amounts of gabbro, diorite, carbonate rock, and quartz sandstone. Cottonwood Canyon and Josephine Canyon gravels have little or no gabbro, diorite, carbonate rock, or quartz sandstone; instead these gravels consist almost entirely of various granitic and volcanic rocks. As illustrated next, distinctive clasts and variations in lithologic proportions can be traced to specific catchment basins and help to identify previous positions of streams on the piedmont.

Gravel lithology is affected by drainage history on the piedmont, especially by capture and rerouting of major tributaries. For example, Madera Canyon Wash has followed several courses on the piedmont since it built a thin alluvial fan in early Pleistocene time, and each course had its own tributary system. During middle Pleistocene time, Madera Canyon Wash flowed directly north from the canyon mouth, where it was joined by Florida Canyon Wash, which still flows along the northern part of the early Pleistocene Madera Canyon fan. The middle Pleistocene gravel exposed in the banks of Florida Canyon Wash (sample 11, fig. 8) near the mountain front contains much more crystal-poor ignimbrite, more granitic rock, and no volcanics with quartz, unlike gravel derived only from Madera Canyon (samples D24A and D27, fig. 8). These differences reflect a major contribution from the mountain reaches of Florida Canyon, where granitic rocks of Precambrian age dominate (Drewes, 1980), and presumably, crystal-poor ignimbrite is abundant but other volcanics with quartz are not.

In late Pleistocene time, the Madera Canyon Wash flowed along the southern margin of the old alluvial fan, turning abruptly west at the mouth of the canyon and joining Chino Canyon Wash downstream. Chino Canyon Wash drains largely granitic terrane and joins Madera Canyon Wash on the piedmont about 8 km downstream from where the latter leaves the mountains. Gravel below the junction of Chino Canyon Wash and Madera Canyon Wash (sample 13, fig. 8) contains more granitic rock than terrace gravel on Madera Canyon Wash above the junction (sample D23). Thus, drainage history is reflected in gravel lithology. Abundant granitic-rock clasts in early Pleistocene gravel deposits (sample 20AB) below the modern junction reveal that Chino Canyon Wash has a long presence along the south side of the piedmont below Madera Canyon. The presence of abundant volcanic rocks with quartz suggests a contribution from early Pleistocene fan gravel, originally derived from Madera Canyon. During early Pleistocene time, a piedmont tributary of Chino Canyon Wash was already eroding the early Pleistocene Madera Canyon fan, but it did not capture the wash draining Madera Canyon until late Pleistocene time.

Figure 7. Summaries of clast lithology for early Pleistocene to Holocene gravel deposited by Madera Canyon Wash (600 pebbles), Montosa Canyon Wash (348 pebbles), Cottonwood Canyon Wash (101 pebbles), and Josephine Canyon Wash (561 pebbles). Gravels of Madera Canyon Wash include contributions from adjacent Florida Canyon Wash and Chino Canyon Wash (fig. 8).

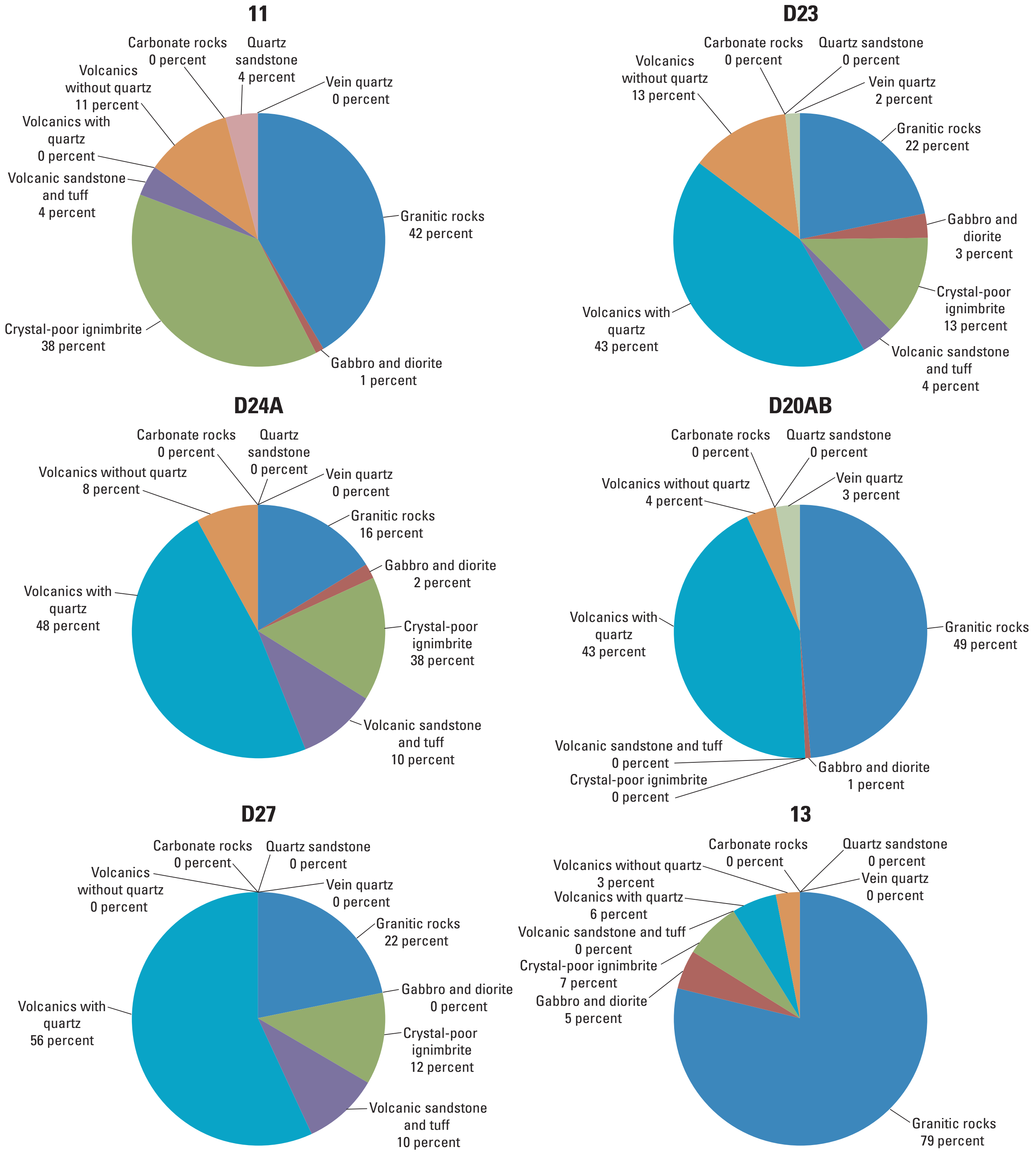

Figure 8. Summaries of clast lithology for gravel of Madera Canyon Wash as it changed course during Pleistocene time. Pie diagrams on left show terrace gravel, upstream (samples 11 and D24A) and downstream (sample D27), deposited by middle Pleistocene courses of the wash (fig. 1). Abundant granite and ignimbrite in the chart for sample 11 indicates a contribution from Florida Canyon Wash. Volcanics with quartz may be from Madera Canyon. Pie diagrams on right show late Pleistocene terrace gravel above (sample D23) and below (sample 13) junction with Chino Canyon Wash. Middle chart on right (sample D20AB) is early Pleistocene terrace gravel below junction with Chino Canyon Wash. Granitic rocks from Chino Canyon Wash are most abundant in gravel below the junction. Sample localities (fig. 1) are indicated by numbers or the letter “D” followed by a number; letters following locality numbers in figure 8 refer to samples taken at the same site.

Particle Size and Sorting

The particle size and sorting of gravel reflects downstream distance, stream competence, and transport and sorting mechanism. As with gravel lithology, our study of particle size focused on gravel deposited below Madera Canyon, Montosa Canyon, Cottonwood Canyon, and Josephine Canyon. For deposits on the north and south sides of the early Pleistocene Madera Canyon fan, particle size and sorting may reflect additional streamflow from Florida Canyon and Chino Canyon, respectively. Particle size was estimated by direct measurement along tape traverses on vertical outcrops of gravel instead of by sieving. Data are presented as cumulative frequency curves and statistics for quartiles and sorting. Methods, sample locations, data, and statistical computations are described in appendix B of this report. Sample localities are shown in figures 1 and 2.

Decreasing particle size downstream is well shown by comparing particle-size distributions for upstream and downstream locations of gravel deposited by Montosa Canyon Wash (figs. 9*A* and 9*B*) and the middle Pleistocene Madera Canyon Wash (figs. 10*A* and 10*B*). Other factors also influence particle size, and these can be illustrated by different terraces within the same reach—that is, where the downstream distance is approximately the same. Thin gravel of erosional terraces that overlie basin fill (QTs in fig. 1) is almost always coarser grained than basin fill (compare the particle-size curve for sample D24BU for Qh with that of D24BL for QTs in fig. 10*A*). The tendency for younger deposits to be coarse grained is also seen in early and late Pleistocene gravel along the present course of the Madera Canyon Wash (fig. 10*C*). The effect of transport mechanism is apparent from the slope of cumulative frequency distribution curves: a sample from gravel interpreted as a possible debris flow (sample D25B, fig. 10*D*) is flatter than clast-supported streamflow deposits (samples D25A and D25C, fig. 10*D*) at the same locality.

Perhaps the terrace gravels on Josephine Canyon Wash are the most striking example of the influence of continued reworking on particle size (fig. 11). The youngest (Qh and Ql in fig. 2), thinnest terrace deposits are the coarsest grained, and the oldest (Qo and Qm in fig. 2) and thickest deposits are the finest grained. When the old depositional terraces of Josephine Canyon Wash were eroded, fine sediment was winnowed and coarse particles were left as lags on newly formed erosional terraces. Particle size for all of the terrace gravels of the Josephine Canyon Wash was determined along a 3-km reach midway along the wash, about 5–8 km from the apex of the early Pleistocene Josephine Canyon fan and about 5–8 km upstream from the confluence with the Santa Cruz River (figs. 1 and 2).

The relation between deposit thickness and particle size and sorting was examined to search for criteria to distinguish depositional from erosional terrace deposits. Streams that are primarily aggradational, that is, they deposit sediment and raise their channel level, will form depositional terraces with thick fills. For example, the oldest and highest gravels (Qo and Qm, fig. 2) of Josephine Canyon are as much as 18–20 m thick; these are deposits of aggrading streams. Streams that are primarily degradational, that is, they cut down and during equilibrium, cut laterally, would be expected to form erosional terraces covered by thin, coarse lag deposits. For example, the young gravels (Ql and Qh, fig. 2) of Josephine Canyon are mostly 2–3 m thick but have larger median particle size than older terrace gravel; these are deposits of degrading streams that, when they reach equilibrium, cut laterally. Terrace steps record an overall history of degradation, but degradation may be punctuated by periods of lateral cutting during equilibrium or even by deposition during aggradation.

The deposits studied range from ≈2 m to as much as 20 m thick, but most are less than 12 m thick (fig. 12*A*). Within deposits <12 m thick, those ranging up to 6 m thick are interpreted as deposits of dominantly degradational streams. The thinnest (2–4 m thick) deposits may represent a single cycle of channel cutting and filling, followed by winnowing of fine grains, as reflected in larger overall particle size compared to nearby thick deposits (for example, Josephine Canyon, fig. 11). An intermediate class of deposits, 6–12 m thick, forms a “tail” on the primary mode of deposit thickness (fig. 12*A*). The intermediate class of deposits is not distinguishable by particle size or sorting from thin deposits on erosional terraces, but its greater thickness suggests some degree of aggradation by repeated deposition.

Most gravel deposits of Santa Cruz River tributaries are well sorted by the criteria of Trask (Krumbein and Pettijohn, 1938), having sorting coefficients (So) of less than 2.5. Sorting values compare well with those of streamflood deposits (water-flood deposits of Costa, 1988, who reported an average Trask sorting coefficient range of 1.8–2.7) and are well below values of debris-flow deposits (sorting coefficient range of 3.6–12.3, Costa, 1988). In this regard, the highest sorting coefficient (3.4) was calculated for the early Pleistocene gravel at sample locality 19 (fig. 1), in proximal deposits near the mouth of Montosa Canyon. The uppermost, weathered part of the fan gravel at locality 19 could be the remnant of a debris flow as indicated by large boulders on the surface (fig. 6*B*). However, the relatively high coefficient probably results from taking a composite sample of the entire outcrop, where lenses of both coarse and fine gravel are combined. Most of the gravel at sample locality 19 was deposited by streamflood, as indicated by stratification, imbrication, and sorting. In contrast, the deposit at locality 11 (figs. 1 and 6*D*; sample D25B, fig. 10*D*), interpreted as a possible debris flow, has a sorting coefficient of 2.4, well within the range of streamflood deposits.

A scatterplot of deposit thickness versus median particle size reveals little if any correlation between the two parameters (fig. 12*B*). Except for one anomalously thin measurement (locality D4, fig. 2), where the terrace surface has been eroded, thick aggradational deposits of early and middle Pleistocene age on Josephine Canyon (J on figs. 12*B* and 12*C*) plot in a separate field. Thickness versus median particle size of terrace deposits of other streams does not vary with age and does not

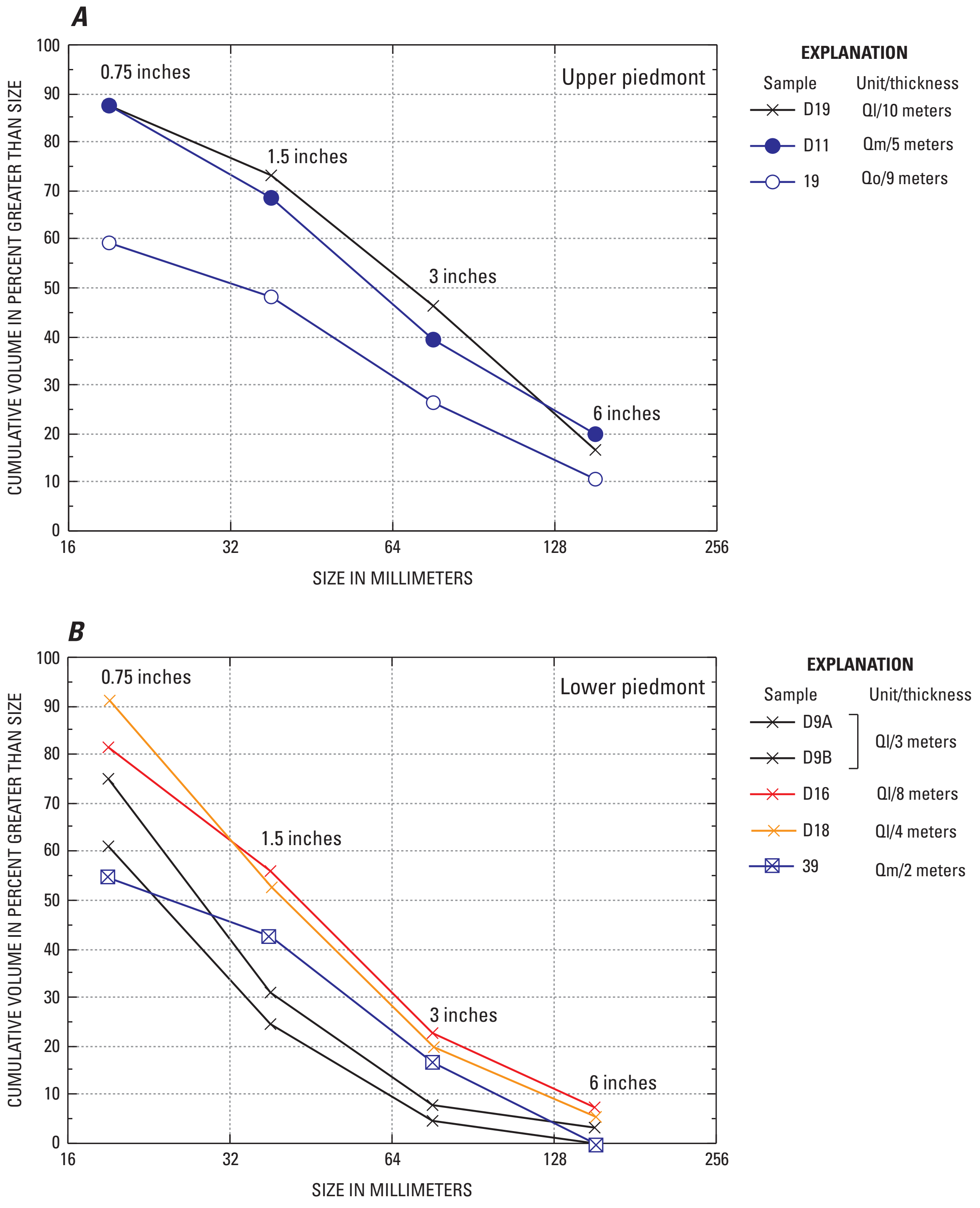

Figure 9. Cumulative frequency curves for particle size in gravel of varying age and distance from the canyon mouth of Montosa Canyon Wash. A, Upper piedmont; B, Lower piedmont. Sample localities in figure 1; exact locations and data in table B1.

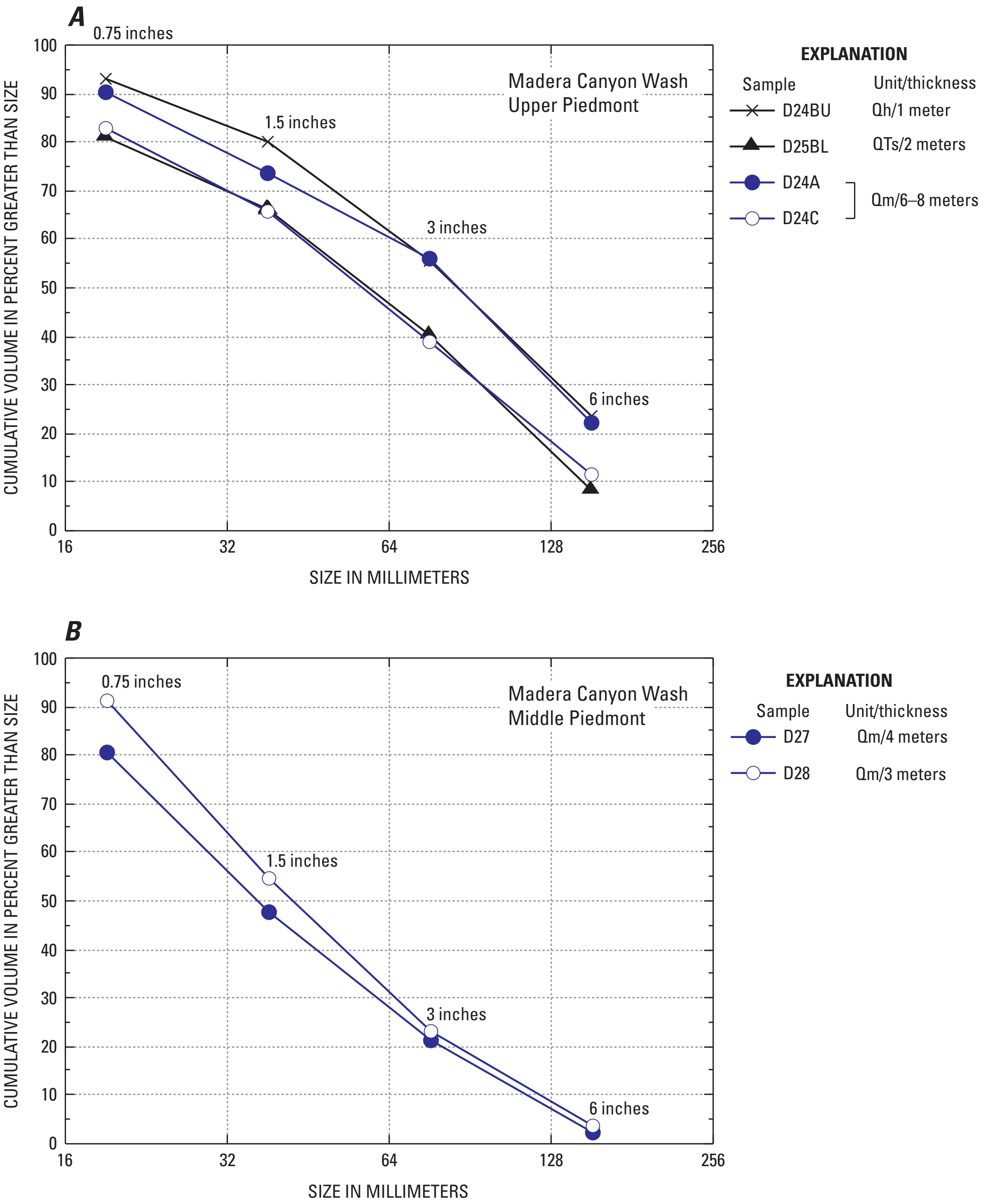

Figure 10. Cumulative frequency curves for particle size in gravel deposited by Madera Canyon Wash and Florida Canyon Wash. *A*, Gravel deposited on the upper part of middle Pleistocene Madera Canyon Wash (samples D24A and D24C. Also shown are samples D24BL and D24BU, of units QTs and Qh from the same location, to show the coarsening effect of reworking old fan gravel. *B*, Gravel from the midpoint (powerline road) of the middle Pleistocene Madera Canyon Wash (samples D27 and D28). *C*, Gravel deposited by the late Pleistocene (samples D22 and D23) and the early Pleistocene (samples D20A and D20B) Madera Canyon Wash. *D*, Gravel deposited by the middle Pleistocene Florida Canyon Wash and Madera Canyon Wash near their former junction (samples D25A, D25B, and D25C). The flat curve for sample D25B may reflect deposition by debris flow. Sample localities in figure 1; exact locations and data in table B1.

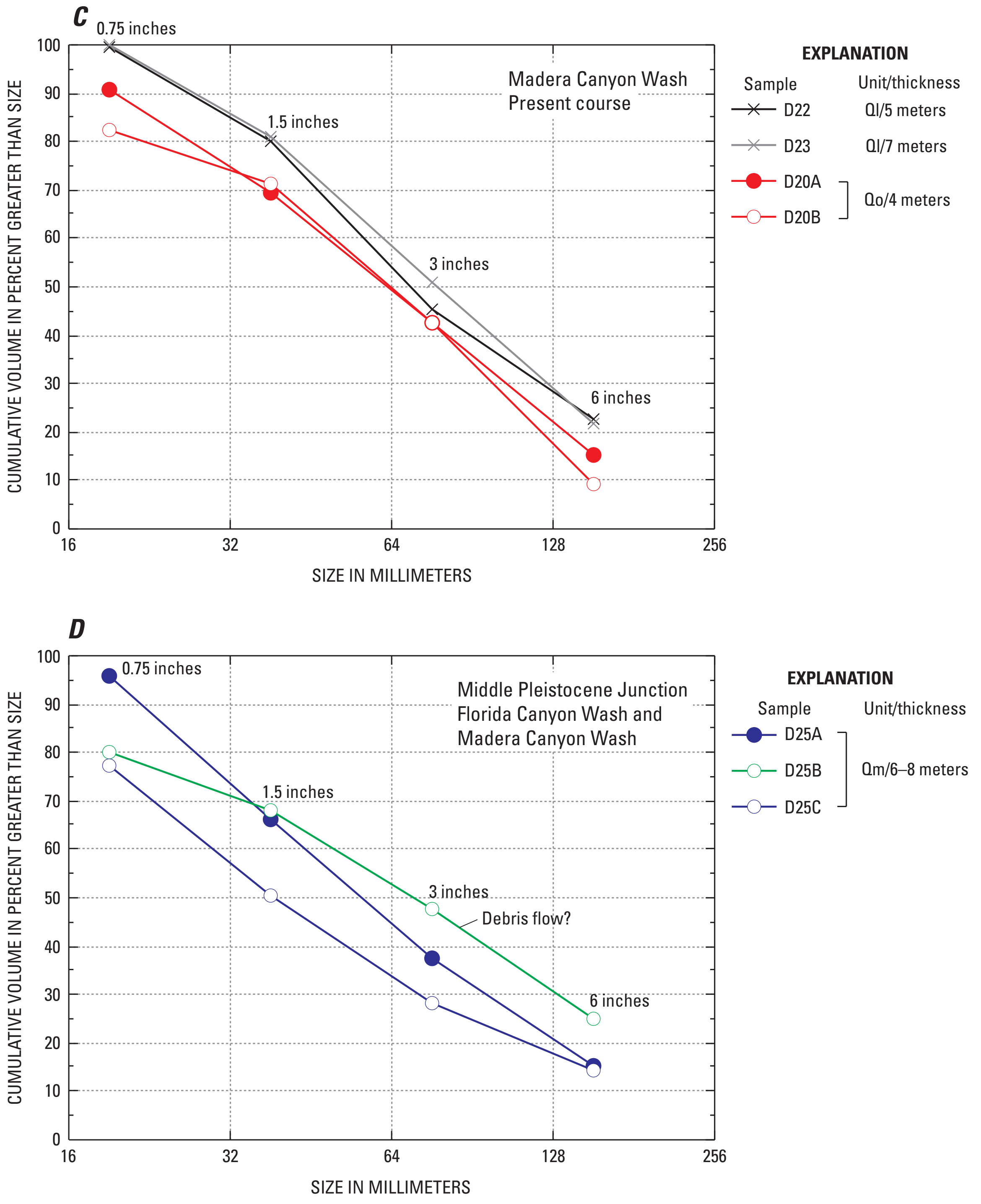

Figure 10. Cumulative frequency curves for particle size in gravel deposited by Madera Canyon Wash and Florida Canyon Wash. *A*, Gravel deposited on the upper part of middle Pleistocene Madera Canyon Wash (samples D24A and D24C. Also shown are samples D24BL and D24BU, of units QTs and Qh from the same location, to show the coarsening effect of reworking old fan gravel. *B*, Gravel from the midpoint (powerline road) of the middle Pleistocene Madera Canyon Wash (samples D27 and D28). *C*, Gravel deposited by the late Pleistocene (samples D22 and D23) and the early Pleistocene (samples D20A and D20B) Madera Canyon Wash. *D*, Gravel deposited by the middle Pleistocene Florida Canyon Wash and Madera Canyon Wash near their former junction (samples D25A, D25B, and D25C). The flat curve for sample D25B may reflect deposition by debris flow. Sample localities in figure 1; exact locations and data in table B1.—Continued

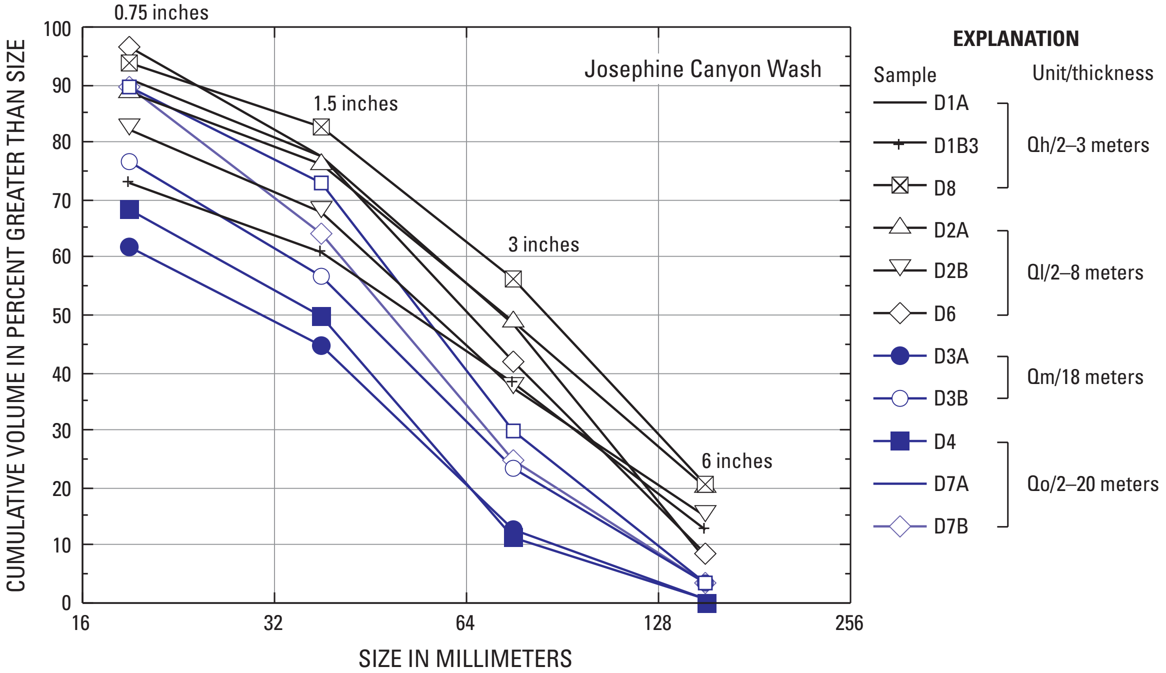

Figure 11. Cumulative frequency curves for particle size in gravel of varying age within a 3-km reach of Josephine Canyon Wash. Older, thicker gravel is finer grained than younger, thinner terrace gravel. Sample localities in figure 2; exact locations and data in table B1.

differ from terraces of late Pleistocene and Holocene age of Josephine Canyon. The confounding influence of distance from fan apex probably accounts for much of the variation in median particle size.

Terrace gravel of late Pleistocene age (and perhaps also of Holocene age) tends to be slightly better sorted (So <2) than deposits of older gravel (fig. 12*C*). Many well-sorted deposits of coarse terrace gravel are thin deposits on erosional terraces. Thus good sorting, coarse particle size, and thinness are the essential characteristics that distinguish erosional from aggradational terrace gravel. Aggradational terrace gravel (for example, the basin fill QTs, fig. 1) is often preserved in the geologic record.

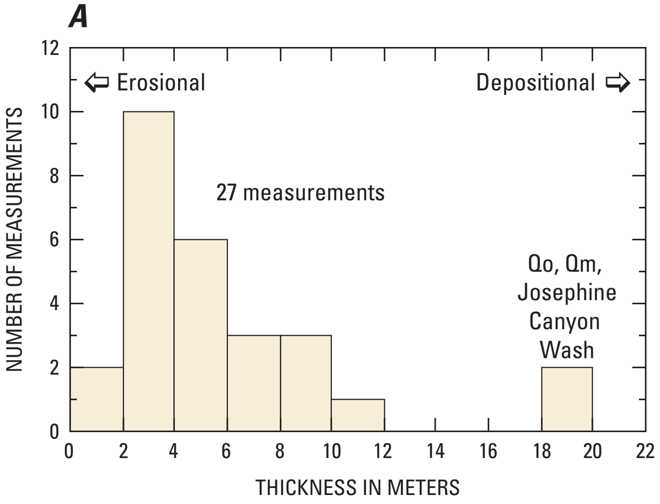

Figure 12. Thickness, sorting, and particle-size relations for terrace fill. *A*, Histogram of terrace thickness on the piedmont east of the Santa Cruz River, Green Valley-Tubac area. *B*, Scatterplot of terrace thickness versus median particle size. *C*, Scatterplot of sorting versus median particle size. High Trask sorting coefficients (So) indicate poor sorting; low coefficients indicate good sorting.

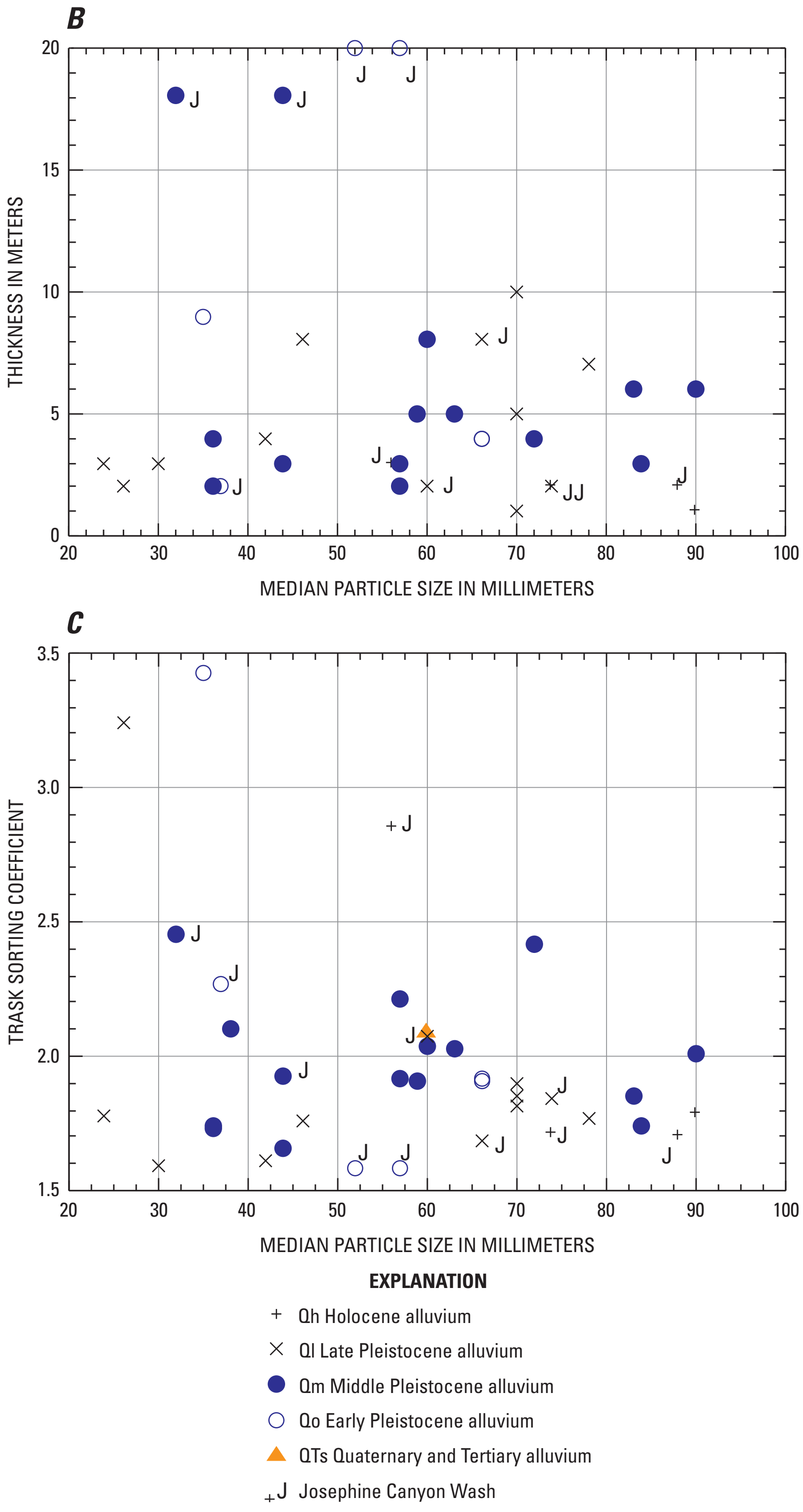

Figure 12. Thickness, sorting, and particle-size relations for terrace fill. *A*, Histogram of terrace thickness on the piedmont east of the Santa Cruz River, Green Valley-Tubac area. *B*, Scatterplot of terrace thickness versus median particle size. *C*, Scatterplot of sorting versus median particle size. High Trask sorting coefficients (So) indicate poor sorting; low coefficients indicate good sorting.—Continued

Discussion and Conclusions

Although canyon cutting on the piedmont defines the overall trajectory of landscape evolution on the Arizona piedmont, downcutting alternated with periods of lateral cutting that created the terraces of the present landscape. Lateral cutting was accompanied by deposition of thin deposits of coarse, well-sorted gravel that protect the terrace surface from erosion. Such thin gravel deposits have the sorting and sedimentary structures of streamflood deposits, replete with bar-and-swale surface topography on young examples; they represent the channel fill of the stream that cut the terrace. Examples of older gravel deposits, of middle Pleistocene age on Cottonwood Canyon Wash, are deeply weathered and do not preserve surface topography, but can be identified by their coarse particle size and good sorting as well as being only a few meters thick. All such terraces with thin gravel deposits are predominantly erosional in origin, the product of lateral cutting during periods of stream equilibrium.

In contrast to erosional terraces, gravel in depositional terraces is thicker (as much as 20+ m) and finer grained than their erosional counterparts in the same reach. Depositional terraces and fans near the mountain front may, however, contain exceptionally large boulders and, in some cases, are well-stratified. Depositional terrace gravels are primarily distinguished by evidence for rapid, repeated deposition—such as abundant fine sediment, poor sorting, and weakly developed bedding without deep scour surfaces—as well as by thickness. Depositional terraces are evidence of stream disequilibrium, when sediment supply overwhelmed the ability of the stream to move all of its bedload downstream.

The sedimentary features in terrace gravel of piedmont tributaries east of the Santa Cruz River are consistent with deposition by ephemeral streams in an arid environment. Trask sorting coefficients are typical of streamflood deposits, as are clast clusters and imbrication. Weakly developed bedding and general absence of clast armor are typical of ephemeral stream deposits (Laronne and others, 1994). Taken together, these features indicate deposition by flash floods in ephemeral streams under a desert climate like the present. In upstream reaches, where stream power exceeds resisting power, ephemeral streams downcut their mountain catchment basins and erode sediment. In middle reaches at near-equilibrium where stream power equals resisting power, streams cut laterally and leave a lag deposit equal to the depth of scour. Most of the sediment eroded from upstream passes through the middle reaches to be deposited downstream. In downstream reaches, where resisting power exceeds stream power, braiding and aggradation take place.

Evidence for deposition by debris flows is not supported by sedimentary features or low Trask sorting coefficients, but debris flows cannot be excluded for some proximal deposits below canyon mouths. Large boulders on terrace surfaces, weak development of bedding, and abundant matrix could be interpreted as evidence for debris flows or, alternatively, deposition by catastrophic floods. Likewise, the variety of flow processes and grain-size sorting in debris flows and related deposits (Hungr, 2005; Iverson, 2003) signals caution in excluding debris flows from interpretation of deposits near canyon mouths. Further investigation of the use of Trask sorting coefficients in describing the range of debris-flow sorting is also needed.

Changes in sediment supply and stream discharge are the underlying causes of terrace cutting (Hancock and Anderson, 2002). Increased stream discharge initiates downcutting, which decreases slope and leads to lateral cutting. Increased sediment supply interrupts downcutting and causes streams to cut laterally. In an arid climate, sparse vegetation and flashy discharge combine to increase sediment supply. For the drainages studied, sediment supply was not sufficient to promote long-term aggradation. Thus, except near the mountain front, streams cut erosional terraces. Only the middle Pleistocene Josephine Canyon Wash formed a depositional terrace downstream from the mountain front.

The 18-m-thick depositional terrace of middle Pleistocene age on Josephine Canyon Wash does not have counterparts on the other tributaries studied. In comparison, the extensive middle Pleistocene terrace of Cottonwood Canyon Wash is distinctly erosional in character, measuring no more than 2–3 m thick at two localities and 6 m thick a little farther upstream. The wide expanse of both terraces suggests an extended period of lateral cutting, but the thick fill of the Josephine Canyon terrace indicates that lateral cutting was followed by aggradation. Although temporal equivalence is not implied, these two contrasting terraces of middle Pleistocene age represent different responses by adjacent drainages. After lateral cutting, the sediment load of Josephine Canyon Wash remained high compared to that of Cottonwood Canyon Wash. The explanation for contrasting responses may be differences in size and geology of the catchment areas of the drainage basins (table 1). Much of the lower part of the large catchment basin of Josephine Canyon Wash is underlain predominantly by Tertiary volcanic and volcaniclastic sedimentary rock, and the lower basin was once covered by easily eroded early Pleistocene fan alluvium. These easily eroded rocks and sediments provided the fill for the middle Pleistocene depositional terrace downstream. In contrast, hard bedrock underlies the small catchment basin of Cottonwood Canyon Wash, and no large volume of easily eroded fan alluvium accumulated near the mountain front.

On tectonically stable landscapes like the piedmont of southeastern Arizona, cycles of terrace formation may represent either climate change or piracy. On Madera Canyon Wash and Montosa Canyon Wash, stream piracy initiated terrace formation through changes in stream discharge and sediment supply. On Cottonwood Canyon Wash and Josephine Canyon Wash, only climate change could have initiated terrace formation.

Evidence that adjacent streams have different histories of downcutting and terrace formation, in response to piracy or adjustment to catchment drainages of varying size and bedrock composition, calls into question the assumption that terraces of adjacent tributaries are age equivalent. Classification of terraces according to weathering and soil development gives a general idea of age but does not establish age equivalence. Studies aimed at assessing links between terrace formation and climate change should focus on large tributaries with well-understood drainage histories.

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Appendixes

Appendix A. Pebble Lithology and Roundness Counts

Pebble lithology and shape were determined at sites where particle size and gravel thickness were measured. Pebble counts consisted of 50–100 pebbles each, 2.5–7.6 cm (1–3 in.) in long dimension. In some cases two counts of 50 pebbles each were made from different parts of an outcrop; these were combined. Global Positioning System (GPS) locations are shown for the separate counts (table A1); data are given in tables A2–A6. Lithologic categories of Lindsey and Melick (2002) were followed with minor modification. Five pebble counts from earlier work (Lindsey and Melick, 2002) were recast because the lithologic categories differed slightly from this report; the recast counts are reported again here. Pebble roundness was classified in categories A–E (angular to well-rounded) of Pettijohn (1975, his fig. 3–24). Additional details of the method are given in Lindsey and Melick (2002) and Lindsey and others (2007).

In accord with previous investigations (Lindsey and Melick, 2002; Lindsey and others, 2007), clasts in terrace gravel are mostly subangular to rounded, with large proportions of subrounded clasts (tables A2–A6). An earlier analysis of lithology versus roundness (Lindsey and others, 2007) showed correlation between the two. A reanalysis using data collected for this report also showed correlation, but gave somewhat different details (table A7). In the new analysis, granitic rocks showed a tendency to round with transport (they did not in the 2007 analysis), whereas tuff, carbonate rocks, and quartz sandstone—all minor constituents with low counts—do not (they did in the 2007 analysis). Crystal-poor ignimbrite stands out in both analyses as a major contributor to total chi-square and shows a pronounced tendency to remain angular during transport. It is by far the most durable lithology counted. Volcanic rocks with quartz are the second most important contributor to chi-square in the current analysis (they were not in the 2007 analysis), showing a strong tendency to round during transport.

Differences between the two analyses may be due to differences in (1) drainages sampled or (2) rock identification and classification. First, the analysis of Lindsey and others (2007) relied on gravel samples taken from tributaries on both sides of the Santa Cruz River, whereas the present analysis uses a larger count based on samples from only the east side of the river. Second, the various types of volcanic-rock pebbles are notoriously difficult to identify and classify consistently, and the two pebble-count studies were made six years apart. Some lithologic categories in the chi-square tables are not comparable because a few rock types were combined differently or not at all. In particular, brown sandstone (determined to be volcanic, here combined with tuff) was kept separate from quartz sandstone and carbonate rocks. For the present analysis, combination of the last two lithologies was not necessary to meet statistical requirements, because more pebbles were counted than in the 2007 study.

Table A1. Sample locations for pebble counts of terrace gravel deposited by Madera Canyon Wash and adjacent streams (designated "south" and "north"), Montosa Canyon Wash, Cottonwood Wash, and Josephine Canyon Wash, east side of Santa Cruz River, Green Valley-Tubac area, Arizona.

[Samples locations, determined by Global Positioning System, are shown in figures 1 and 2; letters A and B refer to multiple samples at same location. Age of map units: Qh, Holocene deposits; Ql, late Pleistocene deposits; Qm, middle Pleistocene deposits; Qo, early Pleistocene deposits (see fig.1 for location of map units). Locations: UTM, universal transverse Mercator; NAD27, North American Datum 1927, zone 12]

Sample number	Tributary	Age	UTM North (NAD27)	UTM East (NAD27)	Elevation (feet)
D1A	Josephine	Qh	3492820	500638	3,503
D1B	Josephine	Qh	3492820	500638	3,503
D2A	Josephine	Ql	3493050	500865	3,535
D2B	Josephine	Ql	3492918	500533	3,534
D3A	Josephine	Qm	3492956	500253	3,548
D3B	Josephine	Qm	3492840	500093	3,470
D4	Josephine	Qo	3493818	500729	3,651
D6	Josephine	Ql	3493522	502552	3,664
D7A	Josephine	Qo	3493778	503198	3,816
D7B	Josephine	Qo	3493778	503198	3,816
D8	Josephine	Qh	3492899	501354	3,502
17	Lower Montosa	Ql	3507062	496800	3,210
19	Upper Montosa	Qo	3504568	502544	3,871
D9A	Lower Montosa	Ql	3506471	496800	3,223
D9B	Lower Montosa	Ql	3506471	496800	3,223
D11	Upper Montosa	Qm	3503776	503248	3,957
D13A	Cottonwood	Qm	3501213	503188	3,863
D13B	Cottonwood	Qm	3501213	503188	3,863
13	Madera south	Ql	3513896	500361	3,090
D20A	Madera south	Qo	3512262	503452	3,404
D20B	Madera south	Qo	3512262	503452	3,404
D23	Madera south	Ql	3511655	504789	3,476
11	Madera north	Qm	3516100	511044	3,682
12	Madera north	Qm	3523650	502773	2,900
D24A	Madera north	Qm	3515309	508777	3,675
D27	Madera north	Qm	3518148	504839	3,180

Table A2. Summary of pebble counts for terrace gravel of Madera Canyon Wash and adjacent streams (includes contributions from Florida Canyon and Chino Canyon Wash), Montosa Canyon Wash, Cottonwood Canyon Wash, and Josephine Canyon Wash, east side of Santa Cruz River, Green Valley-Tubac area, Arizona. Counts converted to percent for pie diagrams of figure 7.

Lithology	Madera Canyon Wash	Montosa Canyon Wash	Cottonwood Canyon Wash	Josephine Canyon Wash	Totals
Granitic rocks	222	73	18	119	432
Gabbro and diorite	11	32	0	7	50
Crystal-poor ignimbrite	138	13	0	33	184
Volcanic sandstone and tuff	22	54	6	39	121
Volcanic rocks with quartz	146	75	62	251	534
Volcanic rocks without quartz	48	46	14	111	219
Carbonate rocks	0	40	0	0	40
Quartz sandstone	8	13	0	1	22
Vein quartz	5	2	1	0	8
Totals	**600**	**348**	**101**	**561**	**1,610**

Table A3. Lithology versus roundness for terrace gravel of Madera Canyon Wash and adjacent streams, Green Valley-Tubac area, Arizona. *A*, North part, Florida Canyon Wash plus Madera Canyon Wash (samples 11 and 12) and Madera Canyon Wash only (samples D24A and D27). *B*, South part, Chino Canyon Wash plus Madera Canyon Wash (samples 13 and D20AB), Madera Canyon Wash only (D23), and totals for all samples, both parts.

[All data are counts. Roundness values are A, angular; B, subangular; C, subrounded; D, rounded; E, well-rounded (Pettijohn, 1975, his fig. 3–24). Ql, late Pleistocene deposits; Qm, middle Pleistocene deposits; Qo, early Pleistocene deposits. Σ, lithology totals. See table A1 and figure 1 for sample locations. "AB" refers to combined sample. Counts converted to percent for pie diagrams of figure 8]

***A.* North part, Florida Canyon Wash and middle Pleistocene Madera Canyon Wash**

Lithology	Qm sample 11						Qm sample 12						Qm sample D24A						Qm sample D27					
	Roundness						Roundness						Roundness						Roundness					
	A	B	C	D	E	Σ	A	B	C	D	E	Σ	A	B	C	D	E	Σ	A	B	C	D	E	Σ
Granitic rocks	7	15	16	3	0	41	0	1	9	3	0	13	0	0	5	3	0	8	0	1	7	3	0	11
Gabbro and diorite	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0
Crystal-poor ignimbrite	2	23	13	0	0	38	0	26	35	5	0	66	0	2	6	0	0	8	0	2	4	0	0	6
Volcanic sandstone and tuff	0	0	2	2	0	4	0	0	1	3	0	4	0	0	3	2	0	5	0	0	3	1	1	5
Volcanics with quartz	0	0	0	0	0	0	0	0	0	0	0	0	0	1	16	5	2	24	0	2	17	8	2	29
Volcanics without quartz	0	1	9	1	0	11	0	0	9	4	0	13	0	0	4	0	0	4	0	0	0	0	0	0
Carbonate rocks	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Quartz sandstone	0	0	2	2	0	4	0	0	4	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0
Vein quartz	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Totals	**9**	**39**	**43**	**8**	**0**	**99**	**0**	**27**	**58**	**15**	**0**	**100**	**0**	**3**	**34**	**11**	**2**	**50**	**0**	**5**	**31**	**12**	**3**	**51**

***B.* South part, Chino Canyon Wash and Madera Canyon Wash, and all samples, both parts**

Lithology	Ql sample 13						Qo sample D20AB						Ql sample D23						All samples, both parts					
	Roundness						Roundness						Roundness						Roundness					
	A	B	C	D	E	Σ	A	B	C	D	E	Σ	A	B	C	D	E	Σ	A	B	C	D	E	Σ
Granitic rocks	0	23	51	5	0	79	0	4	33	11	0	48	0	2	12	7	1	22	7	46	133	35	1	222
Gabbro and diorite	0	1	3	1	0	5	0	0	0	1	0	1	0	1	0	1	1	3	0	2	4	4	1	11
Crystal-poor ignimbrite	0	4	3	0	0	7	0	0	0	0	0	0	0	5	8	0	0	13	2	62	69	5	0	138
Volcanic sandstone and tuff	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	0	4	0	0	11	10	1	22
Volcanics with quartz	0	2	4	0	0	6	0	2	29	12	0	43	0	1	33	10	0	44	0	8	99	35	4	146
Volcanics without quartz	0	2	0	1	0	3	0	1	3	0	0	4	0	0	4	9	0	13	0	4	29	15	0	48
Carbonate rocks	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Quartz sandstone	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	2	0	8
Vein quartz	0	0	0	0	0	0	0	3	0	0	0	3	0	2	0	0	0	2	0	5	0	0	0	5
Totals	**0**	**32**	**61**	**7**	**0**	**100**	**0**	**10**	**65**	**24**	**0**	**99**	**0**	**11**	**59**	**29**	**2**	**101**	**9**	**122**	**351**	**106**	**7**	**600**

Table A4. Lithology versus roundness for terrace gravel of Montosa Canyon Wash, Green Valley-Tubac area, Arizona.

[All data are counts. Roundness values are A, angular; B, subangular; C, subrounded; D, rounded; E, well-rounded (Pettijohn, 1975, his fig. 3–24). Ql, late Pleistocene deposits; Qm, middle Pleistocene deposits; Qo, early Pleistocene deposits. Σ, lithology totals. See table A1 and figure 1 for sample locations. “AB” refers to combined sample]

Lithology	Ql sample 17						Ql sample D9AB						Qo sample 19						Qm sample D11						All samples					
	Roundness						Roundness						Roundness						Roundness						Roundness					
	A	B	C	D	E	Σ	A	B	C	D	E	Σ	A	B	C	D	E	Σ	A	B	C	D	E	Σ	A	B	C	D	E	Σ
Granitic rocks	0	4	10	8	0	22	1	3	9	7	0	20	1	5	13	3	1	23	0	0	6	2	0	8	2	12	38	20	1	73
Gabbro and diorite	0	6	16	0	0	22	0	1	0	1	0	2	0	2	4	0	0	6	0	0	2	0	0	2	0	9	22	1	0	32
Crystal-poor ignimbrite	0	4	0	0	0	4	0	2	1	0	0	3	0	5	0	0	0	5	0	1	0	0	0	1	0	12	1	0	0	13
Volcanic sandstone and tuff	1	4	5	1	0	11	0	5	0	0	0	5	0	12	17	6	0	35	0	2	1	0	0	3	1	23	23	7	0	54
Volcanics with quartz	0	6	3	0	0	9	0	7	25	8	0	40	0	8	7	0	0	15	0	2	8	1	0	11	0	23	43	9	0	75
Volcanics without quartz	0	7	6	0	0	13	0	1	13	5	0	19	0	4	3	0	0	7	0	4	3	0	0	7	0	16	25	5	0	46
Carbonate rocks	1	7	8	0	0	16	0	2	7	2	0	11	0	2	2	0	0	4	0	6	3	0	0	9	1	17	20	2	0	40
Quartz sandstone	0	0	0	0	0	0	0	4	2	0	0	6	0	0	0	0	0	0	1	5	1	0	0	7	1	9	3	0	0	13
Vein quartz	0	2	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	2
Totals	**2**	**40**	**48**	**9**	**0**	**99**	**1**	**25**	**57**	**23**	**0**	**106**	**1**	**38**	**46**	**9**	**1**	**95**	**1**	**20**	**24**	**3**	**0**	**48**	**5**	**123**	**175**	**44**	**1**	**348**

Table A5. Lithology versus roundness for terrace gravel of Cottonwood Canyon Wash, Green Valley-Tubac area, Arizona.

[All data are counts. Roundness values are A, angular; B, subangular; C, subrounded; D, rounded; E, well-rounded (Pettijohn, 1975, his fig. 3–24). Qm, middle Pleistocene deposits. See table A1 and figure 1 for sample locations. "AB" refers to combined sample]

Lithology	Qm sample 13AB					
	Roundness					
	A	B	C	D	E	Totals
Granitic rocks	0	5	9	2	2	18
Gabbro and diorite	0	0	0	0	0	0
Crystal-poor ignimbrite	0	0	0	0	0	0
Volcanic sandstone and tuff	0	1	4	1	0	6
Volcanics with quartz	1	9	34	18	0	62
Volcanics without quartz	0	1	8	5	0	14
Carbonate rocks	0	0	0	0	0	0
Quartz sandstone	0	0	0	0	0	0
Vein quartz	0	0	1	0	0	1
Totals	**1**	**16**	**56**	**26**	**2**	**101**

Table A6. Lithology versus roundness for terrace gravel of Josephine Canyon Wash, Green Valley-Tubac area, Arizona.

[All data are counts. Roundness values are A, angular; B, subangular; C, subrounded; D, rounded; E, well-rounded (Pettijohn, 1975, his fig. 3-24). Qh, Holocene deposits; Ql, late Pleistocene deposits; Qm, middle Pleistocene deposits; Qo, early Pleistocene deposits. No vein quartz counted. Σ, lithology totals. See table A1 and figure 2 for sample locations. "AB" refers to combined sample]

Lithology	Qh sample D1AB						Qh sample D8						Ql sample D2AB						Ql sample D6					
	Roundness						Roundness						Roundness						Roundness					
	A	**B**	**C**	**D**	**E**	Σ	**A**	**B**	**C**	**D**	**E**	Σ	**A**	**B**	**C**	**D**	**E**	Σ	**A**	**B**	**C**	**D**	**E**	Σ
Granite	0	2	5	7	4	18	0	0	2	1	3	6	0	3	14	11	5	33	0	0	6	7	2	15
Gabbro and diorite	0	0	1	1	0	2	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	1	0	1
Crystal-poor ignimbrite	0	5	2	0	0	7	0	0	2	0	0	2	0	5	4	3	0	12	0	2	0	0	0	2
Volcanic sandstone and tuff	0	6	6	0	1	13	0	1	2	1	0	4	0	0	3	1	0	4	0	0	0	0	0	0
Volcanics with quartz	0	12	16	8	1	37	0	1	18	9	1	29	0	5	11	12	2	30	0	0	9	13	1	23
Volcanics without quartz	1	8	9	3	1	22	0	2	4	5	0	11	0	2	16	10	1	29	0	1	6	2	1	10
Carbonate rocks	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Quartz sandstone	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Totals	**1**	**33**	**40**	**19**	**7**	**100**	**0**	**4**	**28**	**16**	**4**	**52**	**0**	**15**	**48**	**38**	**8**	**109**	**0**	**3**	**21**	**23**	**4**	**51**

Lithology	Qm sample D3AB						Qo sample D4						Qo sample D7AB						All samples					
	Roundness						Roundness						Roundness						Roundness					
	A	**B**	**C**	**D**	**E**	Σ	**A**	**B**	**C**	**D**	**E**	Σ	**A**	**B**	**C**	**D**	**E**	Σ	**A**	**B**	**C**	**D**	**E**	Σ
Granitic rocks	0	1	7	8	4	20	0	0	1	2	0	3	0	1	10	9	4	24	0	7	45	45	22	119
Gabbro and diorite	0	0	1	2	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	5	0	7
Crystal-poor ignimbrite	0	4	2	0	0	6	0	0	1	0	0	1	0	2	1	0	0	3	0	18	12	3	0	33
Volcanic sandstone and tuff	0	4	3	1	0	8	0	2	5	0	0	7	0	0	3	0	0	3	0	13	22	3	1	39
Volcanics with quartz	0	1	24	17	4	46	0	4	22	3	1	30	0	1	28	23	4	56	0	24	128	85	14	251
Volcanics without quartz	0	4	12	3	0	19	0	3	5	2	0	10	0	1	9	0	0	10	1	21	61	25	3	111
Carbonate rocks	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Quartz sandstone	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
Totals	**0**	**14**	**49**	**31**	**8**	**102**	**0**	**9**	**34**	**7**	**1**	**51**	**0**	**5**	**51**	**32**	**8**	**96**	**1**	**83**	**271**	**166**	**40**	**561**

Table A7. Chi-square analysis of pebble lithology versus roundness, combined samples of gravel deposited by Madera Canyon Wash and adjacent streams, Montosa Canyon Wash, Cottonwood Canyon Wash, and Josephine Canyon Wash.

[Roundness classes of Pettijohn (1975, his fig. 3–24): A, angular; B, subangular; C, subrounded; D, rounded; and E, well-rounded. Degrees of freedom, 14; total χ^2, 174.773; χ^2 P-value <0.0001; G^2, 176.731; G^2 P-value, <0.0001. OBS, observed frequency; EXP, expected frequency; χ^2, Pearson chi-square value; RES, adjusted residual (values of <–1.96 and >+1.96 are significant at the 0.05 level). Vein quartz was too sparse to be included in the analysis. See Lindsey and others (2007) for discussion of statistical methods]

Lithology	**Roundness A+B**				**Roundness C**				**Roundness D+E**				**Totals**
	OBS	**EXP**	χ^2	**RES**	**OBS**	**EXP**	χ^2	**RES**	**OBS**	**EXP**	χ^2	**RES**	
Granitic rocks	79	96.54	3.19	–2.37	225	229.75	0.10	–0.54	128	105.71	4.70	2.92	432
Gabbro and diorite	11	11.17	.003	–.06	28	26.59	.08	.41	11	12.24	.13	–.41	50
Crystal-poor ignimbrite	94	41.12	68.01	9.95	82	97.86	2.57	–2.49	8	45.02	30.45	–6.75	184
Volcanic sandstone and tuff	38	27.04	4.44	2.49	60	64.35	.29	–.83	23	29.61	1.48	–1.45	121
Volcanics with quartz	65	119.33	24.74	–6.91	304	284.00	1.41	2.12	165	130.67	9.02	4.23	534
Volcanics without quartz	43	48.94	.72	–1.04	123	116.47	.37	.95	53	53.59	.01	–.10	219
Carbonate rocks	18	8.94	9.19	3.48	20	21.27	.08	–.41	2	9.79	6.20	–2.90	40
Quartz sandstone	10	4.92	5.26	2.62	10	11.70	.25	–.73	2	5.38	2.13	–1.69	22
Totals	**358**	**358**	--	--	**852**	**852**	--	--	**392**	**392**	--	--	**1,602**

Appendix B. Particle Size Data

Particle size (table B1) was estimated on vertical outcrops using a field method adapted to coarse gravel and steep outcrops that are difficult to sample by sieving. The method also works with indurated gravel. A length of 50–60 in. of tape or a 55-in. walking stick was placed vertically across the outcrop, and all particles with intercepts >0.75 in. were classified into geometric classes 0.75–1.5, 1.5–3, 3–6, 6–12, and >12 in.—and counted.[1] The procedure was repeated until about 300 in. (range of 160–360 in.) was traversed. Classification of particle size only took into account the intercept of the tape or stick where it crossed a particle—no other dimension of the particle was considered. This method gives a linear measure of apparent particle size, which is proportional to area or volume in two or three dimensions. Thus particle size classified by the particle-intercept method is an estimate of relative volume, not relative weight as estimated by sieving. Counts of each size class were then multiplied by the geometric class midpoints (for example, 1.06, 2.12, 4.24, and 8.48 in. for classes 0.75–1.5 through 6–12 in.); for particle intercepts >12 in., actual measurements of intercepts were added together. Results were totaled and subtracted from the total measured length to find the frequency of < 0.75-in. particles. Finally, all class total lengths were converted into percent and plotted as cumulative frequency distributions on a metric $\log_2$ scale.

Particle size determined by direct measurement in outcrops is not suitable for comparison with results from sieving, pending further work. In this report, direct measurements are compared with one another. No sieving was done to determine whether results from direct measurement can be converted to sieve equivalents.

Ideally, particle size was determined for the entire vertical thickness of each terrace deposit. In some cases, access limited measurement to only part of the deposit, but in most cases, particle size was determined for most of the vertical thickness of the terrace fill. For thick terrace fills, particle size was determined only in accessible locations that appeared to be representative of the entire thickness. The thickness of each deposit was estimated or measured where particle size was determined.

Sorting was calculated using the equation of Trask (Krumbein and Pettijohn, 1938) as the square root of P_{75}/P_{25} (largest quartile size divided by the smallest quartile size). Quartile measures (P_{25}, P_{50} (the median), and P_{75}) were determined from cumulative frequency distributions.

Terraces of major tributaries from Florida Canyon Wash to Josephine Canyon Wash on the east side of the Santa Cruz River were sampled. Terrace gravel of varying age was sampled within small, compact areas (table B2) within each piedmont drainage to enable comparison without the complicating influence of distance from the mountain front.

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[1] Particle size classes were determined in the English system and converted to metric (SI) units for display; English particle sizes are given in tables and shown with metric sizes on frequency curves to facilitate use by the U.S. aggregate industry, which uses the English system.

Table B1. Volumetric particle size data and statistics for terrace gravel of Madera Canyon Wash and adjacent streams, Montosa Canyon Wash, an unnamed tributary wash of the Santa Cruz River, Cottonwood Canyon Wash, and Josephine Canyon Wash, east side of Santa Cruz River, Green Valley-Tubac area, Arizona. Samples located in figures 1 and 2; A and B refer to multiple samples at same location, except D2A and D2B, which are from separate locations shown on figure 2. Local area refers to groups of samples located approximately the same distance from the mountain front on a given drainage.

[Stratigraphic units: Qh, Holocene deposits; Ql, late Pleistocene deposits; Qm, middle Pleistocene deposits; Qo, early Pleistocene deposits; QTs, Quaternary and Tertiary deposits. Locations: UTM, Universal Transverse Mercator; NAD27, North American Datum 1927, zone 12; ELEV, elevation. Distance from canyon mouth, where stream leaves the mountain front and enters the piedmont. Local areas: 1, Florida Canyon Wash; 2, Florida Canyon Wash near junction with middle Pleistocene Madera Canyon Wash; 3, present-day Madera Canyon Wash near junction with Chino Canyon Wash; 4, Madera Canyon Wash, upper piedmont; 5, Madera Canyon Wash, middle piedmont; 6, Montosa Canyon Wash, upper piedmont; 7, Montosa Canyon Wash, lower piedmont; 8, unnamed tributary of Santa Cruz river; 9, Cottonwood Canyon Wash; 10, Josephine Canyon Wash. Measures: m, meters; km, kilometers; ft, feet; in., inches; mm, millimeters. Parameters: Pct, percent; P_{25}, P_{50}, and P_{75} are percentiles; So, Trask sorting coefficient; --, no data]

Sample number	Local area	Unit	Thick-ness (m)	Dis-tance (km)	UTM North (NAD27)	UTM East (NAD27)	Elev (ft)	Pct <75 in.	Pct .75–1.5 in.	Pct 1.5–3 in.	Pct 3–6 in.	Pct 6–12 in.	Pct >12 in.	Pct >6 in.	Pct >3 in.	Pct >1.5 in.	Pct >0.75 in.	P_{25} (mm)	P_{50} (mm)	P_{75} (mm)	So	Log So
D1A	10	Qh	3.0	8.7	3492820	500638	3503	27.9	12.0	22.6	25.4	5.7	6.3	12.0	37.4	60.0	72.1	14	56	114	2.854	0.455
D1B	10	Qh	2.0	8.7	3492820	500638	3503	9.8	13.4	29.0	41.0	2.8	4.0	6.8	47.8	76.8	90.2	40	74	118	1.718	.235
D2A	10	Ql	2.0	8.4	3493050	500865	3535	12.0	12.3	27.5	28.9	14.5	4.8	19.2	48.2	75.7	88.0	40	74	136	1.844	.266
D2B	10	Ql	2.0	8.8	3492918	500533	3534	18.4	14.5	30.4	22.6	14.1	.0	14.1	36.7	67.1	81.6	27	60	116	2.073	.317
D3A	10	Qm	18.0	9.0	3492956	500253	3548	38.7	17.4	31.8	12.1	.0	.0	.0	12.1	43.9	61.3	10	32	60	2.449	.389
D3B	10	Qm	18.0	9.2	3492840	500093	3470	24.0	20.1	33.2	19.8	2.8	.0	2.8	22.6	55.8	76.0	20	44	74	1.924	.284
D4	10	Qo	2.0+	8.6	3493818	500729	3651	32.4	18.6	38.4	10.6	.0	.0	.0	10.6	49.0	67.6	12	37	62	2.273	.357
D6	10	Ql	8.0	6.7	3493522	502552	3664	4.3	19.0	35.3	33.3	8.0	.0	8.0	41.3	76.7	95.7	40	66	114	1.688	.227
D7A	10	Qo	20.0	6.0	3493778	503198	3816	11.0	17.0	42.7	26.7	2.7	.0	2.7	29.3	72.0	89.0	35	57	88	1.586	.200
D7B	10	Qo	20.0	6.7	3493778	503198	3816	11.3	25.3	39.3	21.3	2.7	.0	2.7	24.0	63.3	88.7	30	52	75	1.581	.199
D8	10	Qh	2.0	8.0	3492899	501354	3502	6.9	11.3	26.0	36.0	16.0	3.8	19.8	55.8	81.8	93.1	48	88	140	1.708	.232
19	6	Qo	9.0	2.7	3504568	502544	3871	40.7	11.1	21.7	15.8	8.7	1.9	10.6	26.4	48.1	59.3	7	35	82	3.423	.534
39	7	Ql	2.0	9.2	3505746	496167	3226	45.2	12.4	25.9	16.5	.0	.0	.0	16.5	42.4	54.8	6	26	63	3.240	.511
D9A	7	Ql	3.0	8.8	3506471	496800	3223	39.1	36.2	20.0	4.6	.0	.0	.0	4.6	24.7	60.9	12	24	38	1.780	.250
D9B	7	Ql	3.0	8.8	3506471	496800	3223	25.2	43.9	23.1	4.6	3.1	.0	3.1	7.7	30.8	74.8	19	30	48	1.589	.201
D11	6	Qm	5.0	3.2	3503776	503248	3957	12.4	19.1	29.0	19.8	19.8	.0	19.8	39.6	68.5	87.6	32	63	132	2.031	.308
D13A	9	Qm	3.0	2.6	3501213	503188	3863	17.3	20.9	24.1	18.8	18.8	.0	18.8	37.7	61.8	82.7	26	57	127	2.210	.344
D13B	9	Qm	3.0	2.6	3501213	503188	3863	1.3	17.0	28.3	32.5	17.0	4.0	21.0	53.5	81.7	98.7	47	84	142	1.738	.240
D14	9	Qm	2.0	3.6	3500568	502374	3752	7.1	28.6	29.0	18.4	17.0	.0	17.0	35.3	64.3	92.9	32	57	118	1.920	.283
D15	9	Qm	6.0	2.4	3501182	503362	3867	3.5	15.9	28.3	26.9	25.4	.0	25.4	52.3	80.6	96.5	45	83	154	1.850	.267
D16	7	Ql	8.0	7.6	3505432	497769	3320	18.4	25.4	33.4	15.4	2.6	4.8	7.4	22.8	56.2	81.6	24	46	74	1.756	.245
D18	7	Ql	4.0	7.3	3503195	498049	3340	8.8	38.2	33.2	14.1	5.7	.0	5.7	19.8	53.0	91.2	27	42	70	1.610	.207
D19	6	Ql	10.0	.5	3504002	504804	4141	12.6	14.1	27.1	29.4	11.8	5.0	16.8	46.2	73.3	87.4	36	70	130	1.900	.279
D20A	3	Qo	4.0	7.6	3512262	503452	3404	9.1	21.2	27.3	27.3	15.1	.0	15.1	42.4	69.7	90.9	34	66	125	1.917	.283

Table B1. Volumetric particle size data and statistics for terrace gravel of Madera Canyon Wash and adjacent streams, Montosa Canyon Wash, an unnamed tributary wash of the Santa Cruz River, Cottonwood Canyon Wash, and Josephine Canyon Wash, east side of Santa Cruz River, Green Valley-Tubac area, Arizona. Samples located in figures 1 and 2; A and B refer to multiple samples at same location, except D2A and D2B, which are from separate locations shown on figure 2. Local area refers to groups of samples located approximately the same distance from the mountain front on a given drainage.—Continued

[Stratigraphic units: Qh, Holocene deposits; Ql, late Pleistocene deposits; Qm, middle Pleistocene deposits; Qo, early Pleistocene deposits; QTs, Quaternary and Tertiary deposits. Locations: UTM, Universal Transverse Mercator; NAD27, North American Datum 1927, zone 12; ELEV, elevation. Distance from canyon mouth, where stream leaves the mountain front and enters the piedmont. Local areas: 1, Florida Canyon Wash; 2, Florida Canyon Wash near junction with middle Pleistocene Madera Canyon Wash; 3, present-day Madera Canyon Wash near junction with Chino Canyon Wash; 4, Madera Canyon Wash, upper piedmont; 5, Madera Canyon Wash, middle piedmont; 6, Montosa Canyon Wash, upper piedmont; 7, Montosa Canyon Wash, lower piedmont; 8, unnamed tributary of Santa Cruz river; 9, Cottonwood Canyon Wash; 10, Josephine Canyon Wash. Measures: m, meters; km, kilometers; ft, feet; in., inches; mm, millimeters. Parameters: Pct, percent; P_{25}, P_{50}, and P_{75} are percentiles; So, Trask sorting coefficient; --, no data]

Sample number	Local area	Unit	Thickness (m)	Distance (km)	UTM North (NAD27)	UTM East (NAD27)	Elev (ft)	Pct <75 in.	Pct .75–1.5 in.	Pct 1.5–3 in.	Pct 3–6 in.	Pct 6–12 in.	Pct >12 in.	Pct >6 in.	Pct >3 in.	Pct >1.5 in.	Pct >0.75 in.	P_{25} (mm)	P_{50} (mm)	P_{75} (mm)	So	Log So
D20B	3	Qo	4.0	7.6	3512262	503452	3404	17.5	11.4	28.8	33.3	9.1	.0	9.1	42.4	71.2	82.5	32	66	116	1.904	.280
D22	3	Ql	5.0	6.6	3511573	504458	3430	0.6	19.4	34.7	22.4	18.8	4.0	22.9	45.3	80.0	99.4	44	70	145	1.815	0.259
D23	3	Ql	7.0	6.3	3511655	504789	3476	.2	18.9	30.1	29.3	21.6	.0	21.6	50.9	80.9	99.8	46	78	144	1.769	.248
D24A	4	Qm	6.0	4.2	3515309	508777	3675	9.6	16.8	17.6	33.6	22.4	.0	22.4	56.0	73.6	90.4	36	90	146	2.014	.304
D24BL	4	QTs	--	--	3515277	508864	3647	19.0	14.9	25.7	32.0	8.3	.0	8.3	40.3	66.0	81.0	26	60	113	2.085	.319
D24BU	4	Qh	1.0	4.2	3515277	508864	3647	6.9	12.9	24.7	31.7	14.1	9.7	23.8	55.5	80.2	93.1	47	90	150	1.786	.252
D24C	4	Qm	8.0	4.2	3515209	508895	3680	17.2	17.0	26.8	27.5	11.6	.0	11.6	39.1	65.8	82.8	28	60	116	2.035	.309
D25A	2	Qm	5.0	4.4	3515870	510918	3682	4.2	29.4	28.9	22.4	11.8	3.3	15.1	37.5	66.3	95.8	33	59	120	1.907	.280
D25B	2	Qm	4.0	4.4	3515935	510866	3682	19.8	12.0	20.5	22.6	19.8	5.3	25.1	47.7	68.2	80.2	26	72	152	2.418	.383
D25C	2	Qm	--	4.4	3516000	510814	3681	22.7	26.9	22.1	14.1	14.1	.0	14.1	28.3	50.4	77.3	21	38	93	2.104	.323
D26	1	Ql	1.0	10.0	3520299	506257	3194	4.8	20.5	29.7	28.7	16.4	.0	16.4	45.1	74.8	95.2	38	70	130	1.850	.267
D27	5	Qm	4.0	9.0	3518148	504839	3180	19.3	33.0	26.5	18.8	2.4	.0	2.4	21.2	47.7	80.7	23	36	70	1.745	.242
D28	5	Qm	3.0	9.0	3517390	504114	3172	9.0	36.2	31.8	19.4	3.5	.0	3.5	23.0	54.8	91.0	27	44	74	1.656	.219
D29	8	Qm	2.0	6.8	3501535	498673	3430	15.9	38.2	23.3	19.8	2.8	.0	2.8	22.6	45.9	84.1	24	36	72	1.732	.239

Table B2. Classification of particle size samples by local area and stratigraphic unit, terrace gravel of Madera Canyon Wash and adjacent streams, Montosa Canyon Wash, unnamed tributary wash, Cottonwood Canyon Wash, and Josephine Canyon Wash, east side of Santa Cruz River, Green Valley-Tubac area, Arizona.

[Stratigraphic units: Qh, Holocene deposits; Ql, late Pleistocene deposits; Qm, middle Pleistocene deposits; Qo, early Pleistocene deposits; QTs, Quaternary and Tertiary deposits]

Local area	Stratigraphic unit					Totals
	Qh	Ql	Qm	Qo	QTs	
1, Florida Canyon Wash	0	1	0	0	0	1
2, Madera-Florida Canyon junction	0	0	3	0	0	3
3, Madera Canyon Wash, present course	0	2	0	2	0	4
4, Madera Canyon Wash, upper piedmont	1	0	2	0	1	4
5, Madera Canyon Wash, lower piedmont	0	0	2	0	0	2
6, Montosa Canyon Wash, upper piedmont	0	1	1	1	0	3
7, Montosa Canyon Wash, lower piedmont	0	5	0	0	0	5
8, Unnamed tributary wash	0	0	1	0	0	1
9, Cottonwood Canyon Wash	0	0	4	0	0	4
10, Josephine Canyon Wash	3	3	2	3	0	11
Totals	**4**	**12**	**15**	**6**	**1**	**38**

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Lindsey and Van Gosen—**Processes of Terrace Formation on the Piedmont of the Santa Cruz River Valley**—Scientific Investigations Report 2010–5028

ARCHAEOLOGY IN TUCSON

Vol. 9, No. 4 Newsletter of the Center for Desert Archaeology Fall 1995

A Thousand Years of Irrigation in Tucson

by Jonathan B. Mabry and J. Homer Thiel, Center for Desert Archaeology

View of Tucson from Sentinel Peak ("A" Mountain) during the late nineteenth century. The Santa Cruz River flowed year-round between irrigated fields on both sides of the floodplain. The river became entrenched by the 1890s due to a combination of human and natural factors, making gravity irrigation no longer possible. Left of center are the adobe ruins of the San Agustin mission visita (photo no. 12649 courtesy of the Arizona Historical Society).

Historical photographs, newspaper accounts, and the memories of town elders tell us that the Santa Cruz River flowed through Tucson year-round across a wide floodplain that held irrigated fields of wheat, alfalfa, cotton, and vegetables as recently as 100 years ago. These same sources describe how, at the turn of the century, a combination of ill-designed diversion ditches, a declining water table due to overgrazing and over-pumping, and a series of unusually large floods resulted in the entrenched riverbed we see today.

Based on recent archaeological evidence, we now know that this also represented the end of at least a thousand years of continuous irrigated agriculture in the middle Santa Cruz Valley. Over the last two decades—but mostly within the last year—Archaeologists working in the floodplain of the Santa Cruz River in Tucson have found many preserved remnants of prehistoric and historic canals. From this new archaeological evidence, combined with the documentary record, the full history of irrigation and agriculture in Tucson is beginning to emerge.

Early Flood Farming

Archaeological remains of early villages buried in the historic floodplain, recently uncovered by Desert Archaeology, Inc. (DAI), indicate that "flood farming" was practiced along the banks of the Santa Cruz River by at least 800 B.C. (see 1994 *Archaeology in Tucson,* Vol. 8, Nos. 1 ,3, and 4). The geological contexts of these sites, and the plant remains recovered from them, reveal that fields of maize, and probably squash, beans, and tobacco, were watered by overbank floods during the summer monsoons. Because the predictable annual floods also deposited fresh silt, and because the intervening dry season allowed the water table to subside, no fallow cycle (a temporary abandonment of fields) was necessary to prevent salinization and restore soil fertility.

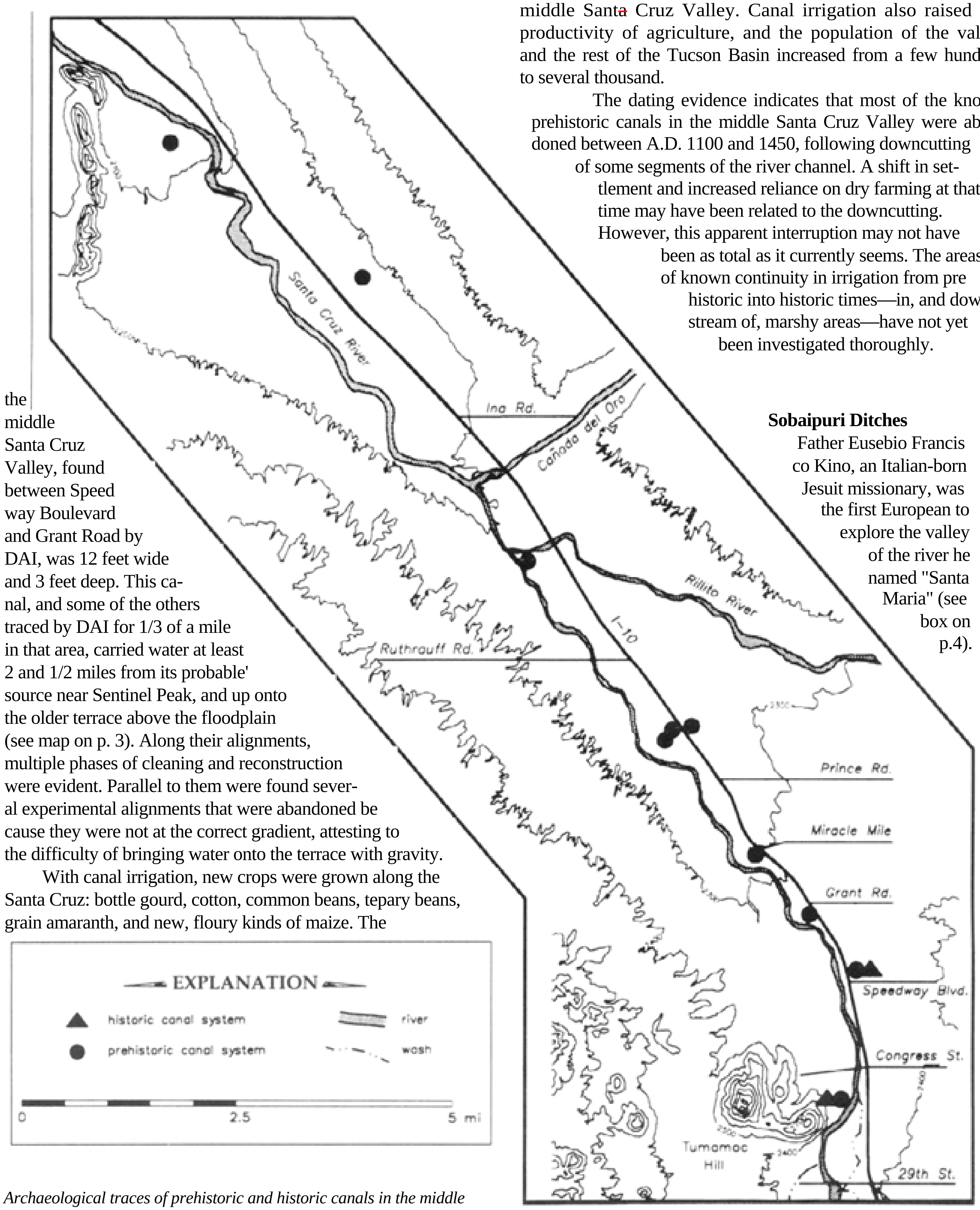
Hohokam Canals

After almost 2,000 years of flood farming in this manner, the first canals were built in the Santa Cruz floodplain. A canal found recently by Statistical Research, Inc., may date to before A.D. 750, making it the earliest known canal in the Tucson Basin. However, based on prehistoric sherds contained in canal sediments and radiocarbon dates of charcoal inclusions, most of the currently known prehistoric canals in the middle Santa Cruz Valley (see map on p. 2) were constructed between about A.D. 950 and 1100—coinciding with the peak period of Hohokam canal building in the Phoenix Basin.

Contrary to what archaeologists had predicted, all the prehistoric canals of the Santa Cruz Valley were not short, shallow ditches. Some were as large as some of the major Hohokam canals in the Phoenix Basin, and rivaled them in their skillful engineering. The largest known prehistoric canal in the middle Santa Cruz Valley, found between Speedway Boulevard and Grant Road by DAI, was 12 feet wide and 3 feet deep. This canal, and some of the others traced by DAI for 1/3 of a mile in that area, carried water at least 2 and 1/2 miles from its probable' source near Sentinel Peak, and up onto the older terrace above the floodplain (see map on p. 3). Along their alignments, multiple phases of cleaning and reconstruction were evident. Parallel to them were found several experimental alignments that were abandoned because they were not at the correct gradient, attesting to the difficulty of bringing water onto the terrace with gravity.

With canal irrigation, new crops were grown along the Santa Cruz: bottle gourd, cotton, common beans, tepary beans, grain amaranth, and new, floury kinds of maize. The lack of salt accumulation in irrigated soils in the Phoenix Basin indicates that a fallow cycle was practiced by the Hohokam in that region, and suggests that it was also practiced in the middle Santa Cruz Valley. Canal irrigation also raised the productivity of agriculture, and the population of the valley and the rest of the Tucson Basin increased from a few hundred to several thousand.

The dating evidence indicates that most of the known prehistoric canals in the middle Santa Cruz Valley were abandoned between A.D. 1100 and 1450, following downcutting of some segments of the river channel. A shift in settlement and increased reliance on dry farming at that time may have been related to the downcutting. However, this apparent interruption may not have been as total as it currently seems. The areas of known continuity in irrigation from prehistoric into historic times—in, and downstream of, marshy areas—have not yet been investigated thoroughly.



Archaeological traces of prehistoric and historic canals in the middle Santa Cruz Valley (map by Catherine Gilman and Geo-Map, Inc.).

Sobaipuri Ditches

Father Eusebio Francisco Kino, an Italian-born Jesuit missionary, was the first European to explore the valley of the river he named "Santa Maria" (see box on p.4).

During his first visit in 1692, Kino found Piman-speaking Sobaipuri people at the village of Bac south of Martinez Hill, and the following year, at the village of Tucson near the foot of Sentinel Peak. The basalt dikes formed by these volcanic hills forced the underground flow to the surface to create marshes ("cienegas" in Spanish) that were ideal for shallow ditches intercepting the high water tables. Springs in the marshes were also tapped, and downstream, where the river flowed on the surface, water was diverted by brush weirs into canals. Between Sentinel Peak and the Rillito, on the east bank of the river, the inhabitants of the village of Oiaur also irrigated crops in the floodplain.

These irrigated oases supported sizeable populations. On November 23, 1697, the Spanish explorer Captain Juan Mateo Manje, traveling with Father Kino, described the scene in his diary: "…after going six leagues, we came to the settlement of San Agustin del Oiaur. . . Here the river runs a full flow of water, though the horses forded it without difficulty. There are good pasture and agricultural lands with a canal for irrigation." He counted 750 people in 186 houses, and at San Xavier, another 830 inhabitants subsisting from irrigated fields. In 1699, Father Kino described the irrigated agriculture at San Xavier (and exaggerated its potential): "The fields and lands for sowing were so extensive and supplied with so many irrigation ditches running along the ground that… they were sufficient for another city like Mexico."

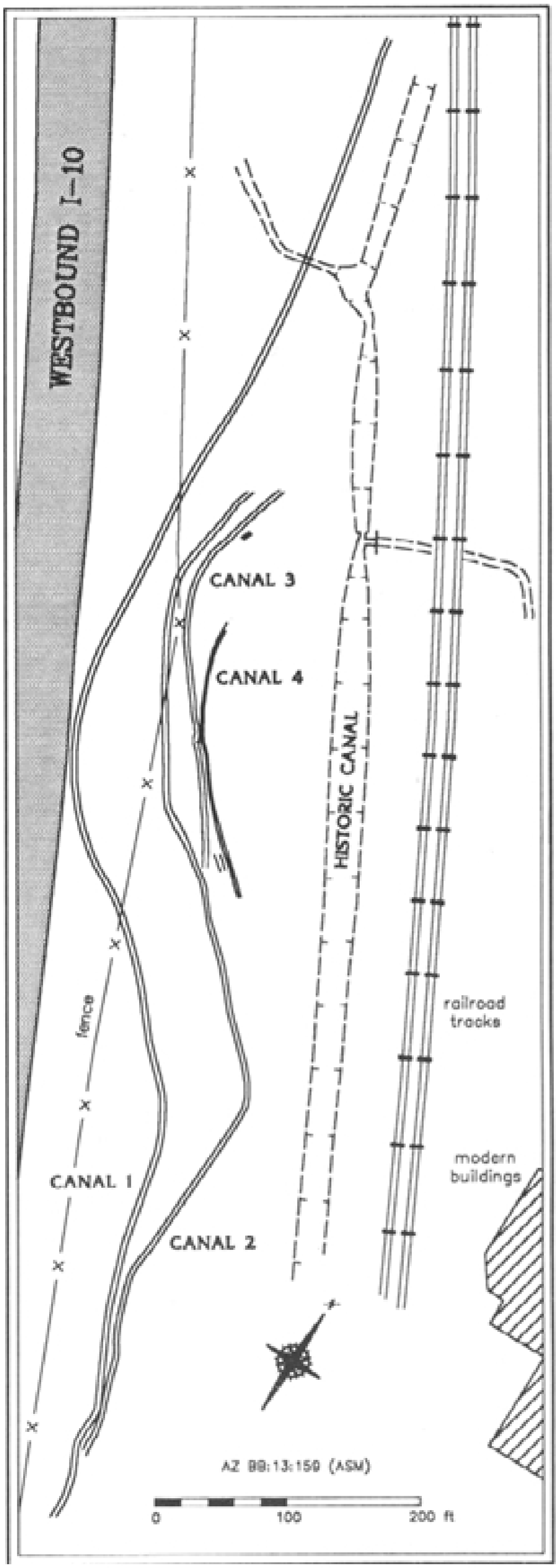
Spanish Acequias

Father Kino introduced wheat and cattle to the village of Bac by 1695, and after he established a mission there in 1701, Jesuit missionaries introduced other Old World crops and livestock, such as barley, peaches, and sheep, to complement the native summer crops and wild food resources of the Sobaipuri and Papago (now known as the Tohono O'odham). The initial church site at San Xavier was adjacent to an existing canal ("acequia" in Spanish). Irrigation was also practiced in the floodplain between the mission and the Rillito.

In 1757, in the wake of Piman revolts and Apache raids, the priest and colonial soldiers at San Xavier attempted to move the mission to a more defensive position at San Cosme (the first Spanish name for Tucson). Malaria and an Indian attack soon forced them to retreat to San Xavier, however. Although the mission at San Cosme had no resident priest after its first few months, and thereafter was only a visita of San Xavier, a fortified residence and a small chapel built there in 1771 and 1772 were the first European-style structures built within the boundaries of modern Tucson (see photo on p. 4).

In addition to the irrigated gardens and orchards within the grounds of the Tucson visita, the Sobaipuris and Papagos living in the vicinity also irrigated fields on the river's west side. After the garrison of the presidio at Tubac was transferred to the east side of the river in 1775, where downtown Tucson is today, the eastern floodplain was also irrigated by Spanish settlers. Increasing competition for the water of the Rio Santa Maria led to a 1776 agreement that guaranteed threefourths for the Indian villages and one-fourth for the presidio. In the 1790s, however, the Indians' share was reduced to one-half.

Gerónimo de la Rocha's 1780 map of the Pimería Alta shows, south of the mission visita at "Tucson" and the new Tucson presidio, a dam diverting water from the river into an acequia through the mission visita. The historic canals found by DAI near the foot of Sentinel Peak (see map on p. 2) may include some of the acequias built near the San Agustin mission in the late eighteenth century.



Prehistoric canals, probably built in the eleventh century ,traced for a third of a mile between Speedway Blvd. and Grant Rd. On the east side I-10. The "East Side Canal," built in 1895-96, follows the same alignment on the edge of the terrace above the floodplain (map by Geo-Map, Inc.)

A woman washing clothes in the Santa Cruz River below the ruin of the Convento of the San Agustin mission visita, 1894 (photo no. 21969 courtesy of the Arizona Historical Society).

A Sonoran Irrigation Community

After Mexico gained independence from Spain in 1821, and new settlers began to arrive from the south, the traditional Sonoran system of irrigated agriculture was established in Tucson. Mediterranean winter crops of wheat, barley, chick-peas, lentils, onions, and garlic followed the native summer crops of corn, beans, squash, pumpkins, chili peppers, tobacco, and cotton. The three "acequias madres" (mother canals) were maintained as common property by a "común de agua" (irrigator community), and an elected "zanjero" (overseer) supervised water distribution. The irrigation schedule was flexible, with water turns arranged according to varying crop needs, and water shortages were shared proportionally. First use of water was reserved for fields south of the "hospital road" (later St. Mary's Road), while fields to the north were irrigated only during relatively wet years. This northern area grew hay and was used as pasturage for cattle. The canal alignments, field boundaries, and property lines of this traditional irrigation system are recorded on a map surveyed during the Civil War for Colonel David Fergusson of the United States Army (see map on p. 5).

Mexican rancheros irrigated cattle pastures in the valley south of Tucson. In 1849 Jose Maria Martinez, former comandante of the Tucson presidio and a famous Apache fighter, cleared land east of San Xavier, on the west side of the river, and cut a ditch to the spring called "Punta de Agua." The Acequia de Punta de Agua irrigated his field west of what came to be known as "Martinez Hill," and the "Agua de la Misión" acequia irrigated fields of the Papagos at the mission.

Anglo forty-niners passing through on their way to the California gold fields described the farmlands near Tucson and San Xavier as "rich and fertile to the extreme." In 1852, John Russell Bartlett, conducting a survey of the new border after the Mexican-American War, was impressed by the scene that greeted him in Tucson: "irrigating canals in every direction, the lines of which are marked by rows of cottonwoods and willows, presenting an agreeable landscape."

Anglo Water Development Schemes

The 1854 Gadsden Purchase opened the territory south of the Gila River to Americans, and newly arriving "Anglos" impounded the river at several points to provide heads of water to power flour mills. Agriculture was the next focus of Anglo attempts to profit from water development (though Hispanic businessmen were also partners). In the early 1880s, Samuel Hughes, W. C. Davis, and Leopoldo Carillo purchased floodplain land upstream of the traditional fields. They cleared them for new fields and excavated deep ditches to increase the water supply to the vegetable gardens of their tenants, mostly Chinese who had arrived as railroad workers in 1880.

The impounding of water in reservoirs and the increased water use by the upstream entrepreneurs diminished the supply to the downstream Mexican-American farmers, who fought for their water rights in court. However, the defendants defeated the 1884-1885 court challenge by citing the western U.S. water law of “prior appropriation” as superceding local

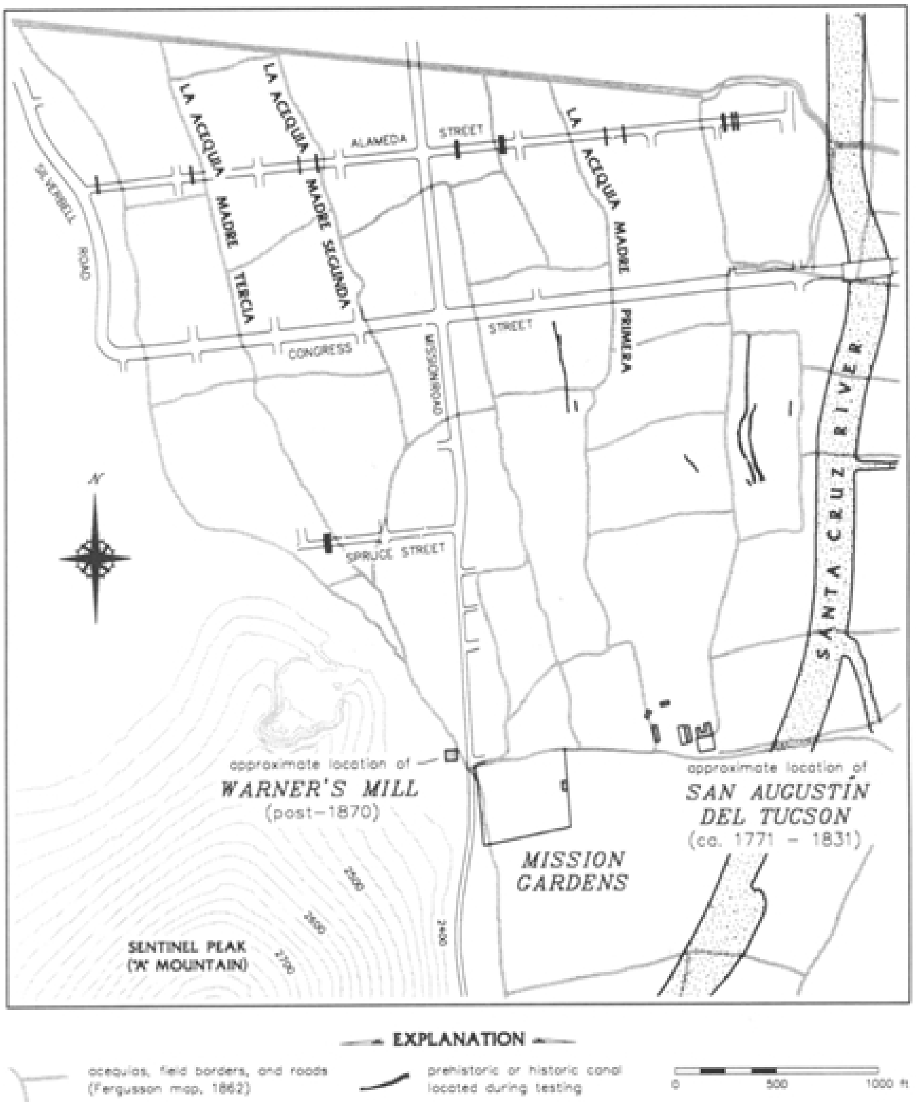
The Changing Names of Tucson and the Santa Cruz River

At the time of Spanish contact in the late seventeenth century, the Piman name for the small settlement at Tucson was *schookson* or *schook-shon,* meaning "at the foot of the black [?]." "Tucson" became the Spanish written form. Many contemporary scholars and Piman speakers believe the name referred to the black volcanic hill known historically as Sierra de la Frente Negra, Sentinel Peak, and Warner's Hill, and known today as "A" Mountain.

On his 1695-1696 map of northwestern New Spain, Father Kino labeled the closely spaced villages of Bac, Tucson, and Oiaur in the middle Santa Cruz Valley as "San Xavier," "San Cosme," and "San Agustín." In his diaries and letters he usually combined the Spanish and Piman names (San Xavier del Bac, San Cosme de Tucson, San Agustin de Oiaur), During the Spanish period, the mission visita at Tucson changed names several times, being referred to as "San Cosme" from the 1690s through the 1750s, "San Jose" in the 1760s, and "San Agustín" from the 1770s until 1831, when it was abandoned.

Kino named the Río Santa María after the patron saint he had assigned to the village of Soamca near its headwaters. The Santa Cruz River acquired its modern name gradually after 1787, when the presidio of Santa Cruz de Terrenate was relocated from the upper San Pedro Valley to Soamca.

customs (the defendants had purchased some of the oldest fields in the valley). This ruling represented the beginning of the end of the traditional system of irrigated agriculture in the Santa Cruz Valley.



Historic canals (acequias) built during the Spanish and Mexican periods in the floodplain near "A" Mountain. Below the surface, archaeologists have found canals near the alignments shown on a Civil War-era map (map by Geo-Map,Inc.)

In place of the irrigation community, corporations competed for the river's water. By 1891, in addition to the three old ditches (then called the El Cumoso, Misional, and Del Rey acequias), 33 other ditches comprising a total length of 56 miles had been constructed in the Santa Cruz floodplain by corporate enterprises. During this swirl of land speculation and water development schemes in the late nineteenth century, the current form of the Santa Cruz River, a dry bed up to 20 feet below the top of the banks, was created by a combination of human error and natural disasters.

Attempting to increase the water supply to his fields north of the hospital road, Sam Hughes constructed a new, deep ditch in 1887 to intercept the subsurface flow. Large floods during the next four years caused the ditch to downcut to the water table lowered by drought and overgrazing, and caused the headcut to erode rapidly southward. Steady progression of the headcut and the channel's increasing width were reported with alarm in the newspaper. By 1910 the headcut coalesced with another downcut segment near San Xavier, resulting in the deeply incised river channel of today. The effect on irrigated agriculture was disastrous: the downcutting of the main channel stranded canal intakes above the river, and other flood channels severely damaged canals.

In 1891, Frank and Warren Allison began work to repair the irrigation system on the west side of the river. They built a new reservoir near the old Warner Dam site and a ditch that extended north to Stevens Avenue (later Congress Street) by 1895 (see photo on p. 6). At first the project was a success, but soon their 1,160 acres of fields were accumulating crop-damaging salts from intensive, uninterrupted irrigation. The unlined, 12-foot-wide historic canal on the east side of 1-10 north of Speedway Boulevard, recently investigated by DAI (see map on p. 3), is probably a remnant of the "East Side Canal" constructed by the Allisons in 1895-1896 after much of their land on the west side became too salinized for agriculture. From their new 10- to 15-ft-deep artesian wells at the foot of Sentinel Peak, the brothers built a flume that carried water across the river to the east bank. The water in this five-mile-long canal powered a new flour mill just north of what is now Speedway Boulevard. It then irrigated their land to the north, which they called "Flowing Wells" after a new source of water they located there. The Tucson Canal Company, incorporated in 1896, financed construction of a canal south of the Allisons', tapping a source near the San Xavier mission.

In 1902 the Allisons sold their property to Levi Manning, a surveyor and businessman who became Tucson's mayor in 1905. He further developed the well field below Sentinel Peak, drilling new wells to tap the now 20-ft-deep subsurface flow of the river. The East Side Canal soon became known as “Manning's Ditch." By 1910, four main canals fed by Manning's wells were irrigating the floodplain west of Tucson.

A group of Chicago and British investors bought part of Manning's land in 1911. Upstream of Manning's Ditch, they developed the "Crosscut"—a line of 19 new wells across the floodplain, ranging from 45 to 150 feet deep and connected underground by a horizontal shaft. Calling themselves the Tucson Farms Company, they also installed electric pumps; replaced the old flume across the river with a 4-foot-diameter concrete siphon below the riverbed; extended Manning's Ditch to a total length of seven miles; lined some canal segments

The Allison brothers' West Side Canal was built in the early 1890s to revive irrigated agriculture after the river became entrenched (photo 110. 4250 courtesy of the Arizona Historical Society).

with cement; and added reinforced concrete headgates, drop structures, and lateral turnouts. The company peddled the land to Midwestern farmers for $200 to $300 an acre, but it was not a financial success. In 1922 a group of farmers formed the Flowing Wells Irrigation District and assumed control of the Crosscut and distribution system. A large flood in 1940 destroyed most of these waterworks, bringing an end to irrigation in the middle Santa Cruz Valley near Tucson.

Conclusion

The long history of irrigation in the middle Santa Cruz Valley includes both impressive achievements and disastrous mistakes. By constructing canals on the older terrace above the floodplain, prehistoric and historic hydraulic engineers were able to maximize the irrigated area. There was continuity in irrigation from prehistoric into historic times in, and downstream of, the marshy cienegas near Point of Mountain, Sentinel Peak, and Martinez Hill, and nineteenth-century canals often followed the same alignments as eleventh-century ones. The scale of some of the prehistoric canals, and their multiple phases of construction and repair, represent significant labor investments over many centuries. The several superimposed channels along each alignment of the prehistoric canals, and the high berms composed of sediments dredged from historic canals, indicate that siltation was a constant problem requiring frequent canal cleaning.

Although Sonoran farmers, and probably their Hohokam and Sobaipuri predecessors, practiced a fallow cycle to prevent salinization, waterlogging, and loss of soil fertility, early Anglo farmers often irrigated intensively without interruption, forcing them to abandon fields after only a few years. By impounding the river to run mills, and by deepening ditches to increase water supplies, nineteenth-century entrepreneurs doomed the traditional system of agriculture and triggered downcutting that permanently ruined the floodplain's potential for gravity irrigation. Today, the perennial river and the rich agricultural lands it irrigated for at least 1,000 years are only recorded in archaeological remains, faded newspapers and photographs, and the memories of Tucson's oldest citizens.

Acknowledgments

Prehistoric canals near Tucson have previously been discovered by the Arizona State Museum, and are currently being investigated by Desert Archaeology, Inc., and Statistical Research, Inc. Information from researchers at those institutions benefited the authors. Historical irrigation in this area is intertwined with social and economic history, and this article also relies on the research of leading local historians, including: Bernard L. Fontana, Charles W. Polzer, James E. Officer, Thomas E. Sheridan, and Jack Williams. Julio L. Betancourt and Raymond M. Turner have documented the historical changes in the Santa Cruz River. They and Douglas Kupel have also researched historic water control along the river. The published works of these individuals can be found in the University of Arizona library.

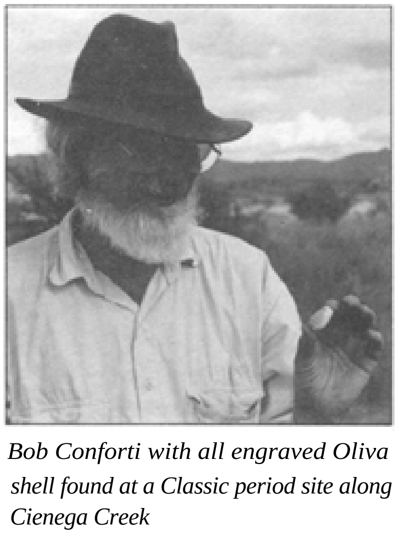
Cienega Valley Survey Update

by Michelle Stevens, Center for Desert Archaeology

The Cienega Valley Survey is being conducted by the Center for Desert Archaeology along Cienega Creek southeast of Tucson. Two principal areas are being investigated: Pima County's Cienega Creek Natural Preserve and BLM's Empire-Cienega Resource Area. Both areas have relatively lush riparian habitats, but the Empire-Cienega Resource Area, being at a higher elevation, also has extensive grasslands.

Since the project began earlier this year, 34 volunteers have surveyed about 3,600 acres. Sixty-two new sites have been recorded, and 18 previously recorded sites have been revisited. Although all of the collected artifacts have not yet been analyzed, preliminary analyses indicate Archaic through Historic period sites are present.

One of the research objectives of this project is to study land-use and settlement patterns during the Archaic and early ceramic periods. Since several deeply buried Archaic sites are already known in this area, a goal of the first field season was to assess the area's potential for yielding Archaic period surface sites. The discovery of several "new" Archaic sites on the surface is encouraging, and confirms our expectations of the area's potential.



Bob Conforti with all engraved Oliva shell found at a Classic period site along Cienega Creek

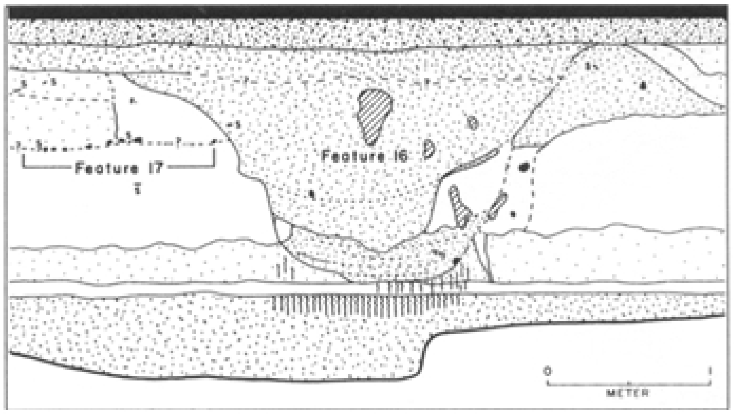
Although about half of the Cienega Creek County Preserve has been surveyed, we are spending most of this season surveying in the largely unexplored Empire-Cienega Resource Area. If you are a current AIT member and want to volunteer, please call Irina at 881-2244 to sign up for a specific date. To become a member, see page 8. Upcoming survey dates are Sunday, November 19; Saturday, December 2; and Sunday, December 17 (8 a.m. to 5 p.m).

CANAL GEOMORPHOLOGY

Reading the Stories of Ancient Canals

by Andrea K. L. Freeman, Center for Desert Archaeology

Geomorphology is the study of the characteristics, origin, and development of landforms. Since a canal is a landform very similar to a river, canal geomorphology is very much like river geomorphology. Geologists who study rivers are interested in understanding how rivers are formed, how they maintain their channels, and what factors change the shape or direction of the river channel. Canals differ from rivers because they are produced, maintained, and abandoned by people; however, their similarities allow archaeologists to use geology as a tool for understanding ancient irrigation systems.



Cross-section of a buried prehistoric canal found on the west side of the Santa Cruz River beneath Alameda Street. The U-shaped profile and mineral stains below are common characteristics of prehistoric canals in the Sonoran Desert.

Shape and Size

Canal shape can indicate the use of a canal segment and sometimes the age of the canal. Prehistoric canals are usually U-shaped in cross-section. Although some historic canals, particularly smaller distribution canals, have a U-shaped cross-section, most main canals built during the historic period are trapezoidal. Historic canals are usually wider and deeper than prehistoric canals, and the width-to-depth ratio is usually much larger.

These wider canals were more efficient, and represent improvements in canal engineering unfamiliar to prehistoric canal builders. Canal size, shape, and number can also provide information about the magnitude of past agricultural systems. Canal size, shape, and slope are critical factors for estimating the amount of water that can be delivered by a canal system, which determines how much land can be irrigated.

Sediments and Stratigraphy

The sediments found within canals usually conform to the overall shape of the canal. Sediments filling a U-shaped canal will take on a "U" shape, and sediments filling a trapezoidal canal will tend to be more horizontal. These sediments are influenced by the river from which 'the canal draws water, and the speed with which that water enters the canal system.

When water is initially drawn from a river, it enters the canal rapidly. Only the larger particles will settle to the bottom, so coarse sands and gravels are usually deposited in canals when they are first used. Slow or stagnant water, characteristic of infrequently used or abandoned canals, will allow finer particles, like clay and silt, to settle to the bottom. These sediments are often removed during canal maintenance, so the sediments that we see often represent only the last use of the canal. The types of sediment found in canals can help archaeologists understand whether the people using them were successful at building and maintaining efficient canals.

The geomorphic context of canal placement can also offer useful information about human decision making. For example, in our study of historic acequias along Alameda Street, we discovered that many of the historic canals were excavated into former channels of the Santa Cruz River. These ancient channels provided topographic depressions into which canals could be built with considerably less effort.

Minerals

Stains from the oxidation of iron and manganese minerals are often found at the base of canals. Their presence indicates waterlogged conditions where water is stagnant, plant growth is present, and no fresh, oxygenated water is entering the system. These conditions are often characterized by dark, clayey deposits; red or orange "rust-like" stains from mineral oxidation; and small, black nodules of manganese or iron.

Changes in the agricultural use of the land and the frequency of canal use may have created the ideal conditions for these minerals to accumulate. Historic accounts of land use west of the Santa Cruz River suggest that certain crops required less irrigation than others. Political disputes over water rights affected the availability of water to parts of the canal system, and also influenced the effort made to maintain canals that were not in use. Since lower water applications and canal abandonments would lead to stagnant water and plant growth, the presence of iron and manganese deposits at the base of canals may mark periods characterized by changes in land use and political conditions.

Shells

Shells of freshwater mollusks (gastropods) and smaller "ostracodes" can provide information about canal siltation and water salinity. The presence of the shells of these animals marks the silting up of a canal. As the flow rate decreases and salt content increases with evaporation, species adapted to higher salinity appear in the sediments.

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ADDRESS CORRECTION REQUESTED

An engraved Oliva shell was recently found at a Classic period site along Cienega Creek (see survey update on page 6).

Time to Renew?

If your address label indicates that your *Archaeology in Tucson* membership has expired, please renew promptly to remain eligible for all activities, newsletters, and discounts on T-shirts and Center for Desert Archaeology publications.

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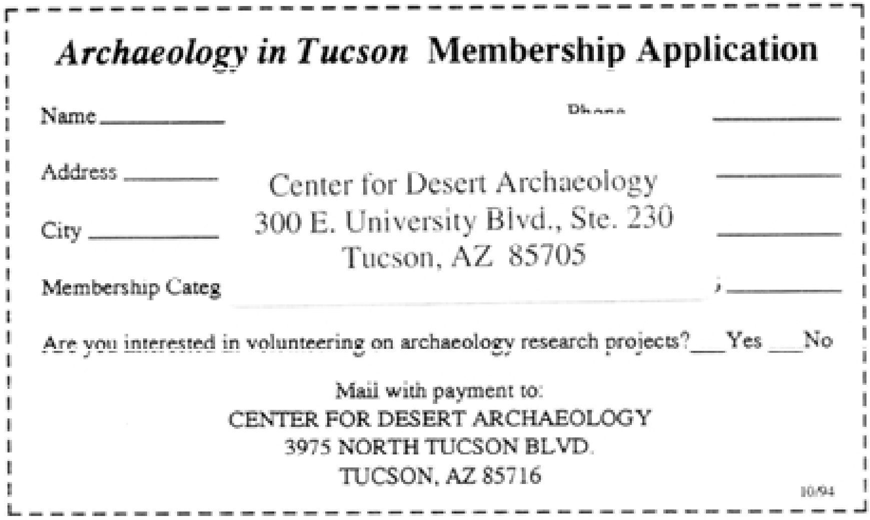

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“SEDIMENT-MORPHOLOGY RELATIONS OF ALUVIAL CHANNELS”

WAITE R. OSTERKAMP

188-199

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12

SEDIMENT-MORPHOLOGY RELATIONS OF ALLUVIAL CHANNELS

By Waite R. Osterkamp[1,2]

ABSTRACT

The interpretation of numerous data collected from alluvial stream channels of the western United States suggests that discharge characteristics are the principal control of channel size, but that sediment characteristics largely determine channel shape. For streams of similar discharge, narrowest channels occur when the sediment load is entirely silt and clay. Channel widths increase with the tractive movement of sand, reaching a maximum in streams that transport only medium- to coarse-grained sand. When the median-particle size of channel material is coarser than sand, the bed and banks are protected and stabilized by armoring, and the resulting channels are narrow.

For the general power function

$$W = a\overline{Q}^b$$

relating width (W) to mean discharge $(\overline{Q})$, the value of the exponent (b) appears to vary with the tractive sediment load of the stream. The lowest value of b, about 0.45, is associated with silt-clay bed channels in which essentially no sediment is moved by traction. The exponent increases to about 1.0 for some braided stream channels in which large amounts of sediment are moved tractively. With increasing armoring of a channel, the value of b decreases, reaching a minimum of about 0.50 for highly turbulent alpine streams that have very low sediment discharge.

BACKGROUND AND PURPOSE

During the last decade, personnel of the U.S. Geological Survey in Kansas have conducted a series of studies to develop empirical relations among discharge characteristics and geometry variables of alluvial stream channels. Data have been collected from hundreds of gage sites throughout the western United States. These data represent conditions ranging from highly ephemeral (discharge no more than 1 percent of the time) stream channels of the Southwest to large streams of the Midwest, such as the Missouri River. In recent years, attention has been concentrated on the formational processes of specific types of stream channels. Geometry-discharge relations have been studied to determine the effects of channel-sediment properties, discharge variability and regulation (in cooperation with the Kansas Water Resources Board), and channel modification (in cooperation with the U.S. Army Corps of Engineers). Reports describing limited parts of these investigations are in various stages of preparation or publication. This paper has been prepared to integrate information from these reports and to give an initial interpretation of the geomorphic dynamics of fluvial systems, with emphasis on the control of sediment properties on the shape and pattern of alluvial channels.

The generalizations presented in this paper are based on width-discharge and width-sediment-discharge relations developed for other studies. Data supporting the relations are given as cited, but several specific examples are described to justify the ideas proposed here. The purpose of this paper, therefore, is to suggest and support several principal generalizations concerning the morphology of natural alluvial stream channels. The generalizations that emphasize the effects of fluvial sediment on the size and shape of alluvial channels are summarized by the following:

1. A minimum channel width is defined by the amount and variability of the discharges conveyed, but it is modified by the availability and transport of specific sediment sizes that form and maintain stable alluvial banks.
2. For streams of similar discharge characteristics, a maximum bed or channel width is defined by the amount and percentage of medium- and coarse-grained sand in the total sediment load.
3. The manner in which the shape of an alluvial channel changes in the downstream direction largely is a function of discharge variability, availability of sediment for transport, and the particle-size distributions of the sediment transported.

MEASUREMENT OF CHANNEL VARIABLES

The study of fluvial processes has proven to be among the most complex and difficult topics of geomorphology because of the number of variables involved, the inconsistent or nonlinear interrelations among those variables, and the lack of suitable methods to quantify some of those variables. The effects of fluvial sediment can be recognized and quantified, although it is still unclear which variables of sediment discharge are the best descriptors.

It is reasonable to assume that only two independent variables determine the size and shape of natural stream channels--climate and geology. Divisions or results of these two primary variables pertinent to alluvial channels are the characteristics of precipitation, temperature, soils, topography, and vegetation. Except for temperature, which probably is of minor consequence, these secondary variables are nearly as difficult to quantify as the primary variables. Realistic quantification appears feasible only by a tertiary breakdown. Although tertiary variables can be treated as independent in the study of fluvial systems, it is obvious that they are not independent in nature but depend on both climate and geology. Pertinent tertiary variables include:

1. Total or mean discharge,
2. Variability of discharge,
3. Temporal distribution of discharge (particularly seasonal distribution and elapsed time since the last erosive flood event),
4. Amount of sediment discharge (mean concentration),
5. Size distribution of sediment,
6. Temporal changes in availability and size distribution of sediment,
7. Type of riparian vegetation, and
8. Maturity of the riparian community.

---

[1] Hydrologist, U.S. Geological Survey, WRD, Lawrence, Kans.

[2] Non-member advisor of Task Committee on Relationship Between Morphology of Small Streams and Sediment Yield, Hydraulics Division, ASCE.

The variables of discharge (1-3) are primarily determinants of channel size or cross-sectional area. The sediment variables (4-6) are determinants of channel shape and are treated as complicating variables of geometry-discharge relations. The variables of riparian vegetation (7-8) help determine both channel size and shape. Suitable methods of quantifying the effects of riparian vegetation are not yet available, and they will be discussed only briefly. Other variables, such as temperature and water chemistry, no doubt influence geometry-discharge relations, but their effects appear to be minor relative to those of sediment.

Geometry-discharge relations of alluvial channels generally can be expressed adequately as width-discharge power functions. For specified conveyance and channel-sediment properties, a change in width must be accompanied by an opposite change in mean depth. Because channel width generally can be measured more accurately than mean depth, most channel-geometry studies relate width to a measure of discharge. The present paper considers relations of width with both mean discharge and various flood discharges of specified recurrence intervals.

The coefficients of power-function equations presented here are based on widths and discharges expressed in meters (m) and cubic meters per second (m^3/s). Particle-size diameters are given in millimeters (mm), and silt-clay percentages are the content, by weight, of bed or bank material with particle diameters of less than 0.062 mm.

WIDTH-DISCHARGE-SEDIMENT RELATIONS

The geometry (simplified here to width) of an alluvial stream channel primarily is the integrated resultant of all rates of water and sediment discharge conveyed through the channel. The relative importance that the rates of water or sediment discharge might exert on channel geometry varies greatly. For example, the widths of armored alpine channels correlate well with mean discharge (Osterkamp and Hedman, 1977), but the widths of highly ephemeral stream channels, which are unable to heal effectively, are determined largely by infrequent, erosive flow events (Wolman and Gerson, 1978). The effects of water and sediment variables cannot be completely separated to evaluate the influence that each exerts on channel width. In order to examine the manner in which channel widths vary with sediment properties, it is necessary to generalize width-discharge relations. Sediment characteristics then can be regarded as modifications or complications of those relations (Osterkamp, 1979a). Summary relations of width and discharge, therefore, are presented before a more detailed analysis of the effects of fluvial sediment is described. The variables are discussed in the order previously listed.

Variation of Width and Discharge

Analysis of data from three diverse groups of perennial stream channels yielded the following relation between width, W, and mean discharge, $\overline{Q}$ (Osterkamp, 1979b):

$$W \approx a\overline{Q}^{0.50} \quad . \tag{1}$$

Values of the coefficient, a, were 7.7 for armored alpine channels, 4.9 for mostly silt and clay channels, and 9.5 for spring-effluent channels of a karst area. These values appear to be determined largely by the channel-sediment characteristics. The exponent value of this relation agrees with values given in numerous previous papers and appears accurate for the groups of relatively stable channels represented, but it is not accurate for channels of most sand-bed streams or ephemeral streams. In general, the widths of perennial stream channels having stable, accretionary banks, which are resistant to erosion by peak discharges, vary closely with the square root of mean discharge.

When channels are similar in all other respects, including mean discharge and sediment characteristics, variable or flashy discharge produces a broad width, and steady discharge is associated with a relatively narrow width. The peak discharges of the flashy streams winnow away fine material, cause bank erosion, and prevent the establishment of a mature, stabilizing growth of riparian vegetation. Channels with steady discharge, such as regulated streams and the spring-effluent channels of southern Missouri, generally have stable banks and are relatively narrow because erosive discharges are rarely conveyed. The effect of discharge variablity (for perennial streams) is illustrated by 96 sand-bed and sand-banks channels of the Missouri River basin. The ratio of the 10-year flood to mean discharge, $Q_{10}/\overline{Q}$, was computed for each, with 55 and 41 of the streams, respectively, having a ratio greater and less than or equal to 60. Power-function equations for the two groups of data were calculated as follows:

$$W = 9.6\ Q^{0.74} \quad (Q_{10}/\overline{Q} > 60) \ ; \tag{2}$$

$$W = 8.0\ Q^{0.62} \quad (Q_{10}/\overline{Q} \leq 60) \ . \tag{3}$$

Aside from the relatively large exponents, it is significant that, particularly for large streams, channels conveying steady discharge (equation 3) are generally narrower relative to discharge than are flashy streams.

Variation in the temporal distribution of discharge is distinguished in several manners, but the most significant effect on channel morphology appears to be the timing of flood events. Studies by Schumm and Lichty (1963), Burkham (1972), and Wolman and Gerson (1978) demonstrated the relation between large erosive floods and channel widths. Numerous data from different streams show that channel material is relatively coarse grained following the winnowing effects of an erosive flood. Limited channel-sediment data (unpublished) have been collected from various streams that have been widened by peak discharges, such as Plum Creek, south of Denver, Colorado, and the Cimarron River in southwestern Kansas. These data, with written descriptions and photographic evidence (Schumm and Lichty, 1963; Burkham, 1972), indicate the changes in bed- and bank-material particle sizes that occur during and following historic flooding.

Effect of Sediment on Width-Discharge Relations

Recent studies (Andrews, 1979; Richards, 1979) have suggested a direct relation between channel size and total sediment discharge. Results from numerous sites in the Missouri River basin (Osterkamp and Hedman, in review) further indicate that sediment concentrations for streams of similar water discharges have a marked effect on width-discharge relations only if a significant portion of the sediment load is moved by traction. Extensive data show that, during normal discharge rates (below flood stage), most sediment coarser than about 0.5 mm is moved primarily by traction (Visher, 1969; Middleton, 1976). When the sediment is suspended and distributed through the entire water depth, variations in load have minimal effect on channel width. Variations in the tractive load that is transported through a portion of water depth (generally not more than about

0.2 m) largely determine a required channel width to maintain movement.

The effect, as indicated by bed and bank material, that the size distribution of fluvial sediment exerts on channel morphology is illustrated by the linear relations of figure 1. The relations are based on data from nearly 300 gage sites, mostly in the Missouri River basin (Osterkamp and Hedman, 1977; in review), that have been separated into groups according to particle-size distributions of bed and bank material. The bed material is assumed representative of the tractive load of the stream. Bank material is formed primarily of sediment from suspension and by coarse sizes deposited on recession of peak discharges. The equations show that narrowest channels and lowest exponents occur when bed material is mostly (greater than 60 percent) silt and clay (fig. 1, line 1). If no sand and coarser sizes are available for transport, all sediment is carried in suspension. The bed and bank materials are nearly homogeneous, and the channel tends to be narrow, deep, and U-shaped.

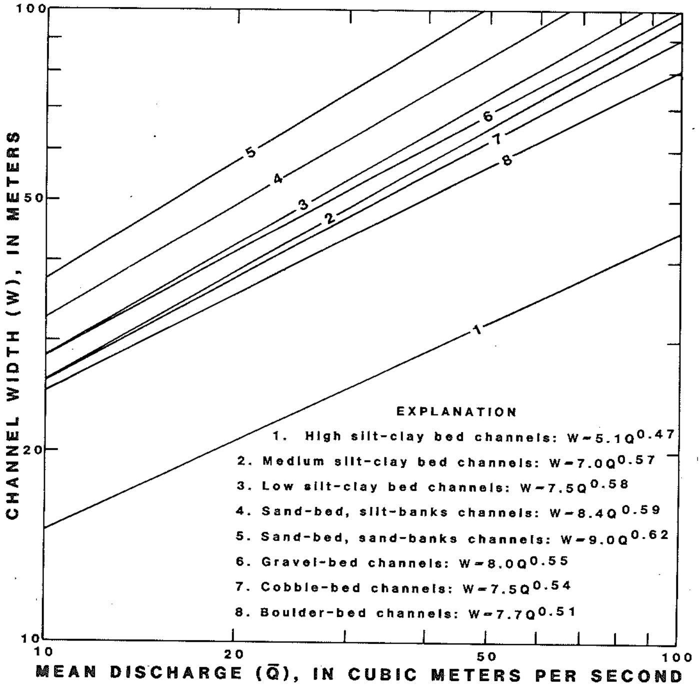

FIG. 1.--Relations of width to mean discharge for channels of specified sediment characteristics

Lines 2 and 3 (fig. 1) relate widths to mean discharges of channels with bed material containing 31 to 60 and 11 to 30 percent silt and clay, respectively. Although these channels consist predominantly of fine particle sizes and tend to have stable, cohesive banks, the increased widths result from the tractive movement of small to moderate amounts of sand. Fluvial-sorting processes, which enrich the bed material with sand and the bank material with silt and clay (Osterkamp and Wiseman, 1980), form a channel section with sloping sides and a nearly horizontal sand bed. Line 1 (fig. 1) suggests that nearly all of the sediment conveyed by the channel consists of fine particle sizes, and lines 2 and 3 suggest that the sediment supply includes both fine sizes and sand. Lines 4 and 5 (fig. 1) relate width to discharge data of stream channels where the bed material is dominated by sand sizes (less than 11 percent silt-clay content and a median-particle size of less than 2.0 mm). The sand-bed, silt-banks channels (line 4) are formed when a sediment supply has significant portions of both sand and finer sizes. Sand-bed, sand-banks channels (bank material with less than 70 percent silt and clay) are formed when the suspended load of fine sizes is small relative to the coarser sizes moved by traction (line 5). Owing to the sand, these channels maintain wide, horizontal beds and have poorly cohesive banks that are susceptible to erosion by peak discharges.

The narrowest and deepest channels occur when sand is not available for transport. Conversely, the widest and shallowest, and often braided, channels occur when the entire sediment supply is of sand size. Similarly, the smallest exponent or slope is associated with channels having high silt and clay in the bed and banks, and the largest exponent is related to channels with the most sand in bed and banks (fig. 1).

To show an extreme condition suggested but not illustrated by figure 1, width and mean-discharge data were collected from various braided streams of similar sediment conditions in the Sand Hills area of Nebraska (Osterkamp and Hedman, in review). The data yield the relation:

$$W \simeq 3.0\bar{Q}^{1.0} , \qquad (4)$$

which suggests that downstream changes in discharge for these streams are accommodated totally by adjustments in channel width, not by changes in mean channel depth or water velocity. This observation is consistent with bank-material data (Osterkamp and Wiseman, 1980), which suggest that water velocities near the wetted perimeter and processes of bank sorting do not change significantly in the downstream direction. In other words, increases in discharge for braided streams do not result in increased channel depth, and because all flow (at normal discharge rates) remains in proximity to the wetted perimeter, velocities also remain nearly constant in the downstream direction. Considering the extremes of tractive movement--narrow channels formed entirely of silt and clay (fig. 1, line 1) or highly braided channels formed entirely of sand--it is inferred that the exponents of the width-mean discharge relations range from roughly 0.45 to 1.0.

Lines 6, 7, and 8 are power-function relations for (nonglacial) channels with median-particle sizes of bed material corresponding to gravel, cobbles, and boulders, respectively. Abundant sand in bed material commonly is available for transport in gravel-bed channels, whereas sand ordinarily is protected in cobble-bed channels and, particularly, in boulder-lined channels. Generally, the banks of these channels are armored by the same coarse sizes that armor the beds (Osterkamp and Wiseman, 1980). The lines and equations (fig. 1) show decreasing channel widths and power-function exponents with increasing bed-material sizes. Implicit in these trends are increases of channel gradient, channel roughness and armoring, and decreasing tractive sediment movement at normal discharge rates. For highly turbulent, well-armored alpine streams, only moderate channel widths are required because minimal amounts of sand and coarser sizes are moved during low to medium flow. At high discharge rates, bed and bank sorting processes occur, and large sizes are moved tractively. Hence, greater widths occur in channels having coarse sizes than in the silt-clay bed channels (fig. 1, line 1), although both types of channels are regarded here as highly stable.

Summarizing the power functions of figure 1, lines 1 through 5 refer to progressive increases in channel sandiness and in width relative to discharge. Increasing sandiness suggests decreasing channel stability because of the corresponding reduction in cohesiveness afforded by the silt and clay of the channel material. As the median-particle size of the bed material increases beyond the sand range, the coarsest, normally immobile sizes cause increased armoring, or protection of available sand, and reduced tractive sediment movement. Lines 5 through 8, therefore, indicate decreasing widths relative to mean discharge and thus increasing channel stability. The exponents of the power function equations (fig. 1), which appear to vary directly with the amount of tractive sediment movement, can be likened loosely to channel instability as used here.

The size distribution of fluvial sediment also helps control channel morphology through sorting processes. Extensive particle-size analyses of bed and bank samples from perennial streams of the Missouri River basin (Osterkamp and Wiseman, 1980) suggest that the formation of stable alluvial banks is dependent on the availability and sorting of specific size ranges of sediment. The bank-material analyses (fig. 2), which represent wide ranges of geologic, topographic, and climatic conditions, show a pronounced tendency toward bimodal distributions. Based on logarithmic-probability analysis of bank samples, the fine-grained subpopulation includes particle sizes up to about 0.35 mm, whereas a coarse-grained subpopulation has sizes greater than about 1.3 mm. Sand sizes in the range between the two subpopulations are generally absent. Analyses of bed samples from the same channel sections give unimodal distributions, do not show deficient sand sizes, and show a size "break" at 0.5 mm (fig. 2).

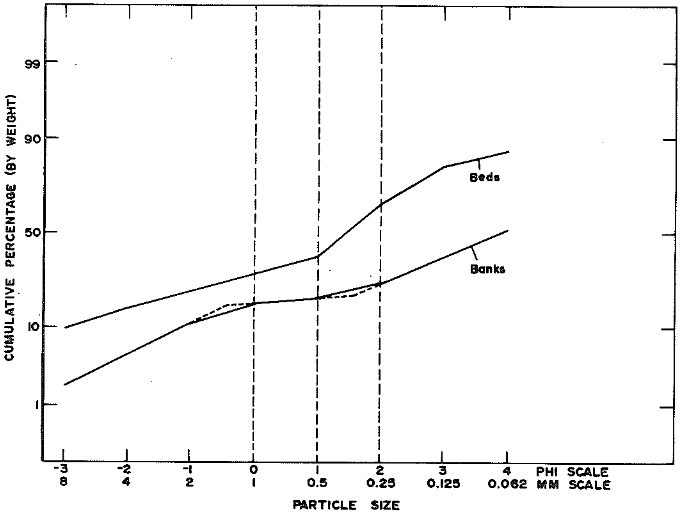

FIG. 2.--Particle sizes of bed and bank material from perennial stream channels of the Missouri River basin. The cumulative size analyses for the beds is the average of 239 samples; that for the banks is the average of 471 samples. Dashed lines are straight-line projections from data points, yielding an inferred range of deficient sand sizes in bank material.

Based on previous studies (Middleton, 1976; Visher, 1969), comparisons of the data with analyses of the suspended-sediment loads, and comparisons of coarsest sizes found in the bed and banks of specific channels, it is inferred that the fine subpopulations of both bed and banks are associated with the suspended loads. The coarse subpopulations of both probably are associated with tractive movement. Sand sizes of 0.35 to 1.3 mm do not occur in the bank material because these sizes are not in suspension at normal discharge rates. At flood discharges, the sand sizes apparently are washed from the bank slopes and coarser sizes probably remain as a lag deposit.

Relatively stable banks are deficient in 0.35 to 1.3 mm sand regardless of channel gradient or basin characteristics. Bank-sorting processes, therefore, appear to be essentially constant in the downstream direction, which suggests that stream velocities at and near the channel perimeter do not change in the downstream direction. If the total-sediment load of a stream is predominantly medium- to coarse-grained sand, wide, unstable channels will result because the fine (less than 0.35 mm) and coarse (greater than 1.3 mm) sizes required for bank stability are not available. Braided channels, such as those of the Sand Hills area in Nebraska, are likely to occur regardless of discharge variability, when virtually all sediment in transport is between 0.35 and 1.3 mm in size.

Short-term to seasonal changes in the availability and size distribution of sediment probably occur in most streams that have a supply of well-graded sediment. Whether the changes are natural or induced, the processes of bank erosion and accretion (release from storage and storage of fluvial sediment) are generally too slow to reflect those changes. Hence, short-term changes are not considered by the equations presented here. Short-term changes in sediment supply represent a stress, or independent variable, affecting the width-discharge-sediment relations. A long-term change in the sediment load and distribution, however, often accompanies the progressive changes by a stream channel to attain stability after a destructive flood (Schumm and Lichty, 1963; Burkham, 1972; Osterkamp, 1979a). As used here, the virtually instantaneous coarsening of bed material due to the winnowing effects of a highly erosive flood is associated with long-term change because years or decades may be required for new storage of fine sediment and a return to pre-flood conditions. Long-term sediment changes, therefore, are a dependent-to-interrelated variable of the width-discharge-sediment relations and are reflected by the equations presented and referenced here.

Flood Relations

Power-function equations that include flood discharges of specified recurrence interval have been developed for the Missouri River basin (Hedman and Kastner, 1977; Osterkamp and Hedman, in review) by using the same techniques as those used for relating channel characteristics to mean discharge at gaged sites. Relations of channel width with flood discharges generally are not as well defined as those relations which include mean discharge because (1) the frequencies of flood discharges generally are not as well defined at gaged streams as is mean discharge and (2) flood discharges generally are conveyed through channel sections of which only a small part of the perimeter is the result of recent fluvial processes.

Nevertheless, the width-discharge equations for specified flood frequencies vary with the channel-sediment characteristics and reflect the influence of fluvial sediment (Osterkamp and Hedman, in review).

The width-discharge relations of the various channel types for the 10-year flood, as an example, show variations similar to those for mean discharge (fig. 1). Flood relations for the various channel types are not provided, but examples are given for channels with sand beds and silty banks (fig. 3). The exponents of the equations increase with recurrence interval, but probably not as a result of increasing tractive sediment movement. Rather, the inferred causes of the increasing exponents are (1) the tendency for attenuation of flood discharges in the downstream direction with increase in recurrence interval and (2) peak rates of precipitation and runoff, per unit area of a drainage basin, tend to decrease with increasing basin size.

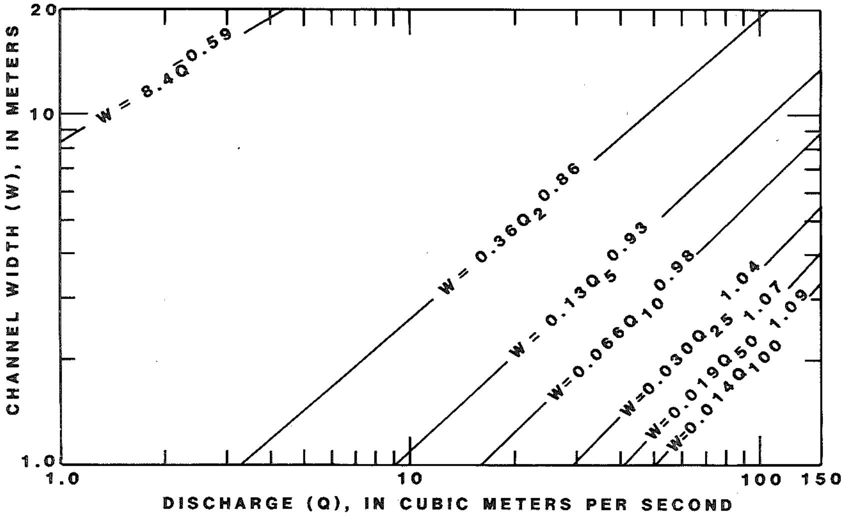

FIG. 3.--Power-function relations of width to discharge characteristics for channels with sand beds and dominantly silt-clay banks. $\bar{Q}$ is mean discharge; Q_2 through Q_{100} are discharges of floods with recurrence intervals of 2 through 100 years.

EXAMPLES

To better characterize the generalizations previously made, figure 4 provides interpretations of how four types of stream channels are altered by floods and then adjusted during subsequent periods of normal discharge rates. Although the relations are hypothetical and are based on a mean discharge of about 1.0 m^3/s, they refer to actual channels and mostly are represented by the general relations of figure 1. The graphs (fig. 4), reading from bottom to top, represent a channel formed of silt and clay in eastern Kansas (fig. 1, line 1), a highly armored alpine stream in Wyoming (fig. 1, line 8), a sand-bed, sand-banks channel in Nebraska (fig. 1, line 5), and a sandy, highly ephemeral stream channel (flow less than 1 percent of the time) in southern Arizona (not represented in fig. 1). Because the ephemeral stream channel is formed by infrequent flow events, discharge rates during periods of flow generally are much greater than 1.0 m^3/s, and the channel is very wide relative to mean discharge (fig. 4).

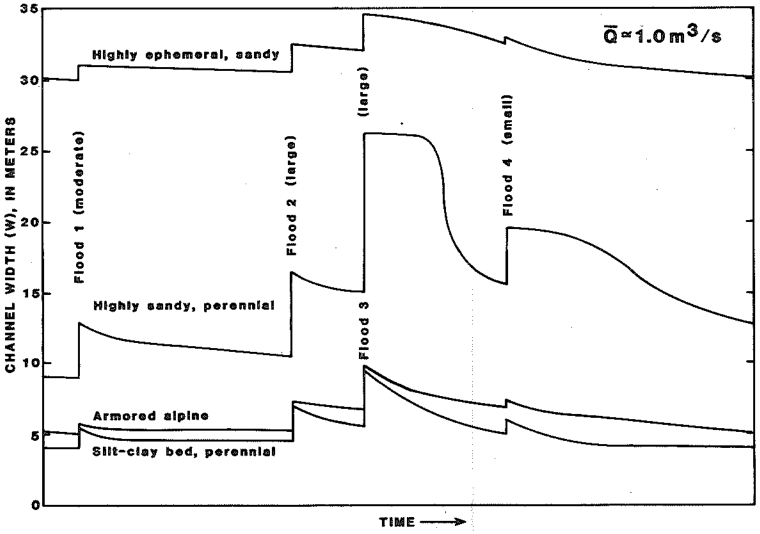

FIG. 4.--Schematic width-time relations for different types of stream channels.

A moderate flood (fig. 4, flood 1) widens all four channels. The alpine stream is widened least owing to the armor of cobbles and boulders. Widening is substantial in the sandy, perennial stream channel because the poorly cohesive banks are readily eroded. The ephemeral stream channel is not widened significantly because the channel was previously shaped by similar flow events and little or no healing was possible during the extended no-flow periods. Following flood 1, bank accretion and channel narrowing occurs in all four cases but is most pronounced for the sand channel that had been widened most. Succeeding floods (fig. 4, floods 2, 3, and 4) alter the various channels according to the timing and magnitude of the floods, the typical discharge characteristics of the streams, and the channel-sediment properties. Flood 2 widens the channels and destroys some flood-plain vegetation, thereby making the channels vulnerable to bank erosion by flood 3. Flood 4 represents an interruption of the healing or narrowing process after flood 3.

The silt-clay bed channel shows significant widening by erosive floods because the banks are poorly protected. Following the various floods, however, narrowing is rapid because abundant silt and clay in suspension is available for bank accretion. The armored channel is not easily widened by peak discharges, but subsequent narrowing is slow owing to the difficulty of replacing either fine or coarse sizes to the banks. The sandy, perennial stream channel is easily widened by the floods, but sufficient fine sediment in transport is available for recovery to occur readily.

The widths of the highly ephemeral stream channel always reflect the influence of infrequent discharges, and neither widening nor narrowing through time is pronounced.

In all cases, it is inferred that erosive or channel-widening discharges winnow the channel material of fine sediment sizes and cause an increase in median-particle size. Erosive discharges also tend to straighten channels and increase the gradients. Preceding flood 1, therefore, the sandy, perennial stream channel (fig. 4) might have been of moderate width, exhibited well developed sinuosity, and had a sand bed and stable banks of silt and fine sand. The width-mean discharge relation might have been described by equation 4 of figure 1. Following flood 3, the channel was more than doubled in width (at the expense of flood-plain area), straightened, and modified to a braided pattern. Most silt and fine sand had been washed from the bed material, and coarse-sand to gravel sizes had been added by destruction and reworking of flood-plain deposits. Whereas equation 5 of figure 1 might have described the width-mean discharge relation prior to flood 2, the braided, highly unstable conditions of this channel following flood 3 are not represented in figure 1.

In all cases, the relations of figure 4 suggest that channel narrowing (bank accretion) is accompanied by (1) a general reduction of bed-material sizes and tractive sediment movement, (2) storage of fine sizes in bank material, and (3) reduction of channel gradient (increased sinuosity). Although supporting data are not available, it is inferred that the rates of channel narrowing generally decrease as stable conditions are approached (Osterkamp, 1979a). An exception is represented by the sandy, perennial stream channel (fig. 4). Following the extensive flood-plain destruction of flood 3, an extended period was required for re-storage of fine sediment sizes in the channel alluvium before significant narrowing could occur. With storage of fines, a change from a braided pattern to a defined channel could proceed rapidly. Channel changes of this sort have been documented for the Cimarron River in Kansas (Schumm and Lichty, 1963), the Gila River in Arizona (Burkham, 1972), and Plum Creek in Colorado (unpublished).

CONCLUSIONS

Regardless of the discharge characteristics in alluvial streams, maximum channel widths occur when fluvial sediment is principally medium- to coarse-grained sand. Narrowest, most stable channels occur when an increased percentage of sediment finer than sand imparts a cohesiveness, or when sediment coarser than sand causes an armoring effect.

If a stream having steady discharge transports only fine-grained sediment in suspension, the channel will assume a narrow (relative to water discharge) and highly stable condition. An opposing, or widening, tendency for a channel section is caused by sand and coarser sediment that moves by traction and requires a width proportional to the effect of the tractive load. If the variability of discharge and sediment characteristics at two sites on a stream are similar, the channel shape at both sites will be similar; however, the channel size will vary with the amount of discharge. If the sediment characteristics differ, both size and shape of the channel will change between the sites.

The equations of figure 1 indicate that the largest exponents for the width-discharge relations should be associated with large rates of tractive sediment movement. However, the equations were developed from data collected at relatively stable sites and do not represent braided conditions. Data from braided streams of the Sand Hills area of Nebraska, however, give an exponent of 1.0 (Osterkamp and Hedman, in review).

As indicated by figure 4, the width-discharge relations of a stream are not constant through time. Temporal changes of the relations, however, are accompanied by changes in the channel-sediment characteristics, roughness, and channel gradient. If little or no net aggradation or degradation is occurring during a suitably defined period, any channel reach can be defined by power-function relations that assume approximate equilibrium.

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

By JOHN T.C. PARKER

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Prepared in cooperation with the
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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.

CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	millimeter
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 net of 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 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

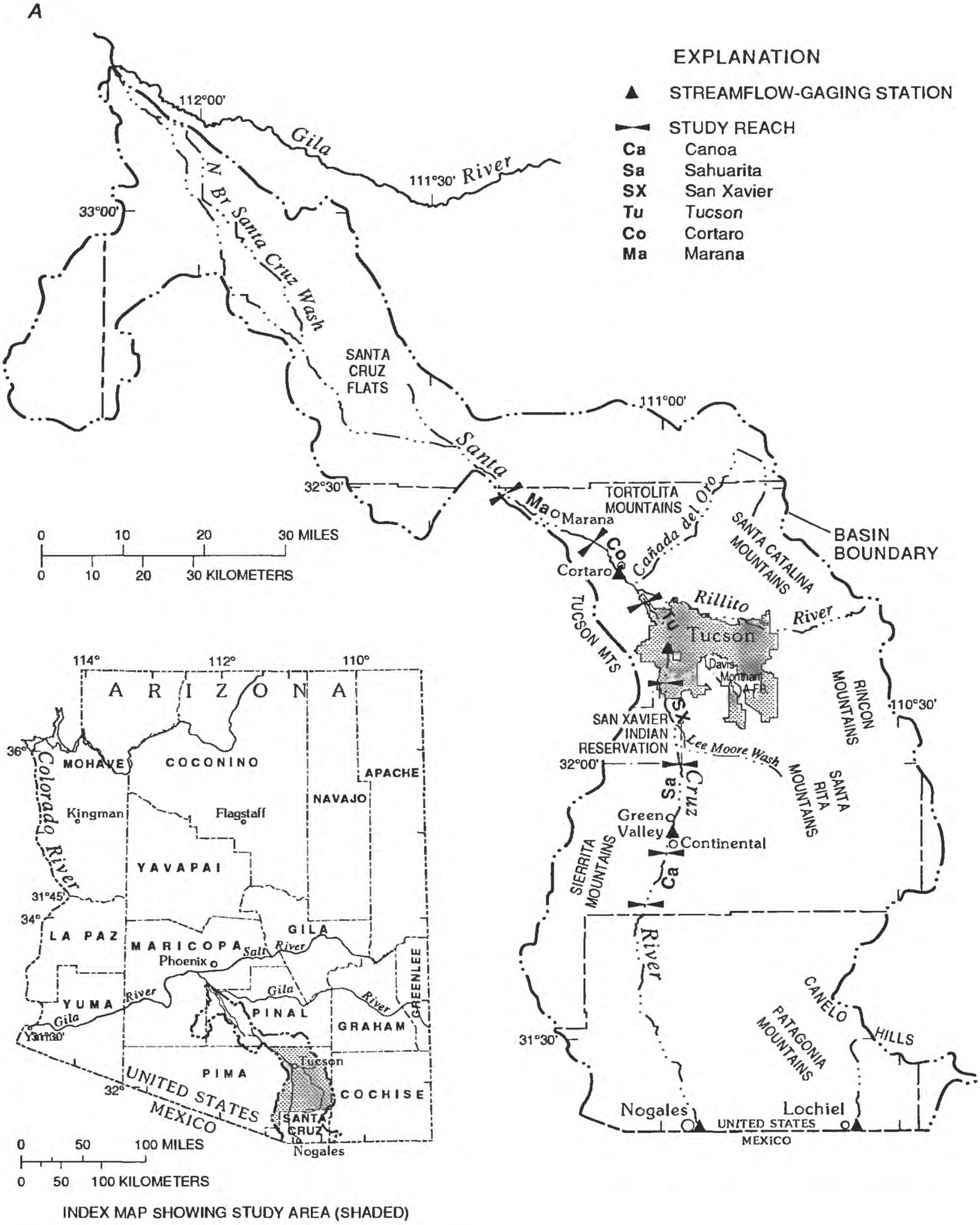


Figure 1. Santa Cruz basin, Arizona.

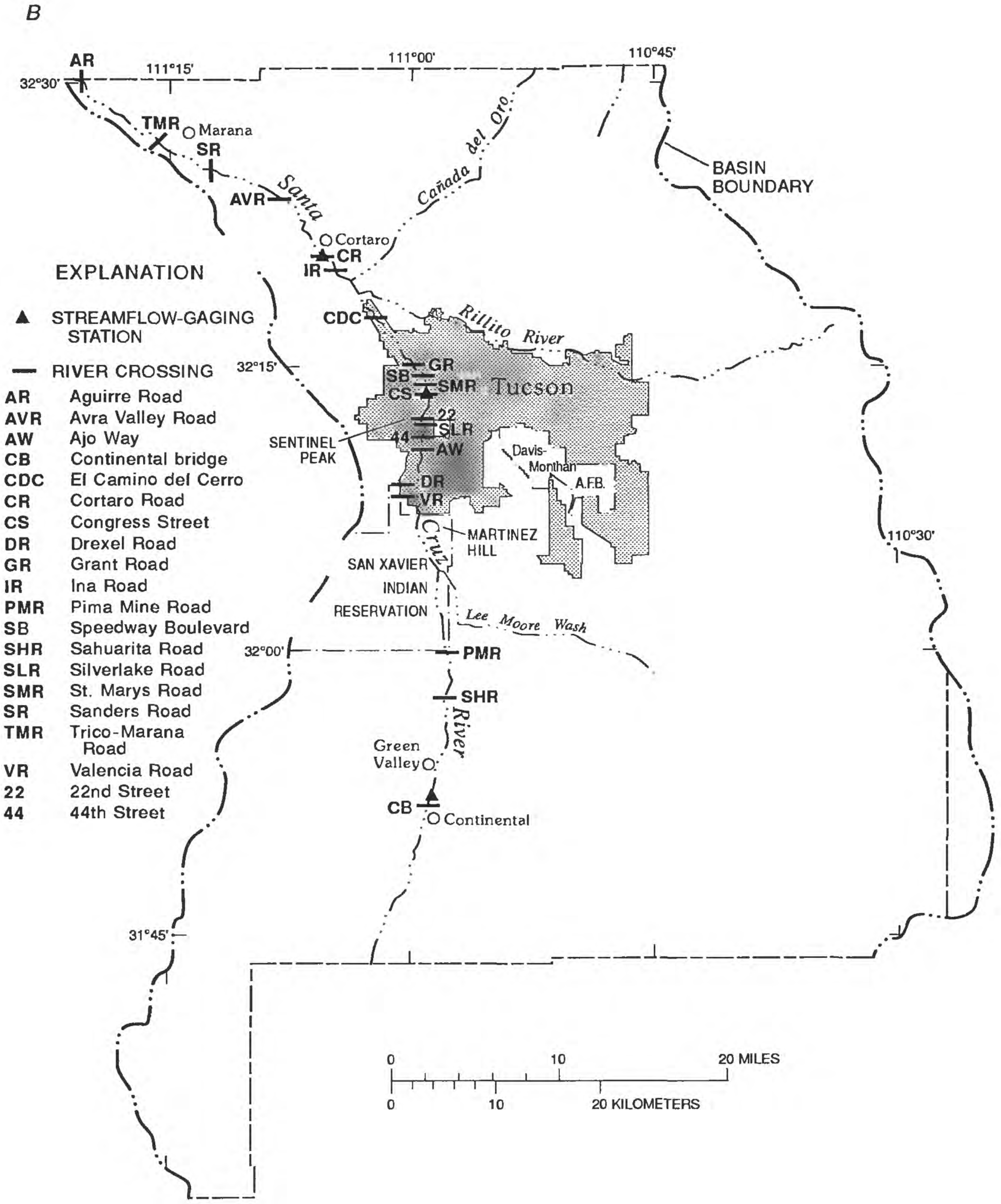


Figure 1. Continued.

30 feet 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, 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 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 north 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-mile 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.

Acknowledgments

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 the 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-mile-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).

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-foot intervals, along the channel axis (fig. 2A). 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. 2A). 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

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]		Channel gradient, in foot per foot[3]	Mean width, in feet[4]		Median width, in feet		Width range, in feet		Standard deviation, in feet		Maximum width increase[5]	Maximum width decrease[5]
			1936	1986		1936	1986	1936	1986	1936	1986	1936	1986	1936-86	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.

new location of each channel center point relative to the channel axis (fig. 2B). Although plots such as figure 2B 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 2A and in the boxed area of figure 2B.

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 channel widening and destroyed the bridge at Congress Street in Tucson. These floods also extended the headcutting through

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.

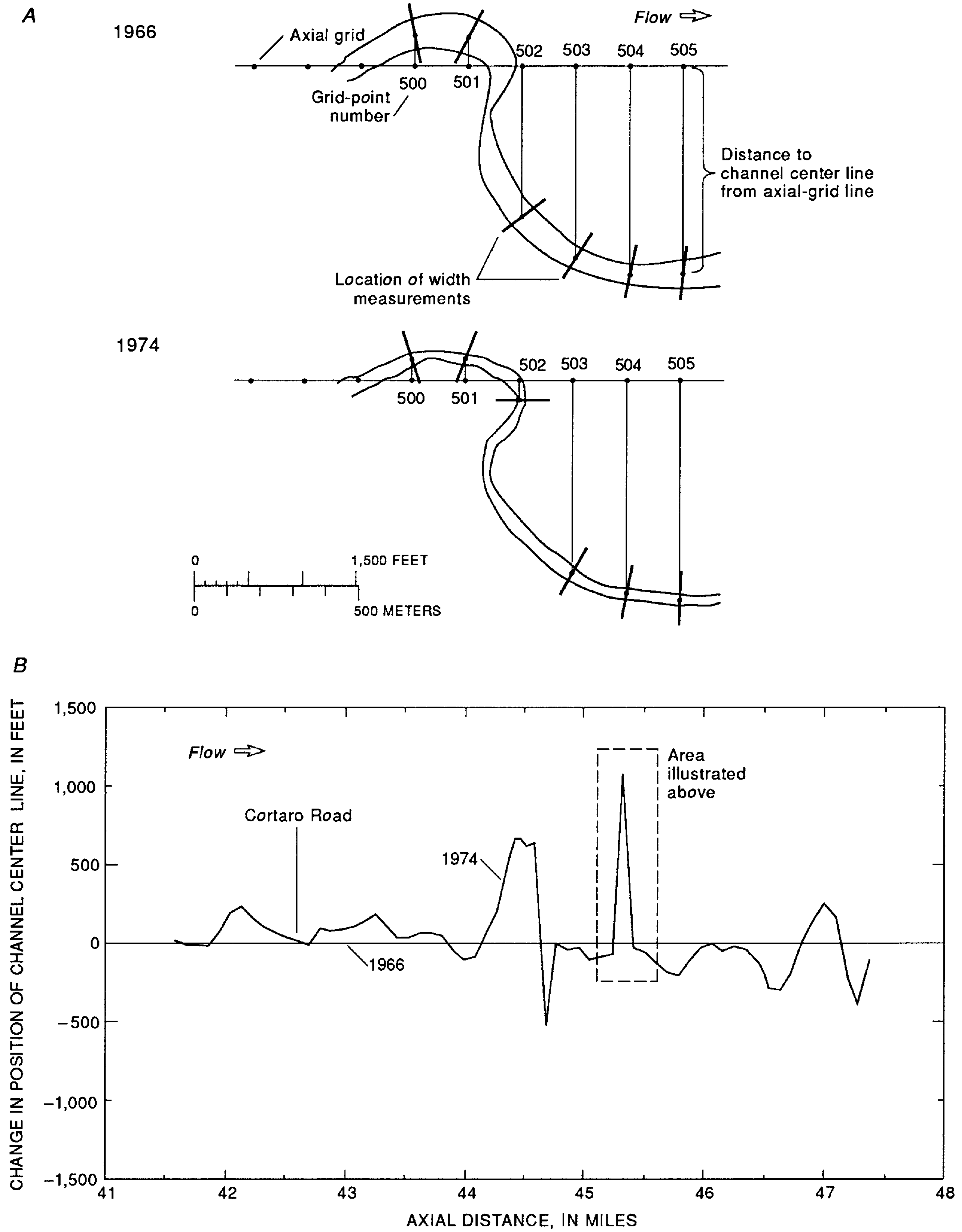
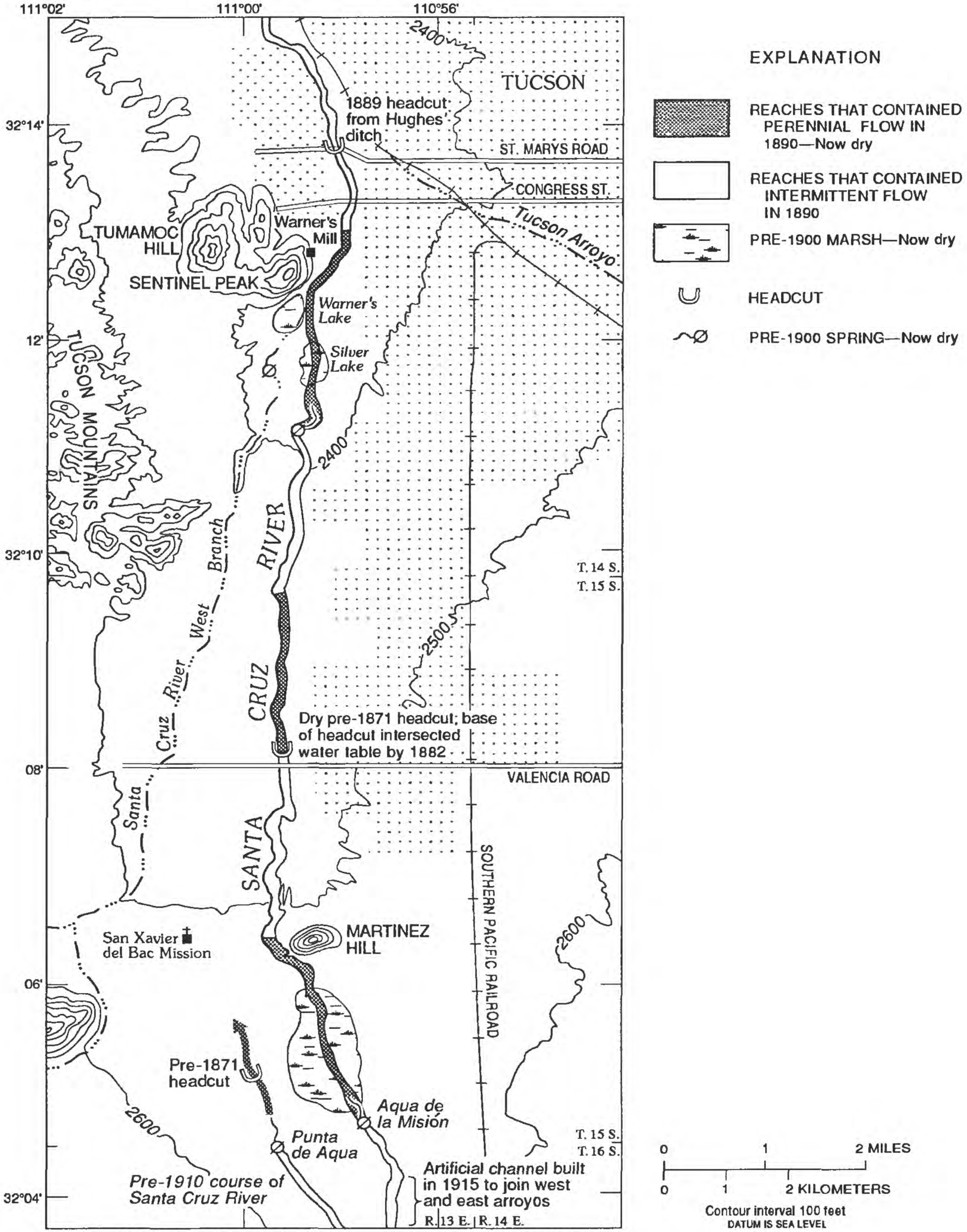


Figure 2. Method of relating channel change to axial reference system. *A*, Measurement of changes in width and channel position from 1966 and 1974. Note large shift in position relative to grid point 502 caused by rotation of meander axis. *B*, Change in position of channel center line with time. Positive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



Base from U.S. Geological Survey, 1:62,500; San Xavier Mission, 1940–57 and Tucson, 1946–57

Hydrology from Betancourt and Turner, 1988

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.

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 south 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 and 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-foot-wide active flood plain. The reach has undergone major channel widening (fig. 4A); however, little natural change occurred before the floods of 1977 and 1983. Much of the change in channel position and stream length (fig. 4B and 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. 4B) 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. 4C). 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. 4D). 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. 5J).

The Cortaro and Marana reaches have had the most complex record of channel change since 1936 (fig. 4E-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

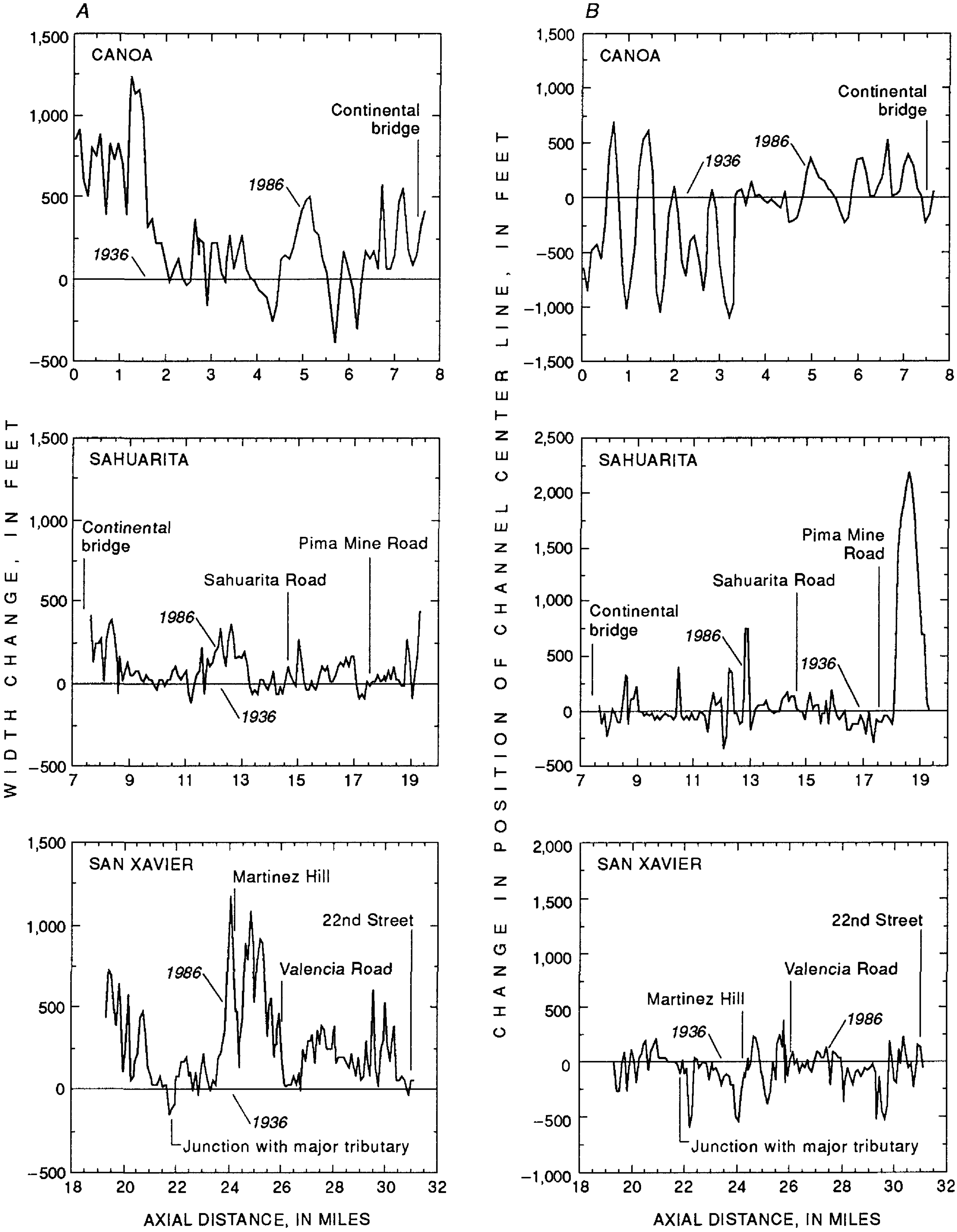


Figure 4. Channel changes on the Canoa, Sahuarita, San Xavier, Tucson, Cortaro, and Marana reaches, 1936–86. *A,* Width change. *B,* Change in position of channel center line. Positive values indicate shift in position toward left side of channel; negative values indicate shift toward right side.

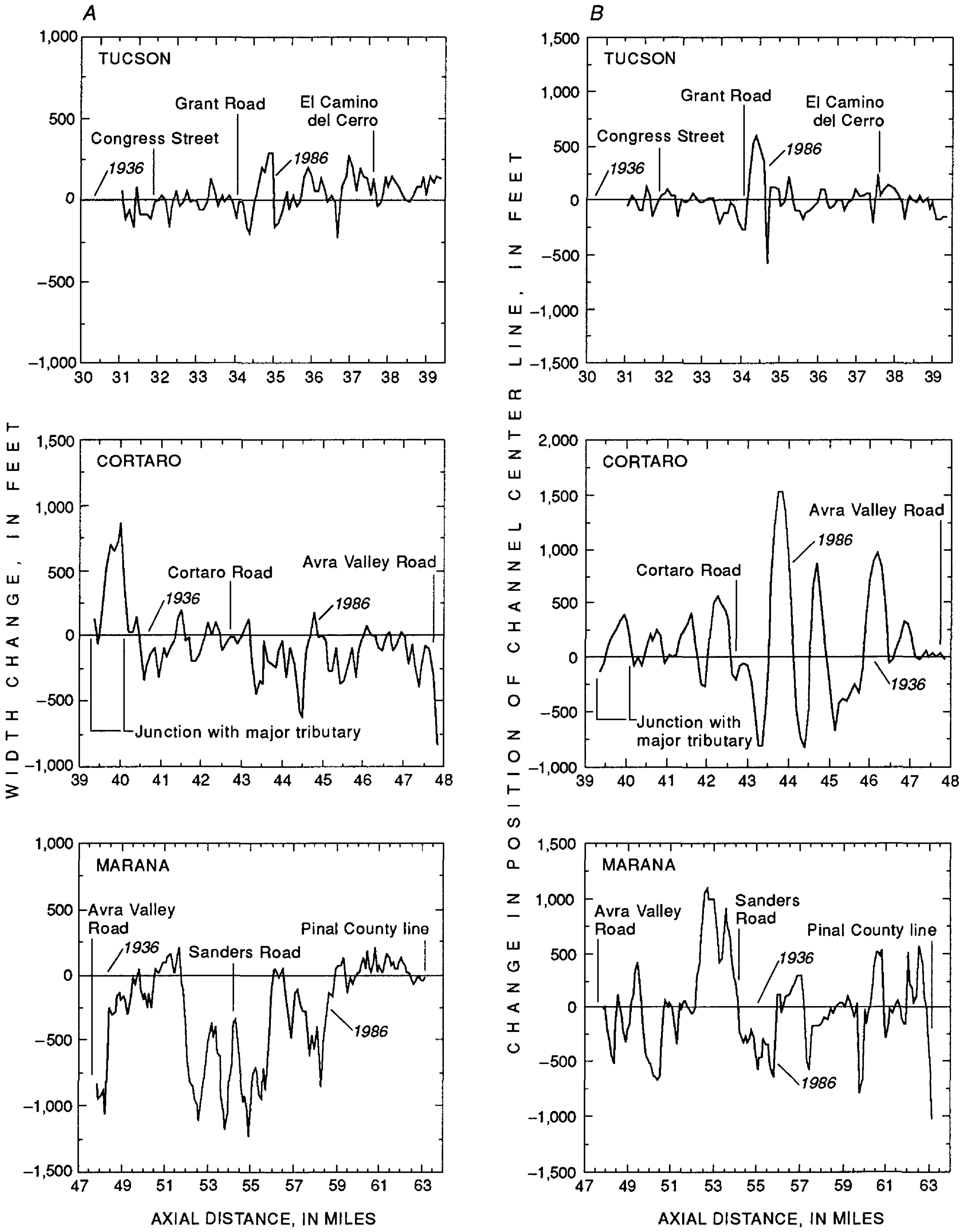


Figure 4. Continued.

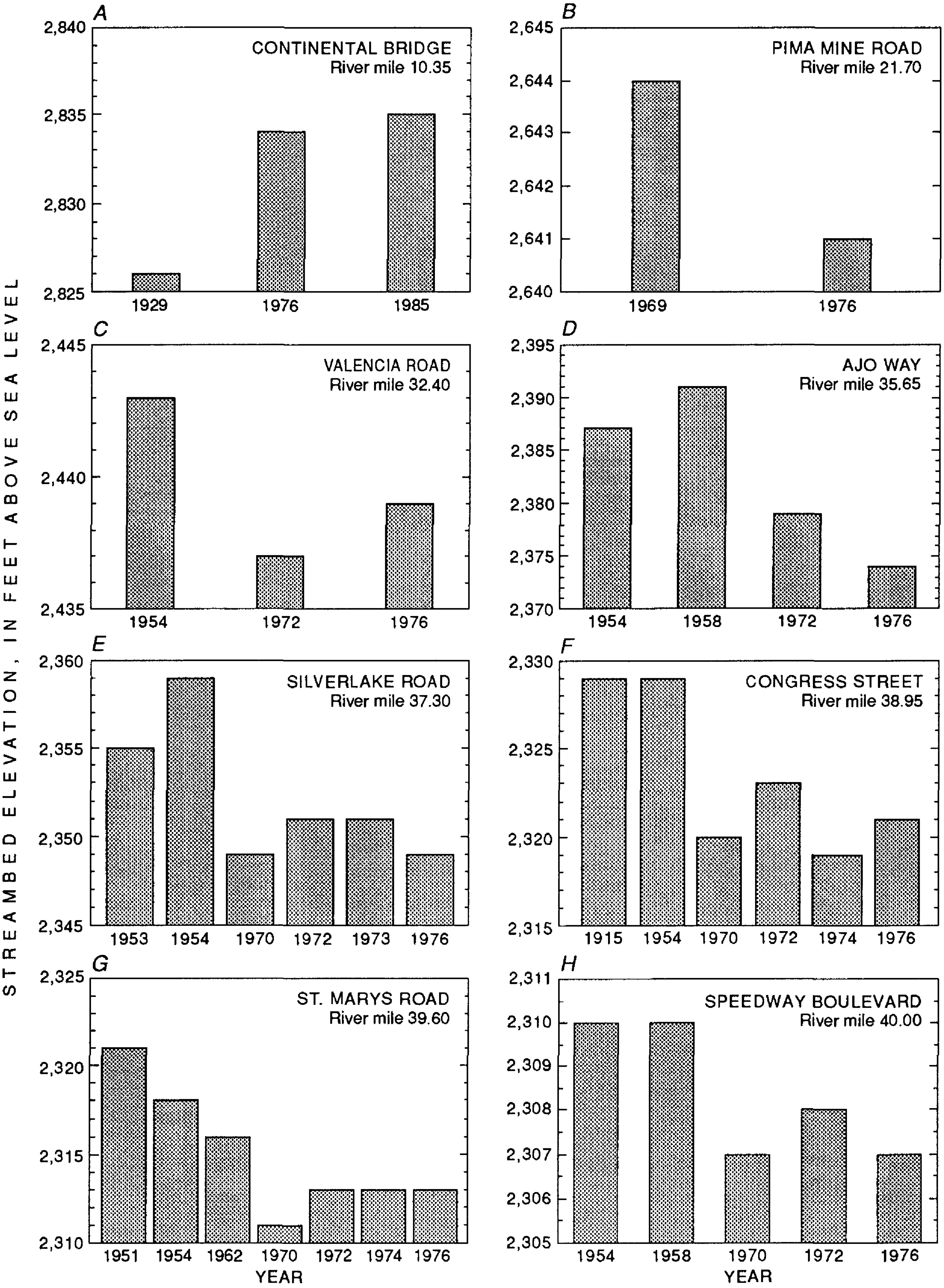


Figure 5. Changes in streambed elevations, Santa Cruz River. Note the vertical scale changes among various graphs. (Source: Data from Federal Emergency Management Agency, 1982, 1987, 1990; Pima County Department of Transportation and Flood Control District.)

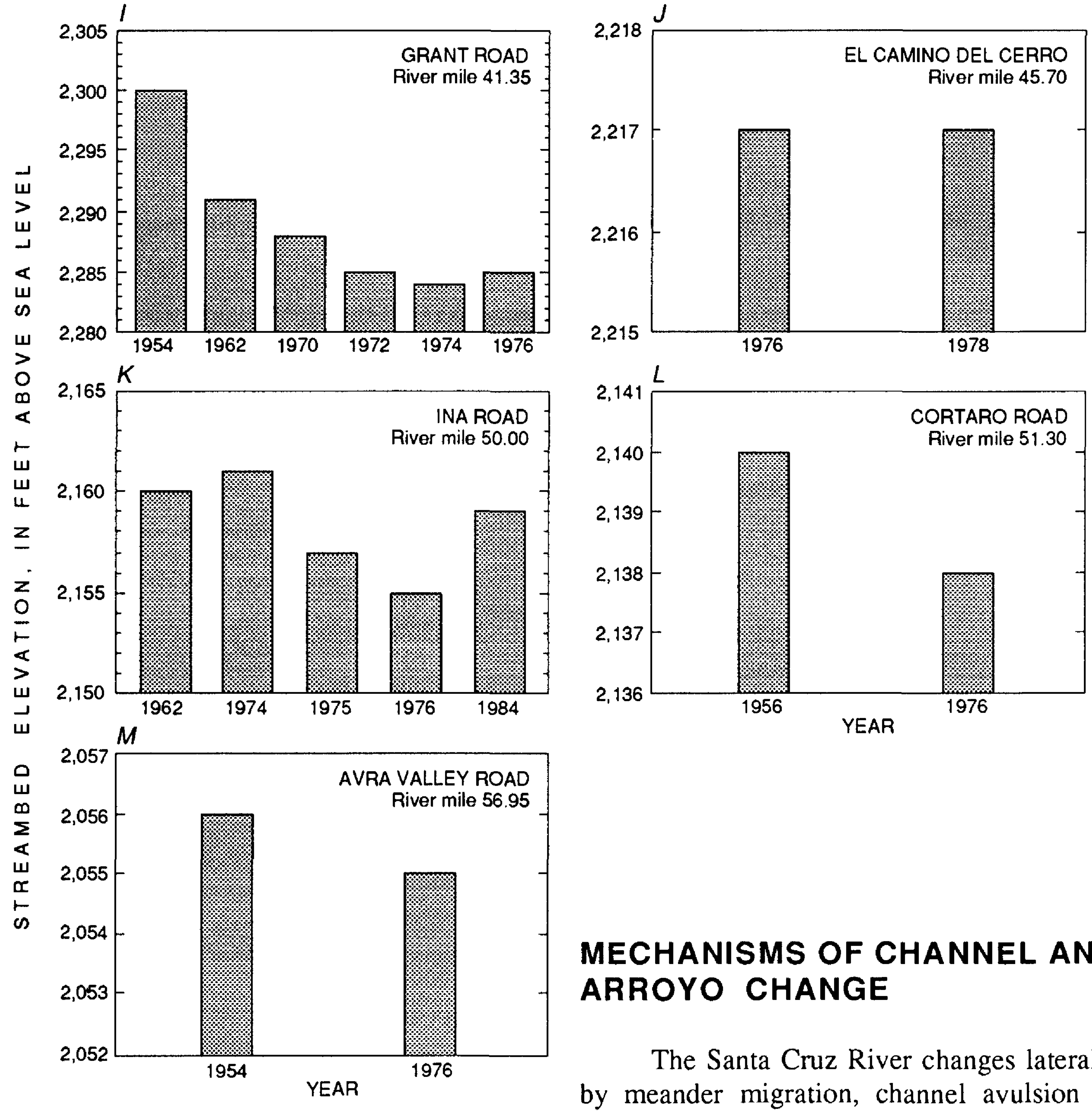


Figure 5. Continued.

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 and 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 morphology, channel sediment, bank resistance, and magnitude of flow. Identification of the type of 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 land fill 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 flood.	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.

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 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 center-line position associated with the inception of meanders and their subsequent downstream translation, lateral 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.

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

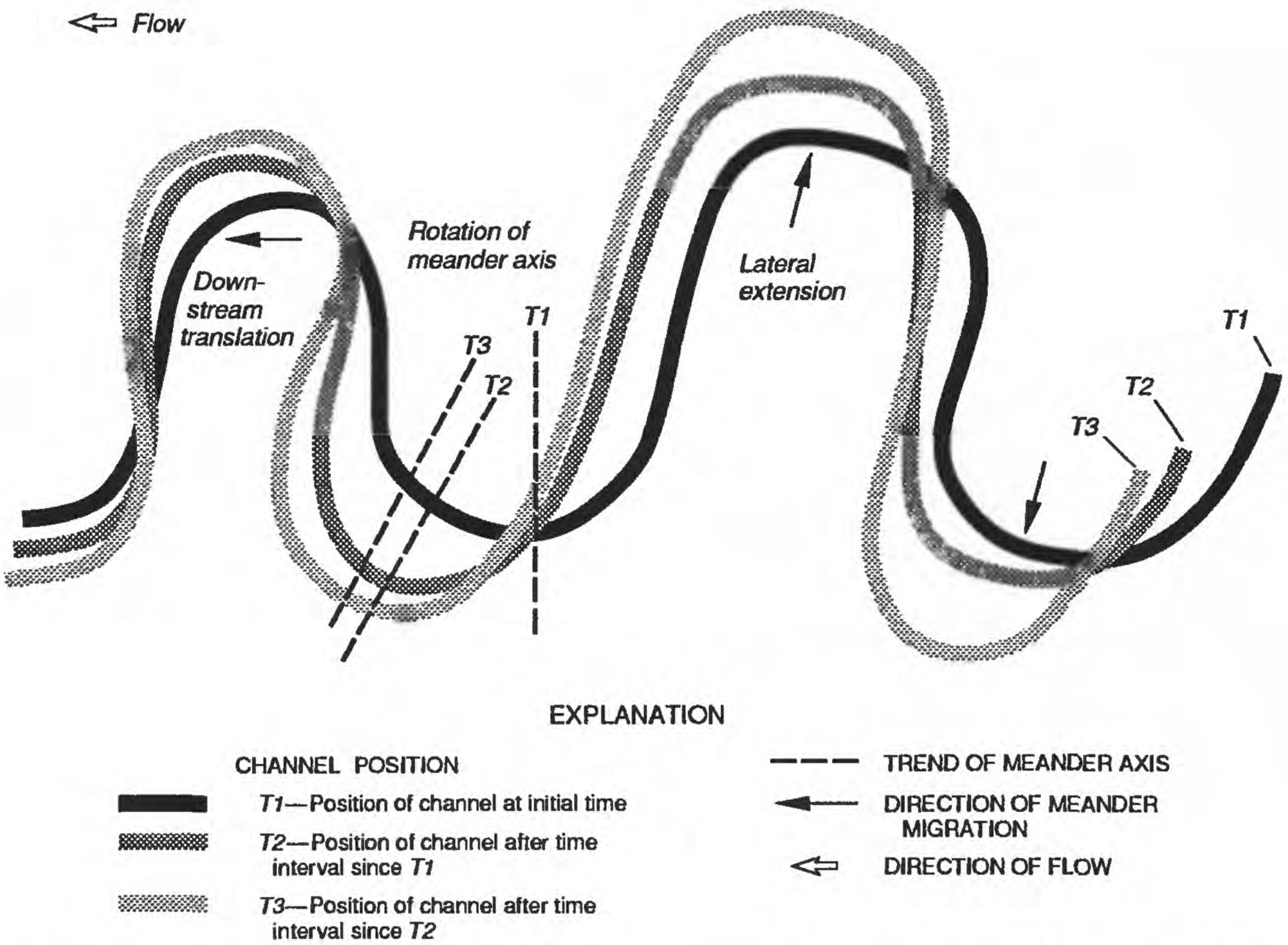


Figure 6. Channel migration caused by downstream translation of meander rotation of meander axis, and lateral extension of meander. Positive values indicate shift in position toward left side of channel; negative values indicate shift toward right side.

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 reach 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 and 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). The position of the channel center line shifted laterally as much as 900 ft because of cutoff at meander A.

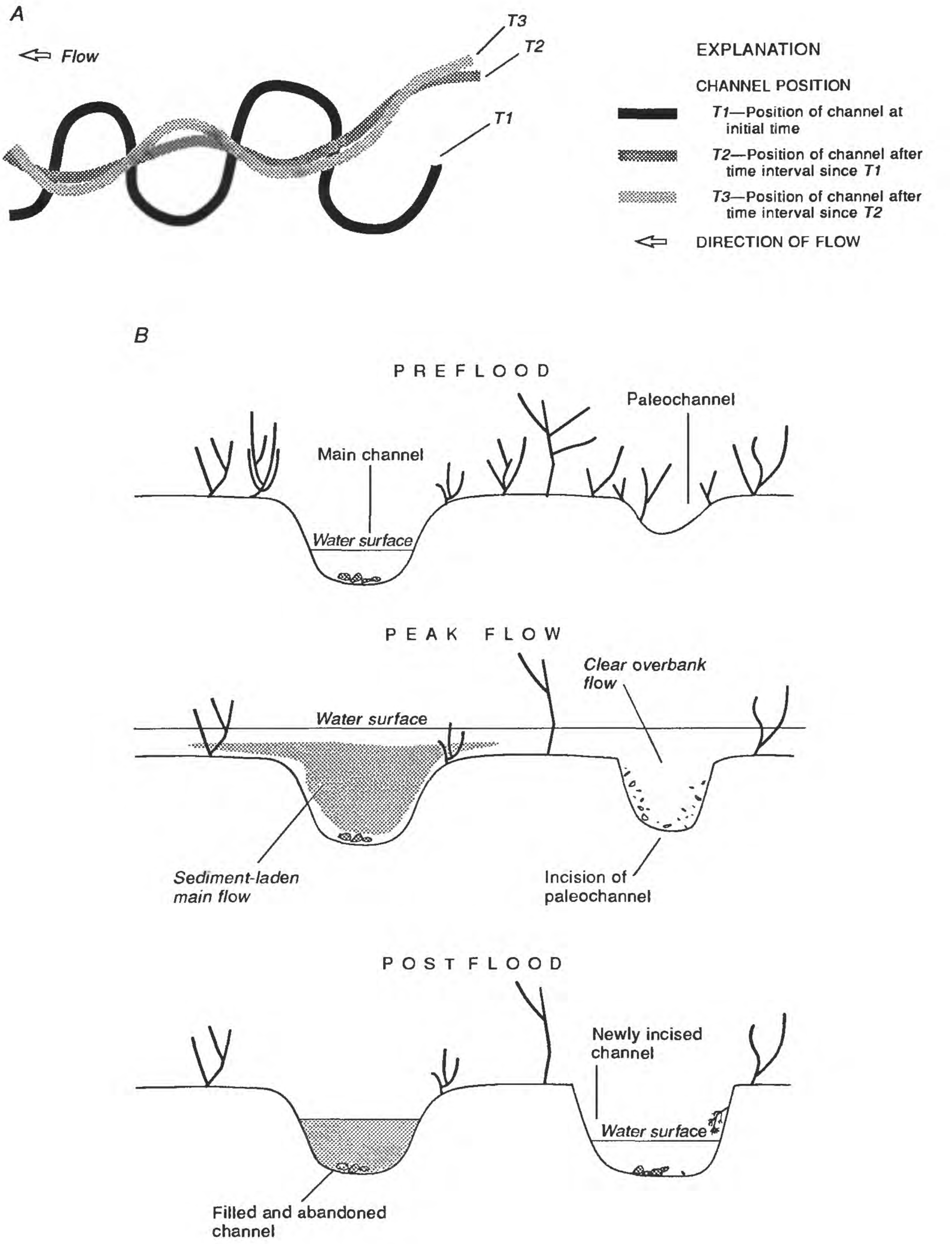


Figure 7. Avulsion and meander cutoff. *A,* Plan view of an initially sinuous channel at time 1 *(T1)* that changes course as a result of a flood *(T2)* and then is modified by subsequent meander migration during low flows *(T3)*. *B,* Processes that produce a lateral shift in channel position by avulsion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

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).

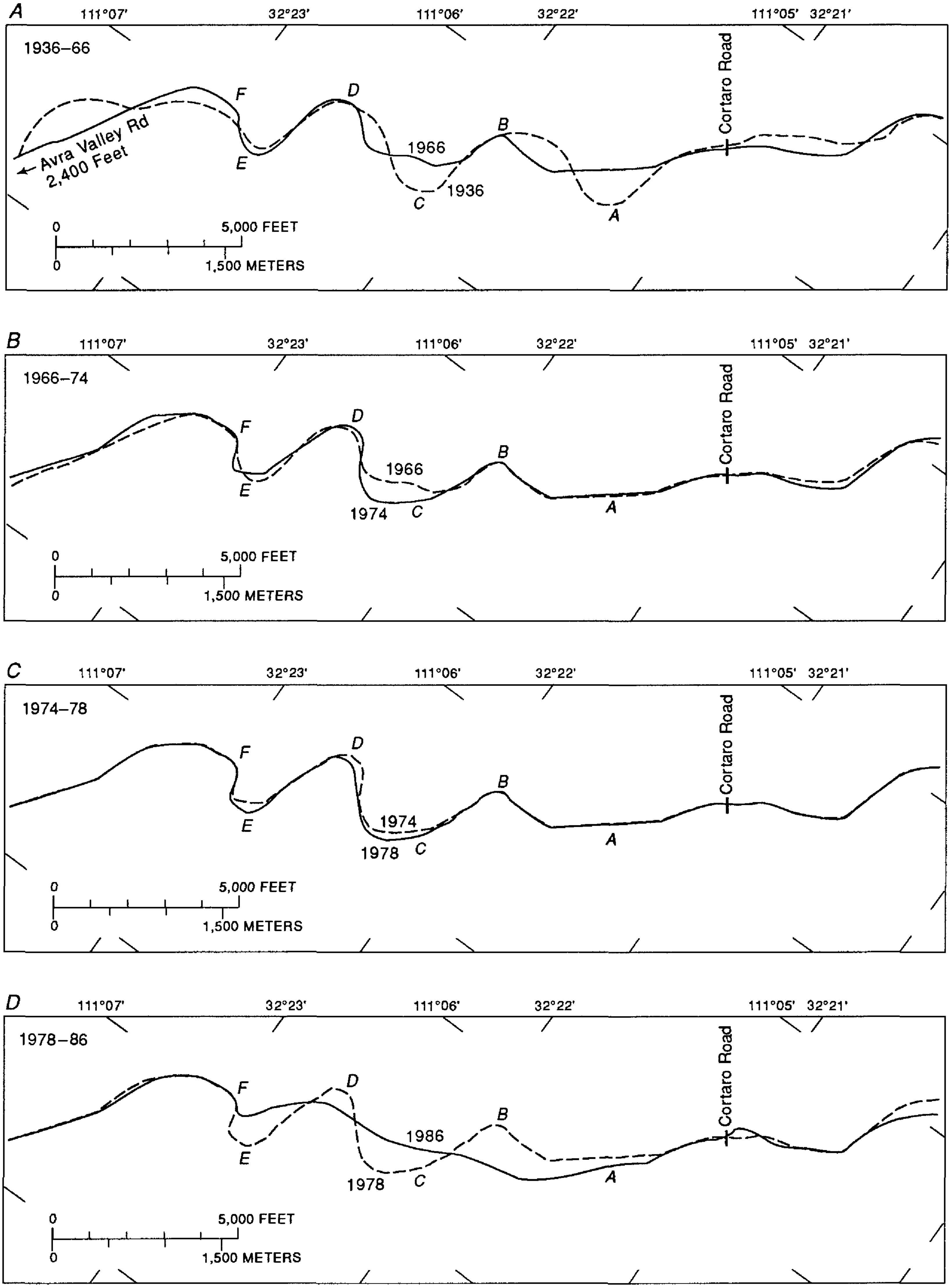


Figure 8. Meander development on lower Cortaro reach. Lines show location of channel center line.

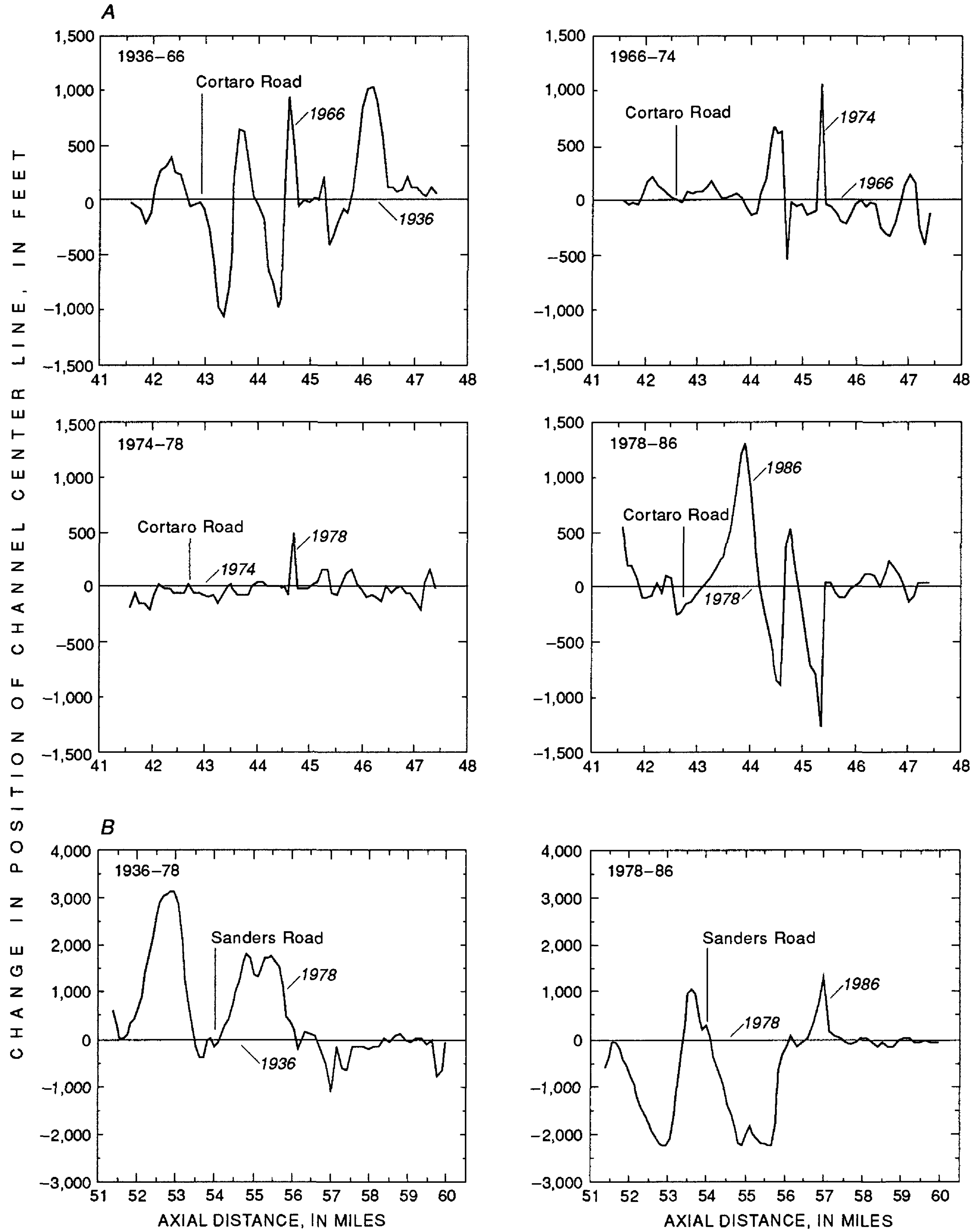


Figure 9. Changes in position of channel center line. A, Lower Cortaro reach. B, Upper Marana reach. Positive values indicate shift in position toward left side of channel; negative values indicate shift toward right side.

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. 11A). 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. 11B). 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 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.

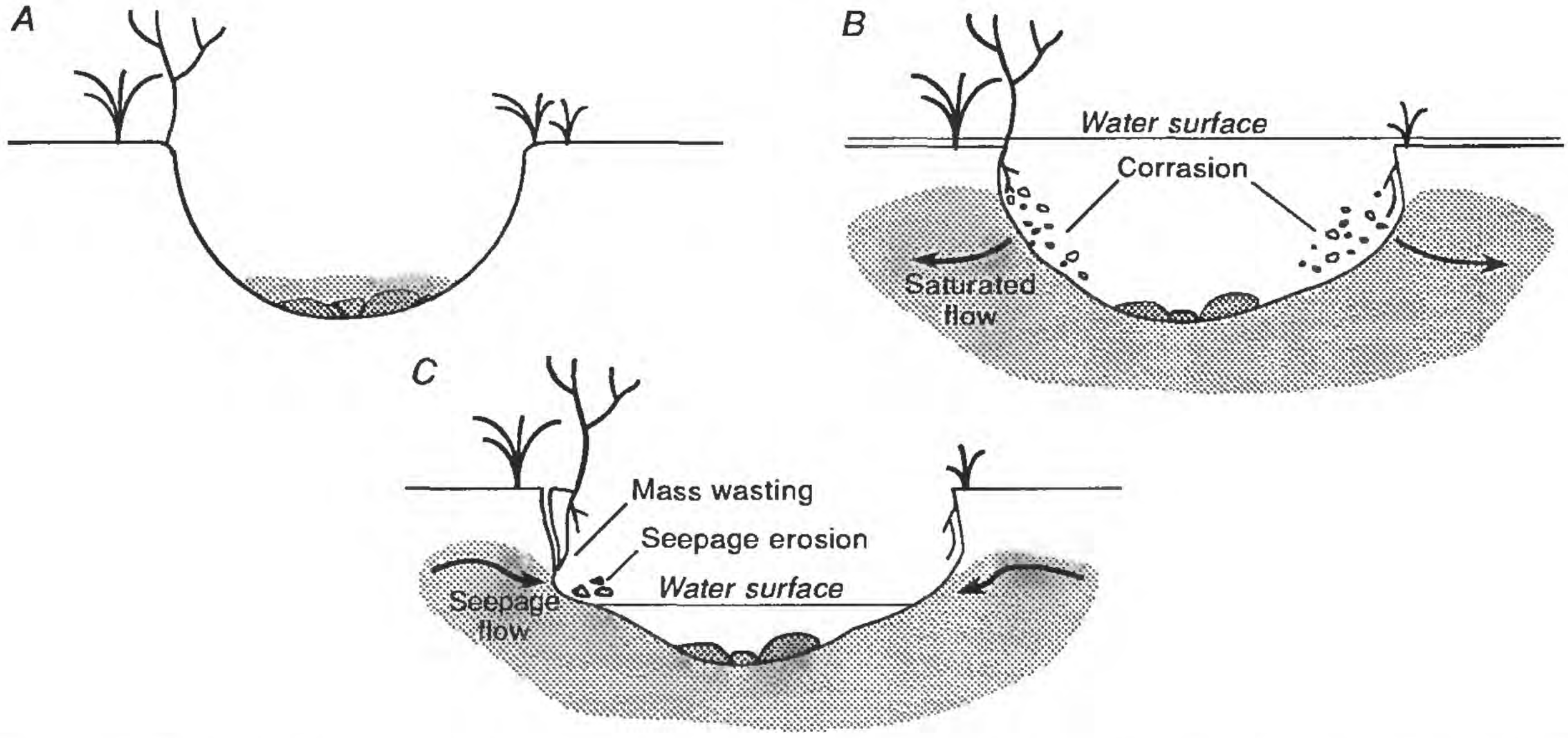


Figure 10. Process of channel widening. *A*, Initial channel. *B*, Corrasion and saturation of banks during rising flow. *C*, Seepage erosion and mass wasting following hydrograph fall.

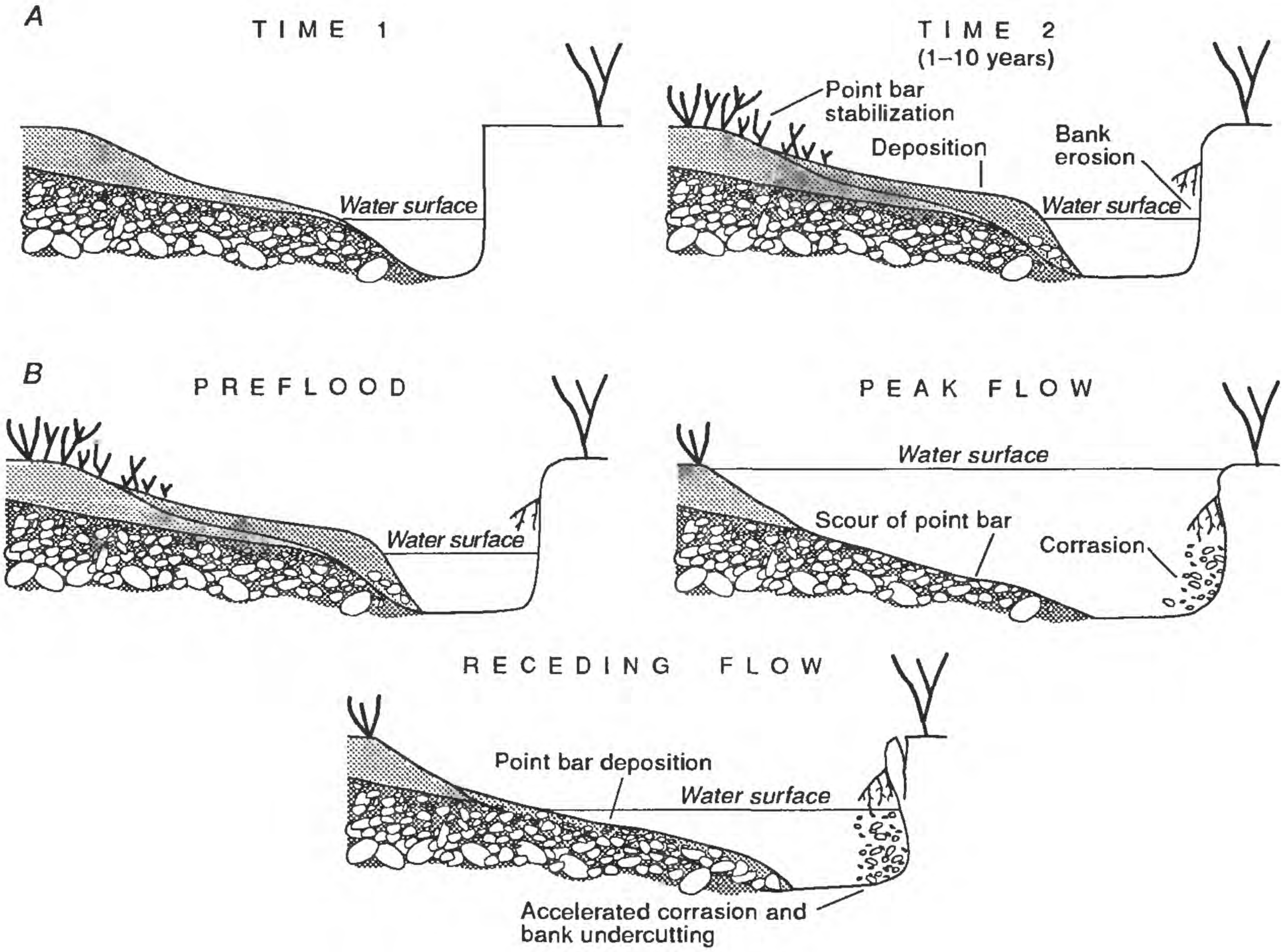


Figure 11. Role of channel migration in channel or arroyo widening. *A*, Migration in response to low to moderate flows producing no significant change in width. *B*, Migration in response to high flows producing channel widening.

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 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 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-foot-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. 13A). 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

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.

axial distance 0.7 mi (fig. 13A) was the result of lateral corrasion by high flow; widening in the unchannelized part of the reach between 0.7 and 1.6 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. 13B; 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.

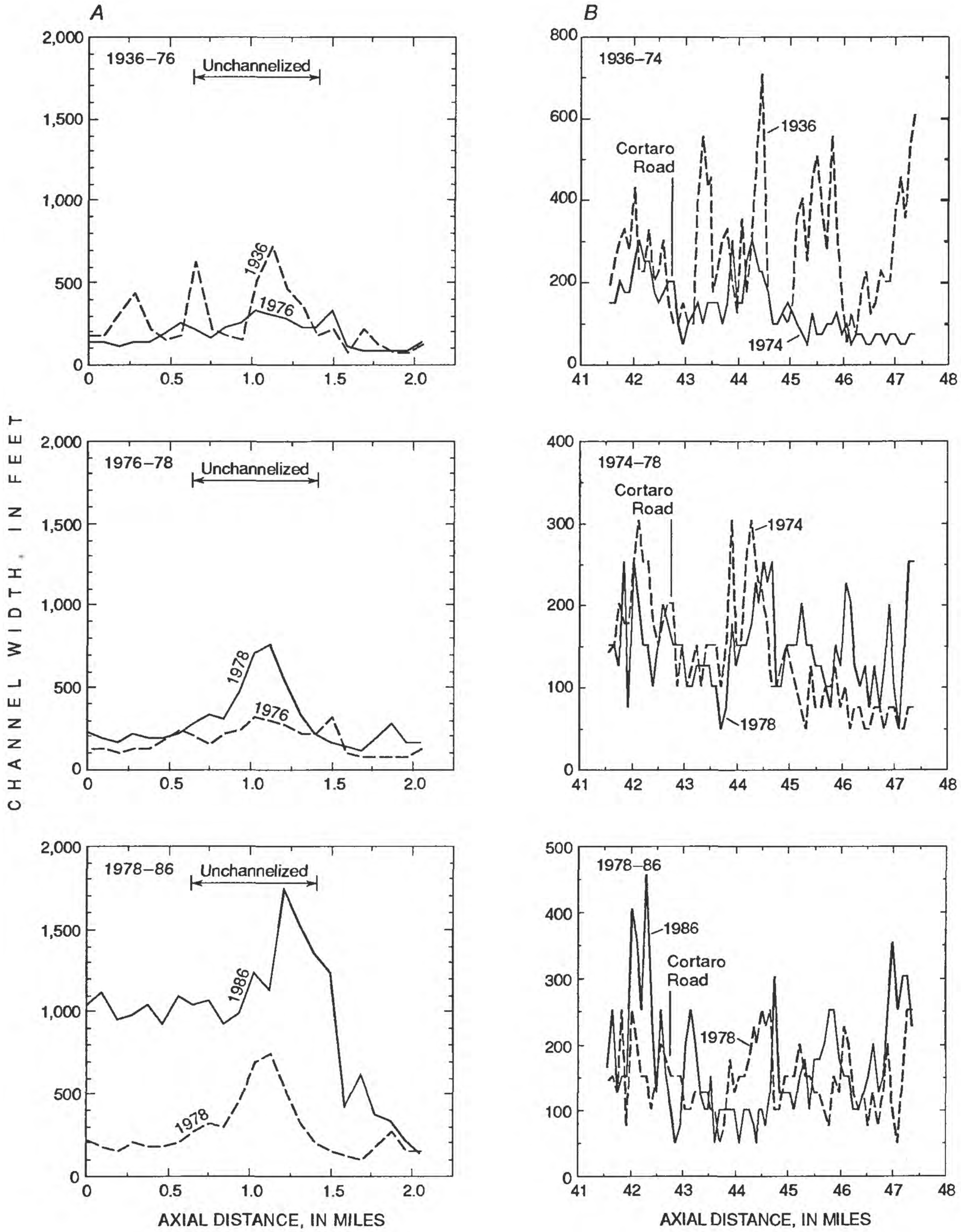


Figure 13. Channel-width changes on the Santa Cruz River. *A*, Upper Canoa reach. *B*, Lower Cortaro reach.

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 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. 5D-K). 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. 5F). 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. 5D-E). As seen in the 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. 5G and I), and maximum degradation had occurred at most sites between Valencia and Grant Roads by 1970-74. Following maximum incision, minor fluctuations in streambed elevation occurred through the 1970's.

Downstream from Grant Road, the record of vertical change is sparse and equivocal. Some change occurred at Cortaro

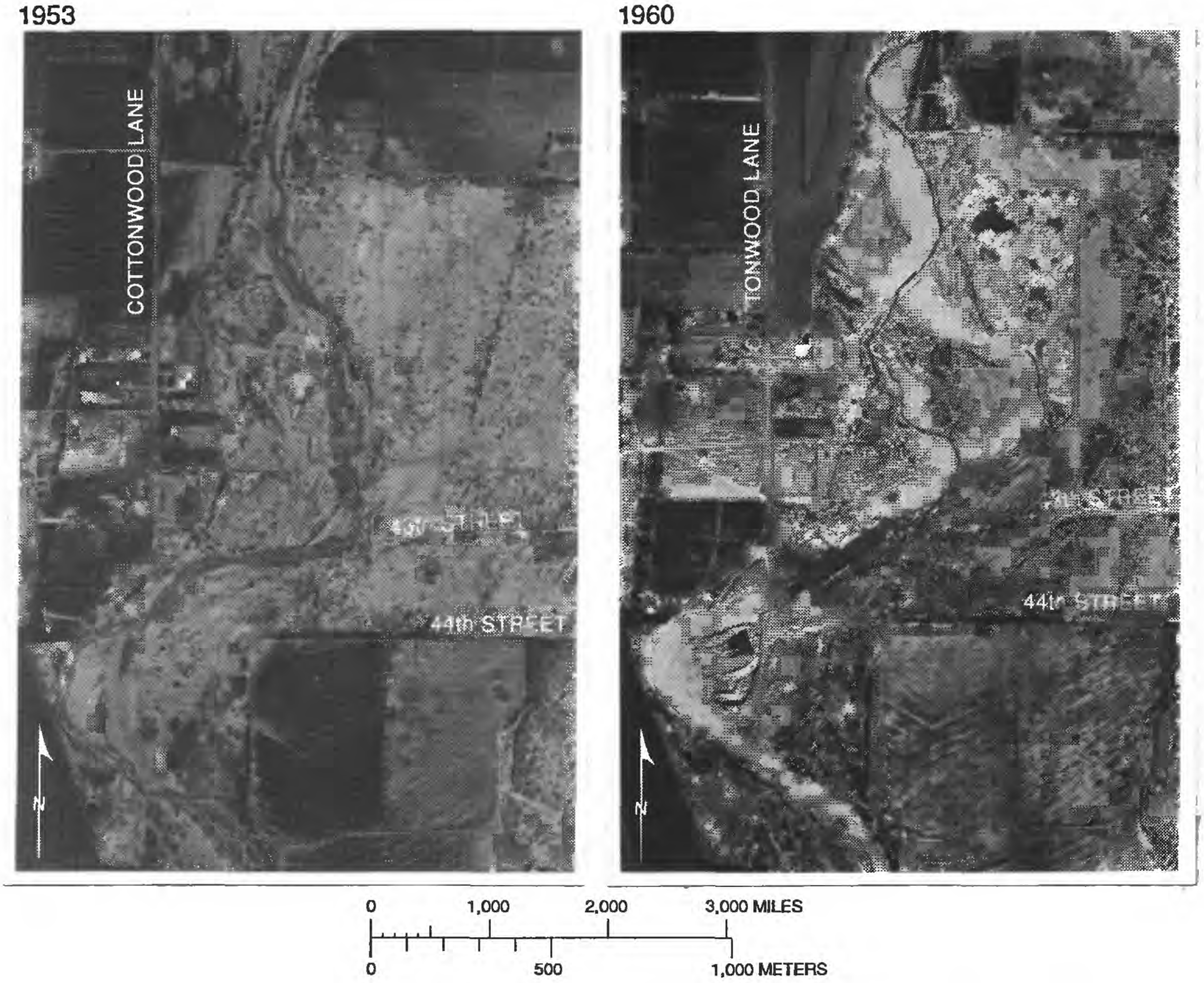


Figure 14. Avulsion within the arroyo in the lower San Xavier reach north of 44th Street, 1953–60. About 4 feet of aggradation occurred in the reach during that interval. (Source: Cooper Aerial Survey, 1953 and 1960.)

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 south boundary of the San Xavier Indian Reservation. In aerial photographs of 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 elevation 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, 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

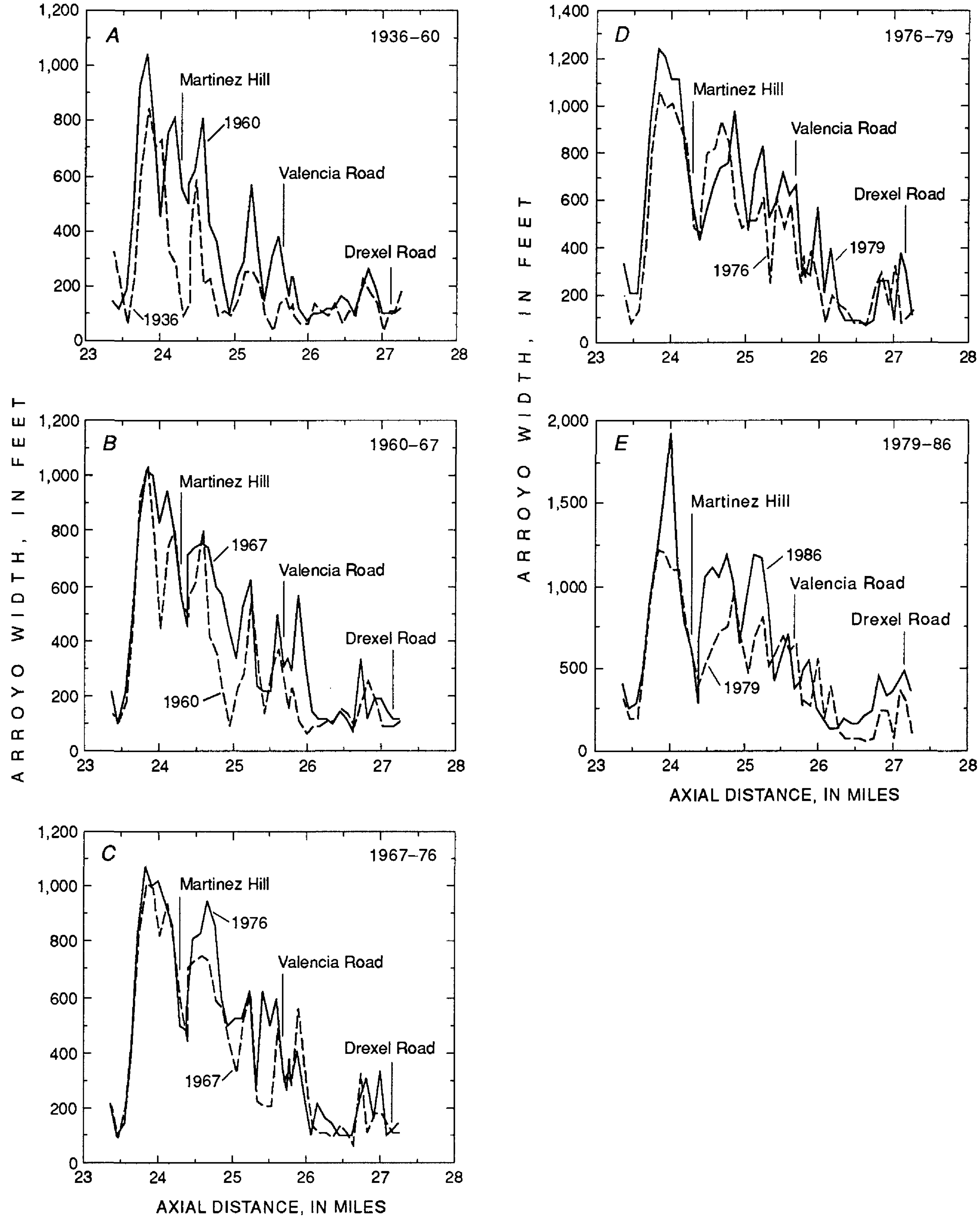


Figure 15. Arroyo widths on the lower San Xavier reach near Martinez Hill, 1936–86.

some places between 1936 and 1986. Mean arroyo width of the entire San Xavier reach increased from 200 to 500 ft.

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. 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).

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 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 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

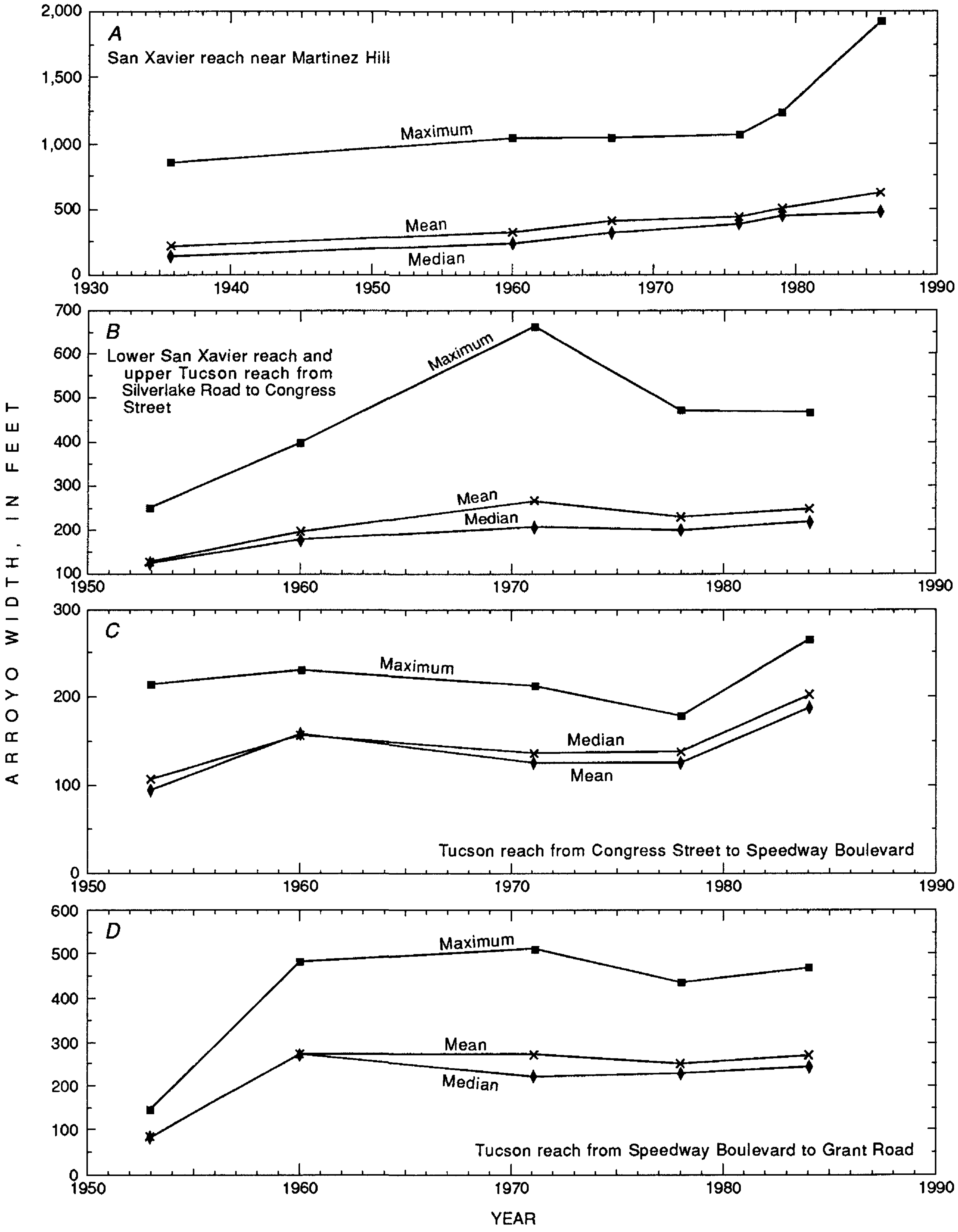


Figure 16. Arroyo-widening statistics for the San Xavier and Tucson reaches.

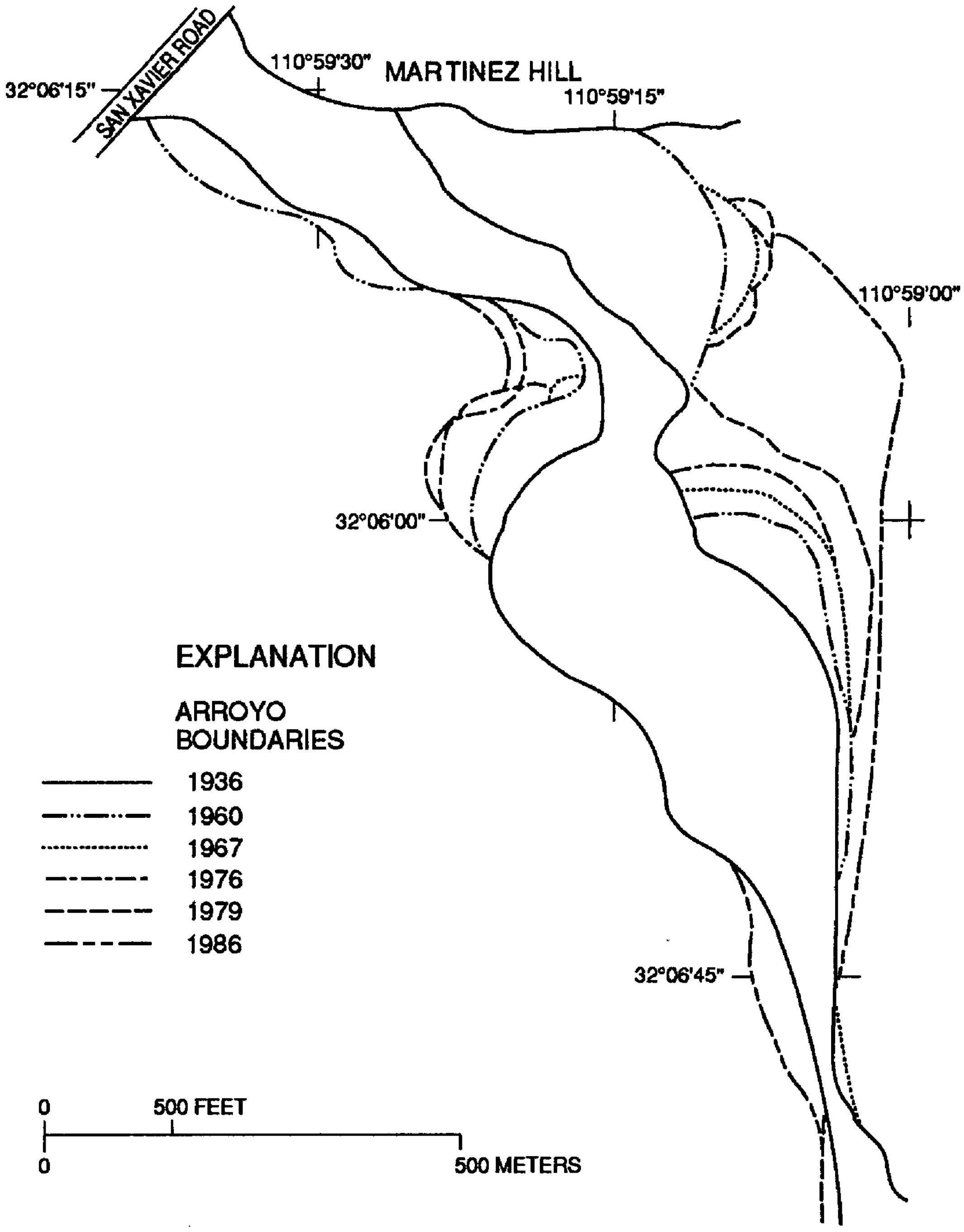


Figure 17. Arroyo widening caused by migration of entrenched meanders in the San Xavier reach at Martinez Hill, 1936–86. (Source: Data from National Archives, 1936; Cooper Aerial Survey, 1960, 1967, 1979, 1986; Kucera and Associates, 1976.)

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. Marys Road to Grant Road were mainly unprotected (Saarinen and others, 1984). Artificial armoring was presumably even less

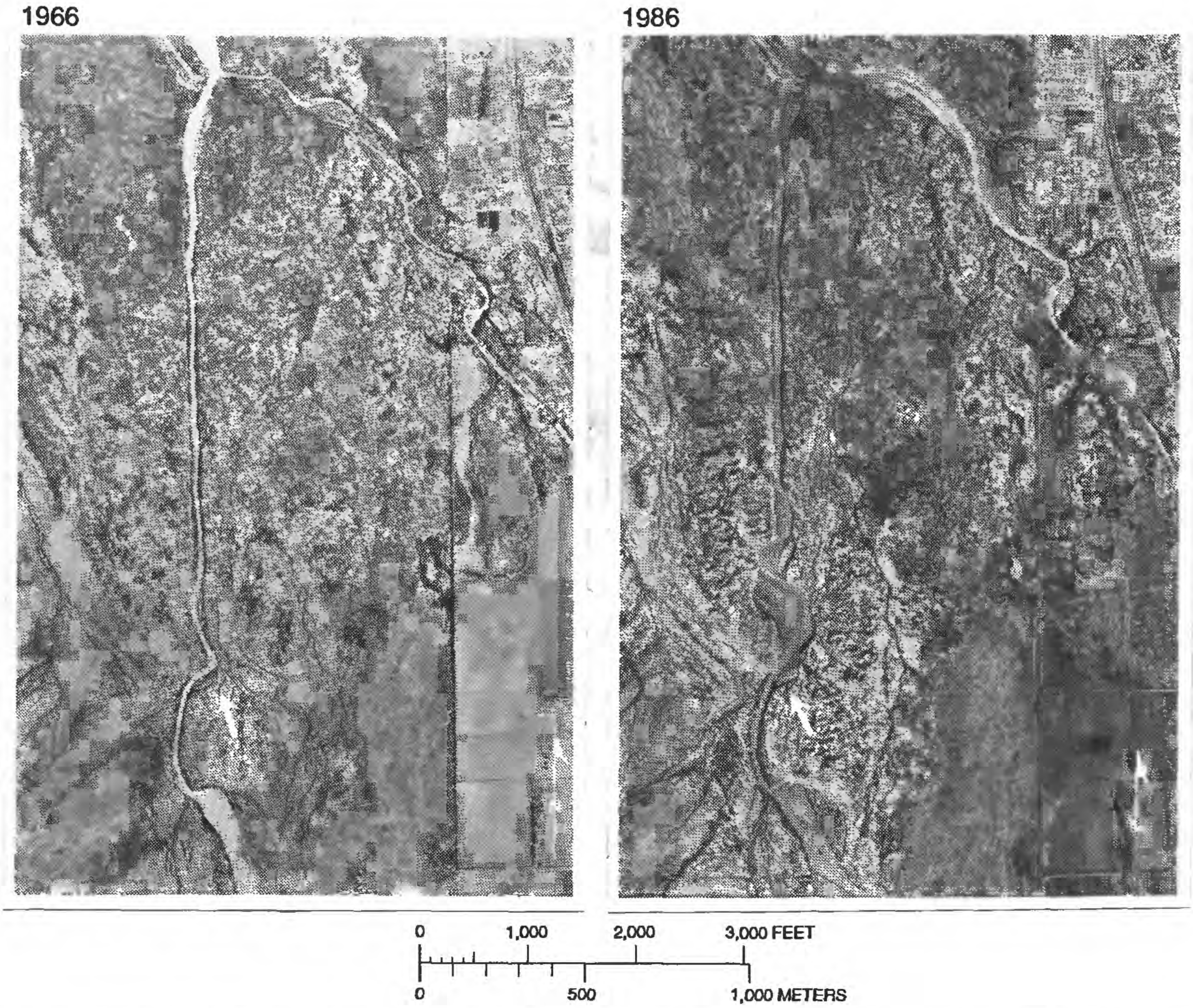


Figure 18. Changes on straight segment of the upper San Xavier reach, 1966–86. Arroyo width changed little except at the upstream end of the reach where an entrenched meander was migrating into the straight segment. Most of the change occurred during the flood of 1983. (Source: U.S. Geological Survey,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

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, 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 and fig. 19; 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

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

[Data from Webb and Betancourt (1990b)]

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	15	36	28	28
		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	23	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

Time interval	Nature and magnitude of channel change		
	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

	Nature and magnitude of channel change		
Time interval	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 Grand 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, 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.

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[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.

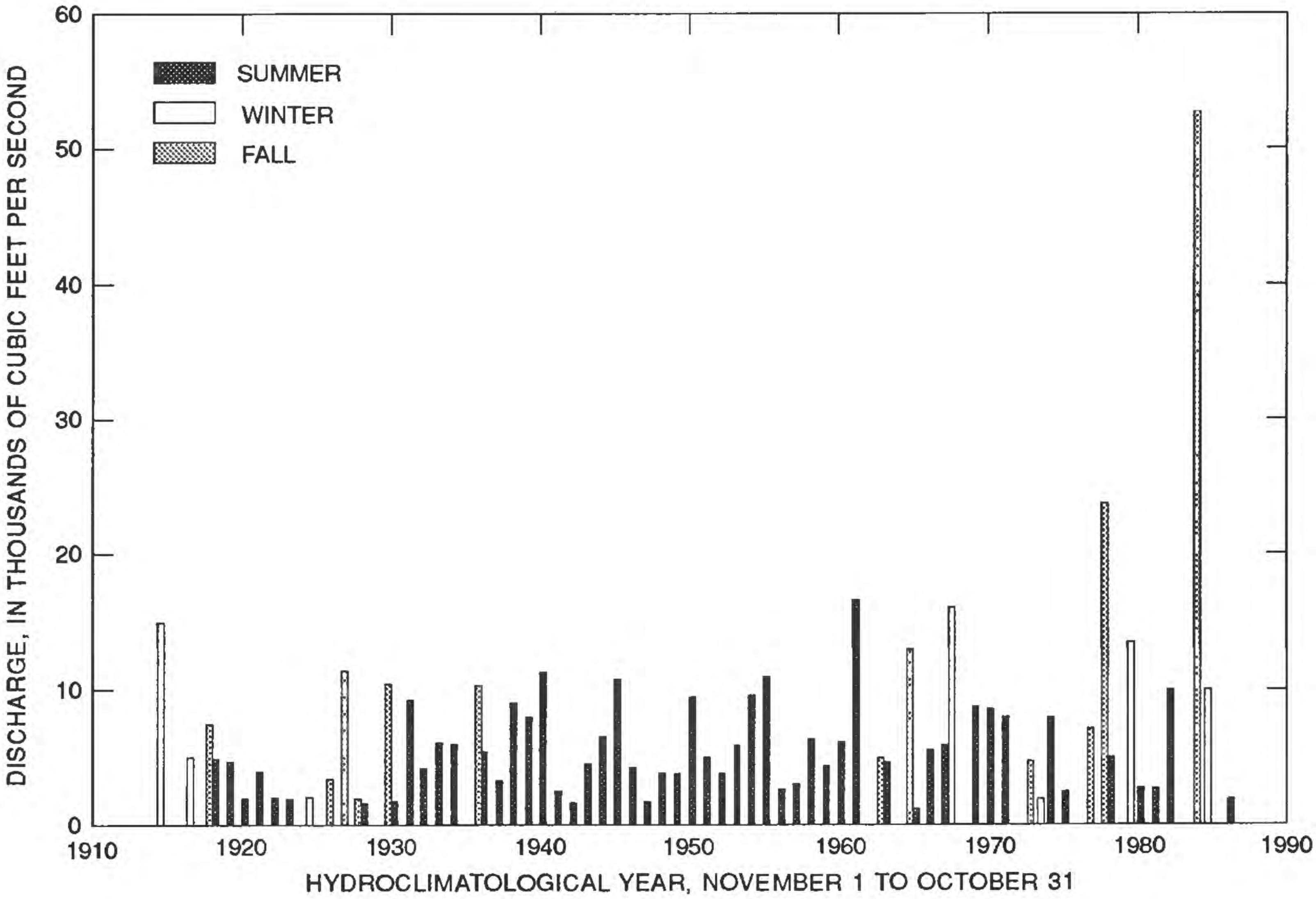


Figure 19. Annual flood series for the Santa Cruz River at Tucson. (Source: Data from Webb and Betancourt, 1992.)

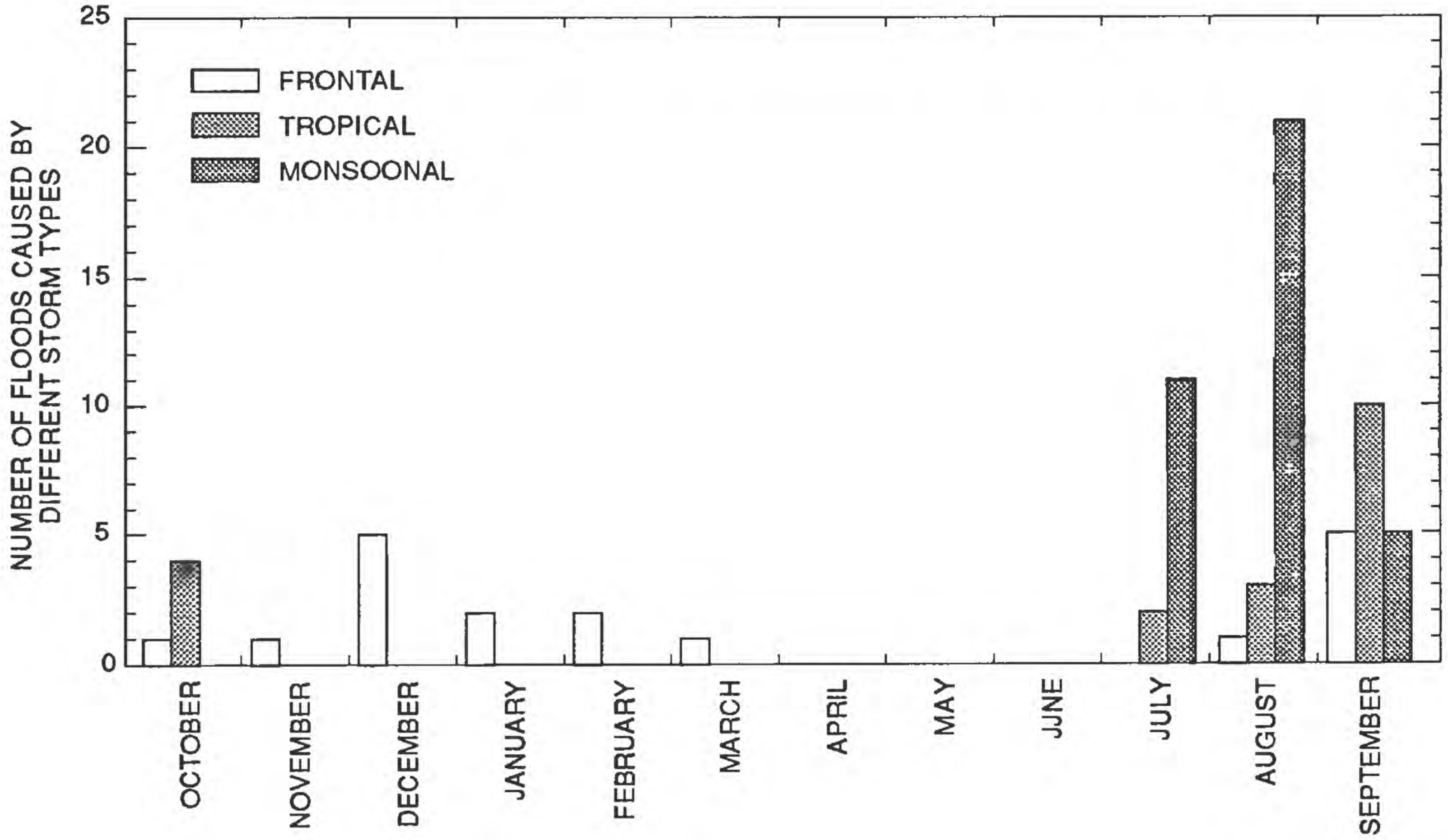


Figure 20. Seasonal occurrence of floods at Tucson caused by monsoonal thunderstorms, frontal systems, and dissipating tropical storms, 1914–84. (Source: Data from Webb and Betancourt, 1992.)

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 San Francisco River (Hjalmarson, 1990), and the Gila and San Pedro Rivers (Roeske and others, 1989). Fall and winter precipitation on those rivers typically account 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. 21A). 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 magnitude 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. 21A). Flow was considerably more flashy at 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

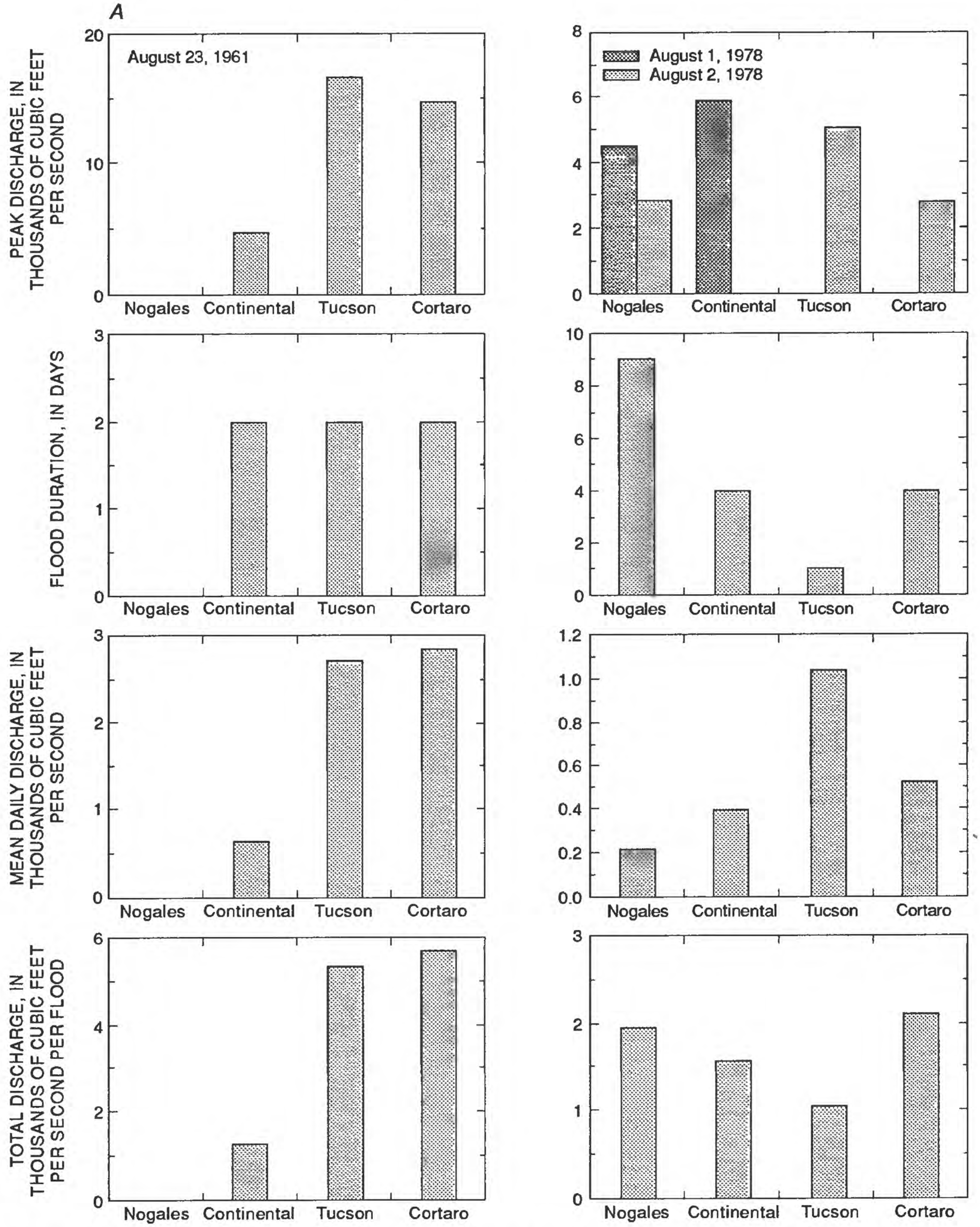


Figure 21. Flow characteristics of floods caused by different storm types at four stations on the Santa Cruz River. (Source: Data from Webb and Betancourt, 1992.) *A*, Floods of August 23, 1961 (no flow recorded at Nogales), and August 1–2, 1978, caused by monsoons. *B*, Floods of December 22–23, 1965, 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.

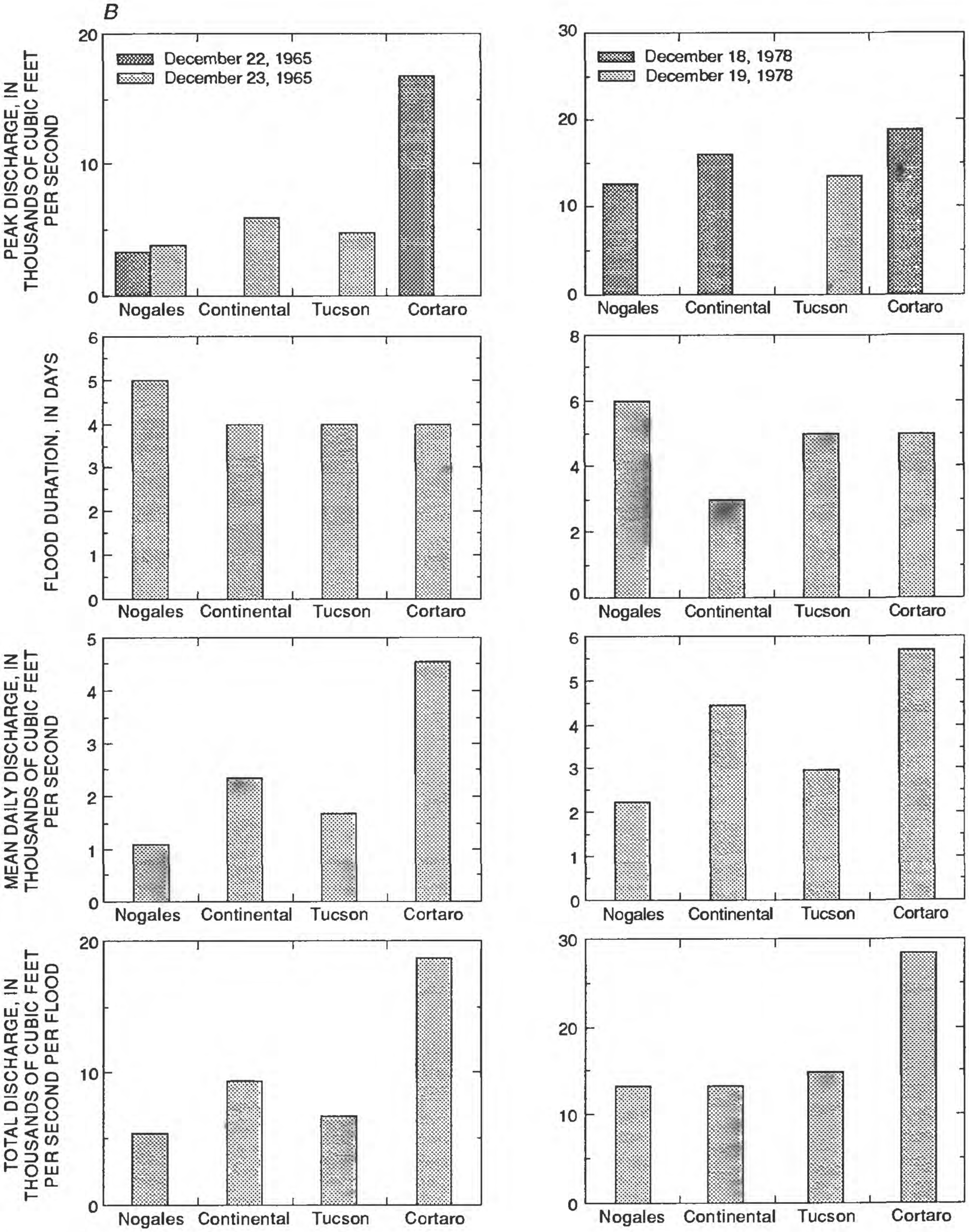


Figure 21. Continued.

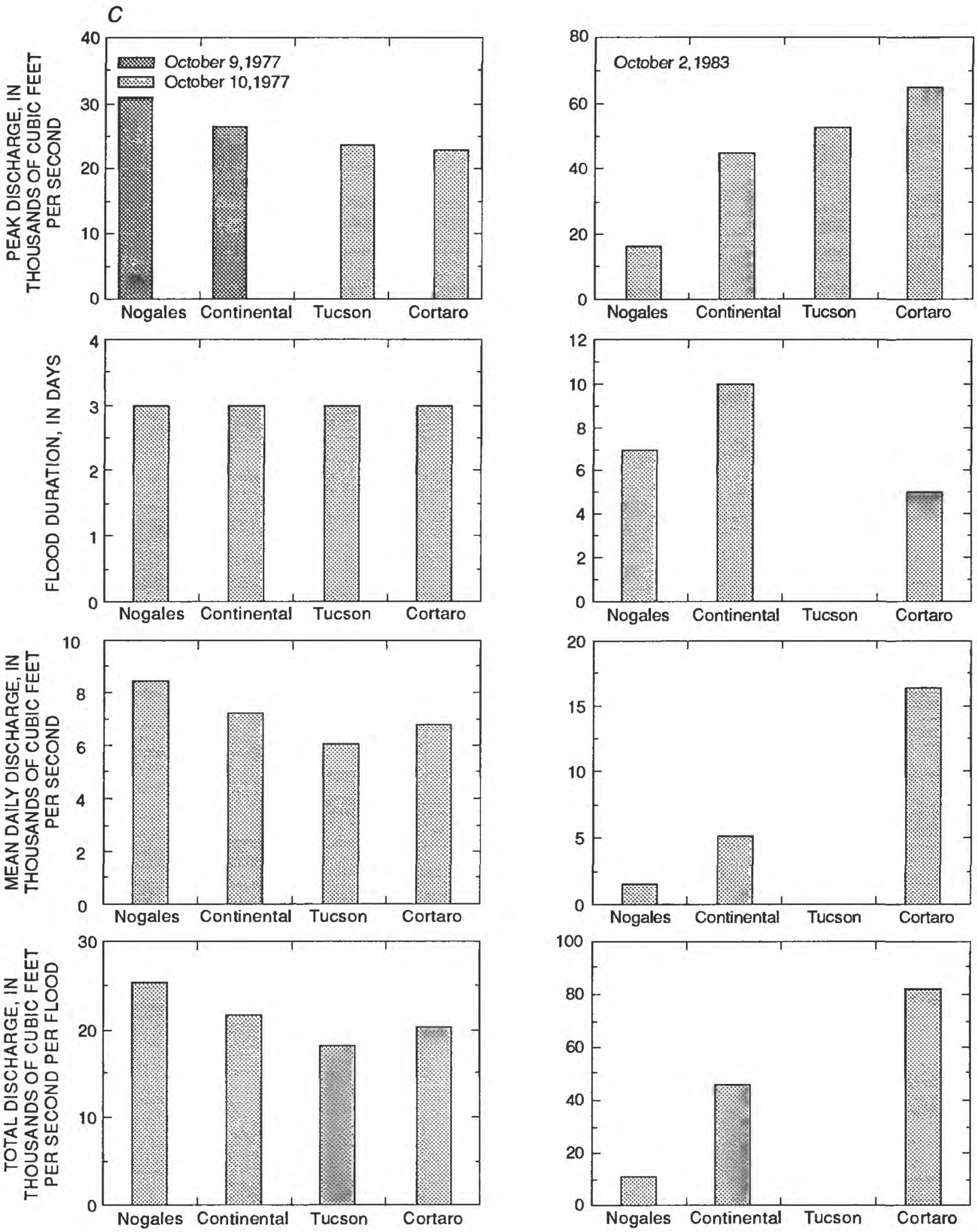


Figure 21. Continued.

antecedent hydrologic or hydraulic conditions at each site.

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. 21B). 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 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. 21C). 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 and fig. 22). Suspended-sediment data collected at Tucson during summer flows of the 1960's plot slightly above those collected during winter flows (fig. 22A). A t-test of the mean summer and winter concentrations, however, 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 sediment concentration had occurred and the data could not be compared with winter data of the 1960's (fig. 22B).

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

Date	Discharge, in cubic feet per second	Suspended-sediment concentration, in milligrams per liter
	Summer flows	
08-18-66	1,200	38,200
08-19-66	1,900	43,400
08-19-66	1,700	45,700
08-22-66	160	28,000
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	18,400
09-15-66	41	5,100
10-03-67	176	18,700
10-05-89	578	4,160
10-05-89	896	6,850
10-05-89	588	5,366
	Winter flows	
12-23-65	4,400	43,600
02-08-66	1,100	29,500
02-11-66	350	19,900
02-11-66	30	19,800
12-23-67	176	18,700

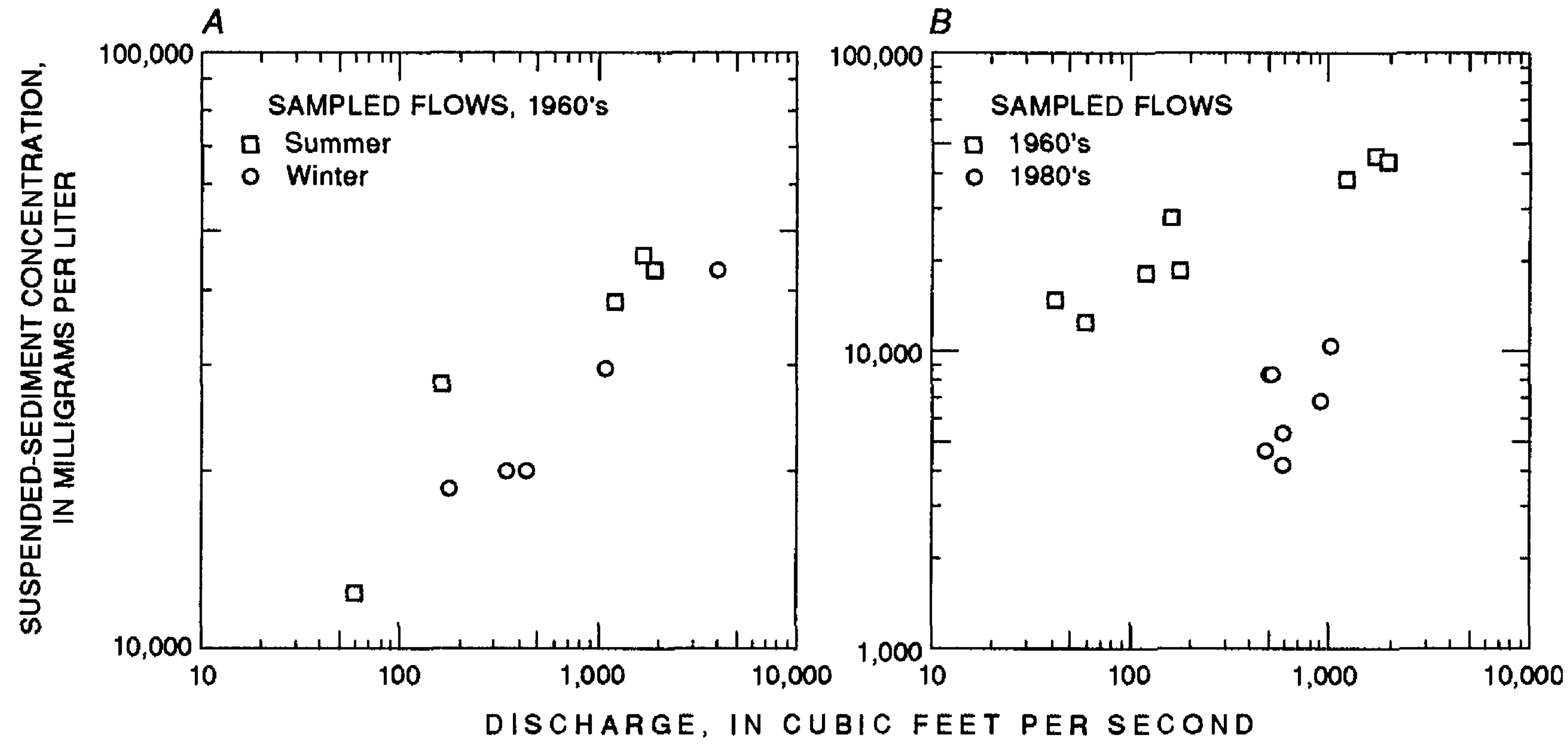


Figure 22. Relation of suspended-sediment concentration and discharge, Santa Cruz River at Tucson.

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 the 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. 16A), 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) 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. 13A). 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. 13A, 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. 21C) to strip 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 the 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 on 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).

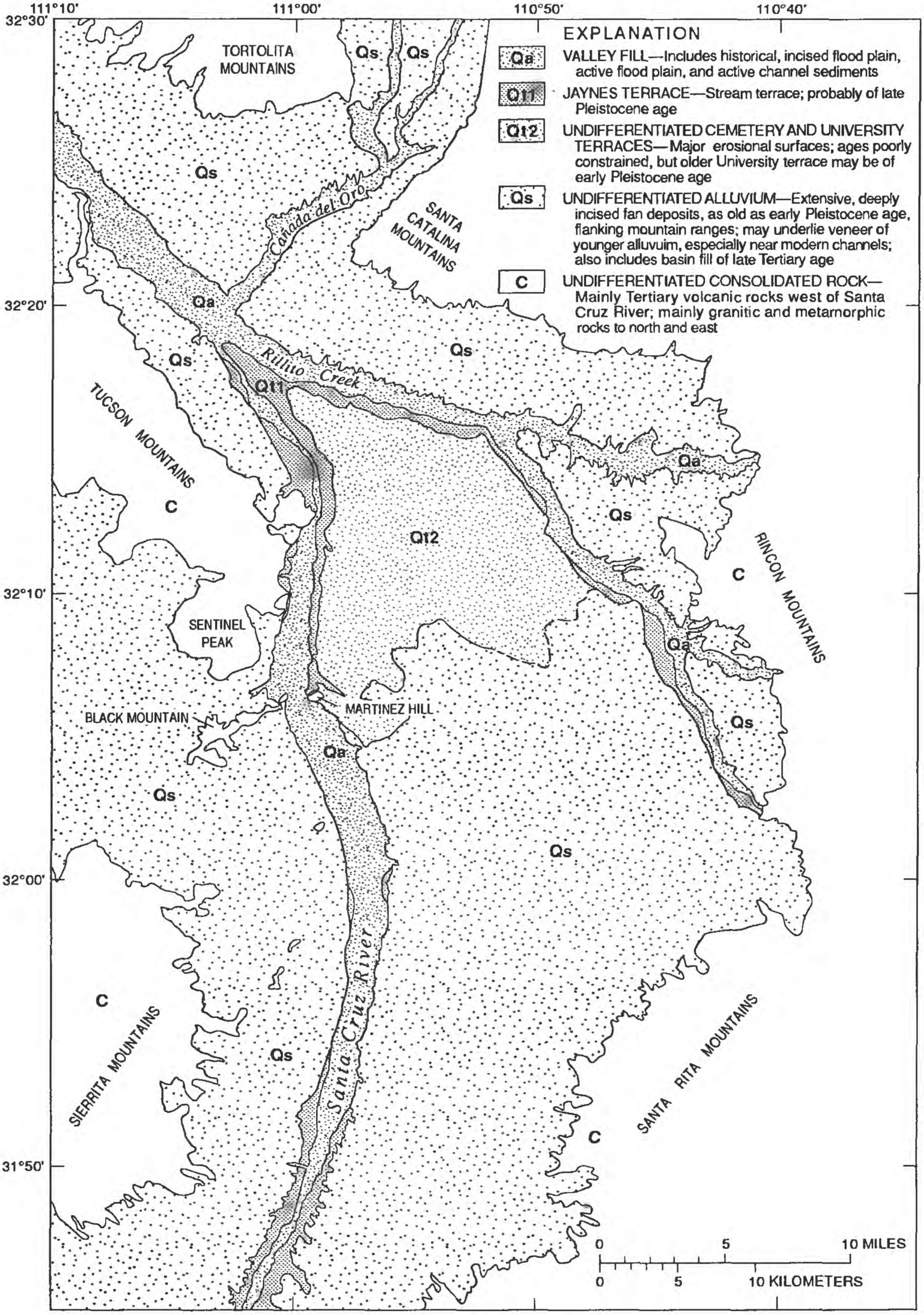
A systematic survey of sediment sources was not done during this study, but field observations and a review of geologic maps of the Santa Cruz River drainage basin (fig. 23) indicate that coarse-grained sediment sources of varying significance include (1) upland tributaries draining bedrock mountain ranges such as the Santa Rita and Catalina Mountains, (2) conglomeratic rock formations of Cenozoic age incised by the Santa Cruz 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 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



EXPLANATION

Qa	VALLEY FILL—Includes historical, incised flood plain, active flood plain, and active channel sediments
Qt1	JAYNES TERRACE—Stream terrace; probably of late Pleistocene age
Qt2	UNDIFFERENTIATED CEMETERY AND UNIVERSITY TERRACES—Major erosional surfaces; ages poorly constrained, but older University terrace may be of early Pleistocene age
Qs	UNDIFFERENTIATED ALLUVIUM—Extensive, deeply incised fan deposits, as old as early Pleistocene age, flanking mountain ranges; may underlie veneer of younger alluvuim, especially near modern channels; also includes basin fill of late Tertiary age
C	UNDIFFERENTIATED CONSOLIDATED ROCK—Mainly Tertiary volcanic rocks west of Santa Cruz River; mainly granitic and metamorphic rocks to north and east

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

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. 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 re-entered 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 Hill 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, 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 (Waters, 1988; Haynes and Huckell, 1986). 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, 1937). 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 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, 1991). 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. 9B). Such a pattern indicates that the flood caused the river to reactivate paleochannels (as suggested in fig. 7B); the river's new course was controlled largely by pre-existing 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. 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. 14A), which was a period dominated by low to moderate annual floods. Slope-stability factors, as well as channel processes, must be considered in

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

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 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 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 will not be 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. 20B and 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, 1986; 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-mile 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 pre-existing 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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FEDERAL PARTICIPATION IN WATERWAYS DEVELOPMENT

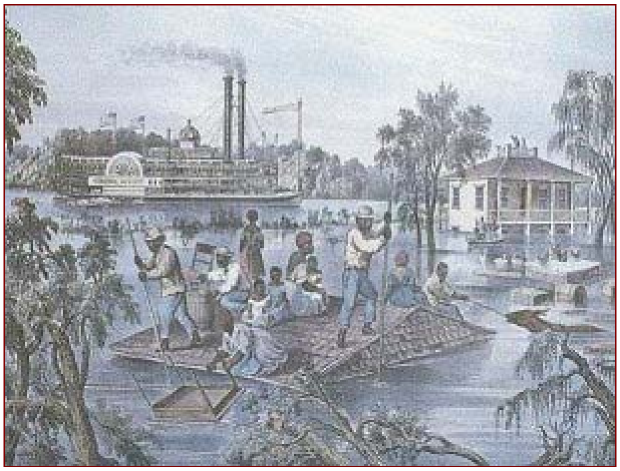
In 1820, Congress began addressing the navigational needs of the nation's interior by authorizing a reconnaissance of the Mississippi and Ohio rivers. It was made by Captains H. Young and W. T. Poussin, and Lt. S. Tuttle of the Engineer Corps of the Army. Fieldwork, begun in 1821, extended from Louisville to the mouth of the Ohio River and from St. Louis to New Orleans on the Mississippi. Also, in 1821, two Engineer officers, Brig. Gen. Simon Barnard and Maj. Joseph G. Totten, were detailed to make a thorough investigation of the Mississippi and Ohio Rivers. Their report, submitted the following year, contained observations on the physical characteristics of the rivers and gave considerable attention to the formation and removal of snags. Legislation was enacted in 1824 directing the removal of snags and other obstructions from the channels of the rivers.

In 1831, a bold attempt was made to improve navigation conditions at the mouth of the Red River by an artificial cutoff, proposed by Capt. Henry M. Shreve. A second cutoff was made at Raccourci Bend, several miles below, by Louisiana in 1848.

Improvements of the Mouth

Improvement of the mouth of the Mississippi River for seagoing navigation was first undertaken by Congress in 1837, with an appropriation made for an accurate survey of the passes and bars at the river's mouth. This survey was conducted by Capt. A. Talcott, Corps of Engineers, and finished in 1838. He recommended a plan for deepening the bars by dredging, but a lack of necessary funds prevented substantial progress on his channel & project.

By 1850, the growing river commerce, together with increasing destruction caused by floods, was creating demand for Federal participation in navigation improvements and flood protection.



A painting of the destruction caused by the floods.

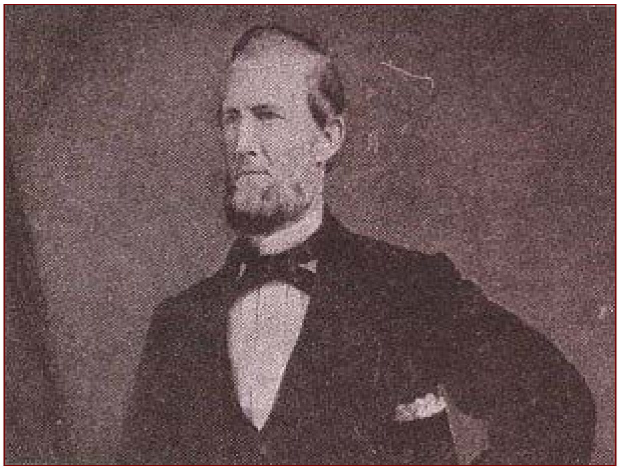
In 1850, the Secretary of War, conforming to an Act of Congress, directed Charles Ellet Jr., an engineer, to make surveys and reports on the Mississippi and Ohio Rivers with a view to the preparation of adequate plans for flood prevention and navigation improvement. His report was most complete, and it exercised considerable influence on later thought.

Also in 1850, Congress appropriated $50,000 for the preparation of a topographic and hydrographic survey of the delta of the Mississippi and for investigations to determine the most practicable plans for flood control and navigation improvements at the mouth of the river. But it was not until 1861 that Capt. A. A. Humphreys and Henry L. Abbott, of the Corps of Engineers, were able to complete their field investigations and submit their now-famous "Report Upon the Physics and Hydraulics of the Mississippi

River; Upon the Protection of the Alluvial Region Against Overflow; and Upon the Deepening of the Mouths." While this report dealt primarily with flood control, it did consider the navigation problem in considerable detail and was a great step forward in the development of river engineering in the United States.

Jetty System

Meanwhile, the problem of keeping the river's mouth open to oceangoing traffic was one of serious growing concern to the Nation. Congress appropriated $75,000 In 1852 for improving the channel at the mouth of the river by contract.



A photograph of Capt. James B. Eads.

It was not until 1867 that dredging operations were resumed at the mouth of the Mississippi River, but still the vexing problem was not solved. No significant progress had been made by 1873 when Capt. James B. Eads, a famous construction engineer, advocated a system of parallel jetties. He offered to open the mouth of the river by making a jetty-guaranteed channel 28 feet deep between Southwest Pass and the Gulf at his own risk. If he succeeded, his fee would be $10,000,000.

After much debate, in 1875 Eads was directed to begin his work, in South rather than Southwest Pass. He faced a difficult task, complicated by the existence of yellow fever and unfavorable financial arrangements; however, he pushed the project to completion. On July 8, 1879, a 30-foot channel was officially declared to exist at the mouth of the Mississippi.

Levee System Advocated

The importance of the Mississippi River to the Nation had, by now, become firmly established. Congress had shown an increasing interest in flood control and navigation problems on the Mississippi, and legislation designed to improve this mighty stream for the use of the Nation was rapidly taking form. In 1874, Congress had authorized certain surveys of transportation routes to the seaboard. Among these was reconnaissance of the Mississippi River from Cairo to New Orleans, made under the direction of Maj. Charles R. Suter, an officer of the Corps of Engineers.

A painting of surveying the Mississippi River.

Five years later, a board of Engineer officers concluded that a complete levee system would aid commerce during periods of high water only. Their conclusion is noteworthy for considering flood control and navigation improvements as part of the same problem.

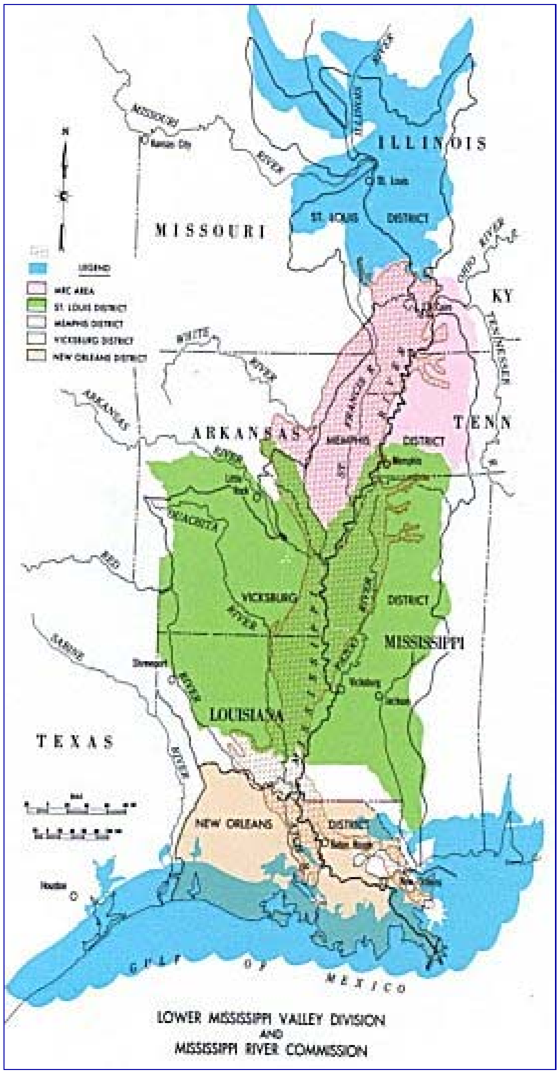
Mississippi River Commission

In that same year, 1879, on June 28, the Mississippi River Commission was created by Act of Congress as an executive body reporting to the Secretary of War. The Commission is composed of seven men nominated by the President of the United States and confirmed by the Senate.

Since the enactment of the Flood Control Act of May 15, 1928, the Commission has served as an advisory and consulting - rather than executive - body responsible to the Chief of Engineers, U.S. Army. The general duties of the Commission include the recommendation of policy and work programs, the study of and reporting upon the necessity for modifications or additions to the flood control and navigation project, recommendation upon any matters authorized by law, making inspection trips, and holding public hearings. The work of the Commission is directed by the President of the Commission, acting as its executive officer, and carried out by U.S. Army Engineer Districts at St. Louis, Memphis, Vicksburg, and New Orleans.

Lower Mississippi Valley Division

The President of the Commission also serves as Division Engineer, U.S. Army Engineer Division, Lower Mississippi Valley, headquartered in Vicksburg. The jurisdiction of this Division extends from about Hannibal, Missouri, to the Gulf of Mexico. Work within the Division is carried out by the Engineer Districts listed above.

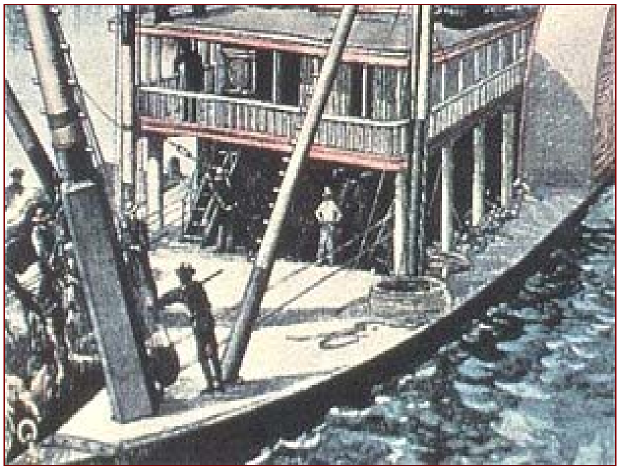


A map of the Lower Mississippi Valley Division
and Mississippi River Commission.
[Click to view larger map.]

Improvements for Navigation

In 1896, Congress authorized a navigation channel 9 feet deep and 250 feet wide at low water between Cairo and Head of Passes. In 1928, the width was increased to 300 feet, and in 1944, the authorized channel depth from Cairo to Baton Rouge was increased to 12 feet at low water, with the authorized width remaining at 300 feet. (The 12-foot channel is to be obtained by a program of bank stabilization and maintained by dredging. Progress is being made on developing this channel, and a 9-foot depth is now being maintained.)

Early improvements of the Mississippi River above Cairo consisted mostly of removal of snags and closure of sloughs to confine low-water flows to the main channel.



A painting of dredging the Mississippi River.

Then in 1907, Congress adopted a project depth of 6 feet between the Missouri River just above St. Louis and Minneapolis, to be obtained by dredging and the construction of wing dams to contract the low-water channel.

As development of inland navigation continued, it became apparent that a depth of 6 feet on the upper Mississippi would not allow it to keep pace with the growing traffic on the 9-foot channels of the lower Mississippi and the Ohio. In 1930, following a careful study of the merits of improvement of the river, Congress authorized construction of a 9-foot channel between Minneapolis and the mouth of the Illinois River, just above St. Louis, providing for the construction of locks and dams. The act was modified in 1932 to provide for some modifications to the improvement plan. Since that time, additional modifications have been made to the basic project.

Under the plan of improvement, 36 locks and 29 dams were constructed. There are no locks and dams below St. Louis.

After the mouths of the Mississippi River had been opened and maintained in a navigable state, Congress authorized in 1945 the development of a navigation channel for oceangoing traffic in the lower reaches of the river. The depths and widths of the channel between Baton Rouge and the Gulf of Mexico are:

- Baton Rouge to New Orleans - 40 by 500 feet
- Port of New Orleans - 35 by 1,500 feet, with portion 40 by 500 feet
- New Orleans to Head of Passes - 40 by 1,000 feet
- In Southwest Pass - 40 by 800 feet
- In Southwest Pass Bar Channel - 40 by 600 feet
- In South Pass - 30 by 450 feet
- In South Pass Bar Channel - 30 by 600 feet
- Mississippi River-Gulf Outlet - 36 by 500 feet
- Mississippi River-Gulf Outlet Bar Channel - 38 by 600 feet

[Continue to River Commerce]

UNITED STATES
DEPARTMENT OF THE INTERIOR
Oscar L. Chapman, Secretary

BUREAU OF RECLAMATION
Michael W. Straus, Commissioner

REGION 3
E. G. Nielsen, Regional Director

REPORT

ON

WATER SUPPLY

OF THE

LOWER COLORADO RIVER BASIN

PROJECT PLANNING REPORT

NOVEMBER 1952

Sheet 8 of 11

Table 22 (Continued)
LOWER COLORADO RIVER BASIN
Analysis of Contributions by States Based on Mean Historic Runoff
For the 1914-1945 Period

Unit: 1,000 acre-feet

River section	Item	Arizona	California	Nevada	New Mexico	Utah	Mexico	Undistributed	Total
GILA RIVER FROM COOLIDGE DAM TO GAGE AT KELVIN, ARIZONA									
Estimated inflow, Coolidge Dam to Kelvin	135	75.2	0	0	0	0	0	0	75.2
Consumptive use, Coolidge Dam to Kelvin	136	10.5	0	0	0	0	0	0	10.5
Volumes conveyed, Coolidge Dam to Kelvin	137	256.5	0	0	186.4	0	14.2	0	457.1
Channel losses, Coolidge Dam to Kelvin	138	$15.2	0	0	¢ 5.2	0	¢ 1.8	0	22.2
Gila River at Kelvin, Arizona	139	241.3	0	0	181.2	0	12.4	0	434.9
SANTA CRUZ RIVER FROM GAGE NEAR NOGALES, ARIZONA, TO GAGE AT RILLITO, ARIZONA									
Santa Cruz River near Nogales, Arizona	140	6.6	0	0	0	0	8.6	0	15.2
Water obtained from average depletion of ground-water basin in Santa Cruz and Pima Counties	141	20.8	0	0	0	0	0	0	20.8
Estimated inflow, Nogales to Rillito	142	83.2	0	0	0	0	1.8	0	85.0
Consumptive use, Nogales to Rillito	143	66.6	0	0	0	0	0	0	66.6
Volumes conveyed, Nogales to Rillito	144	44.0	0	0	0	0	10.4	0	54.4
Channel losses, Nogales to Rillito	145	$20.0	0	0	0	0	¢ 4.7	0	24.7
Santa Cruz River at Rillito, Arizona	146	24.0	0	0	0	0	5.7	0	29.7
SALT RIVER FROM ABOVE ROOSEVELT RESERVOIR TO GRANITE REEF DAM, ARIZONA									
Salt River near Roosevelt, Arizona	147	706.5	0	0	0	0	0	0	706.5
Tonto Creek near Roosevelt, Arizona	148	107.9	0	0	0	0	0	0	107.9
Verde River below Bartlett Dam, Arizona	149	522.4	0	0	0	0	0	0	522.4
Estimated inflow to Granite Reef Dam	150	100.2	0	0	0	0	0	0	100.2
Consumptive use, Roosevelt to Granite Reef	151	.3	0	0	0	0	0	0	.3
Export diversions for City of Phoenix	152	10.2	0	0	0	0	0	0	10.2
Reservoir evaporation depletions from	153	27.0	0	0	0	0	0	0	27.0

Item No.

138. Estimated channel losses of 22,200 acre-feet a year were prorated among Arizona, New Mexico, and Mexico on the basis of the respective volumes conveyed from Mammoth to the mouth of the San Pedro River and from Coolidge Dam to Kelvin on the Gila River. (See Table 14 for total. San Pedro River from Mammoth to mouth, 9,700 acre-feet plus Gila River from Coolidge Dam to Kelvin, 12,500 acre-feet).

139. Item 137 minus Item 138 (see Appendix A, Sheet 38A of Table 6 for total).

140. Average annual historical flow of the Santa Cruz River at the gage near Nogales, Arizona (see Appendix A, Sheet 39 of Table 6 for total). The flow was prorated between Arizona and Mexico on the basis of their respective drainage areas with consideration for upstream depletions of 600 acre-feet a year in Arizona and 5,400 acre-feet a year in Mexico.

141. It was estimated that the ground water stored in this river section prior to 1914 was depleted an average 20,800 acre-feet a year during the 1914-1945 period (see Upper Santa Cruz River in Table 4).

142. The total estimated inflow to this river section was computed as the differential needed to balance the measured flow of the Santa Cruz River at Rillito adjusted for consumptive use, channel losses, and change in ground-water storage in the section. The contribution from Mexico was estimated by applying the runoff rate of the undepleted flow near Nogales to the drainage area in Mexico in this section. The balance of the total estimated inflow was apportioned to Arizona.

143. Consumptive use of irrigation water by crops and noncropped areas in this stream section (A-14-G plus A-15-G in Table 12); all in Arizona.

144. Item 140 plus Items 141 and 142 minus Item 143.

145. The estimated channel losses of 24,700 acre-feet a year in this stream section were prorated between Arizona and Mexico on the basis of the respective volumes conveyed (see Table 14 for total).

146. Item 144 minus Item 145 (see Appendix A, Sheet 42 of Table 6 for total).

147. Average annual historical flow of the Salt River at the gage near Roosevelt (see Appendix A, Sheet 43A of Table 6); all in Arizona.

Table 23 (Continued) Sheet 11 of 14

LOWER COLORADO RIVER BASIN

Analysis of Contributions by States Based on Mean Virgin Runoff for the 1914-1945 Period, Unit: 1,000 Acre-feet

Item numbers not in parentheses are taken from Table 22, based on historic runoff

River section	Item	Arizona	California	Nevada	New Mexico	Utah	Mexico	Undistributed	Total
GILA RIVER FROM COOLIDGE DAM TO GAGE AT KELVIN, ARIZONA									
Estimated inflow, Coolidge Dam to Kelvin	135	75.2	0	0	0	0	0	0	75.2
Undepleted volumes conveyed to Kelvin	(145)	366.4	0	0	192.9	0	15.3	0	574.6
Historic channel losses	138	15.2	0	0	5.2	0	1.8	0	22.2
Virgin channel losses	(146)	$20.8	0	0	¢ 5.2	0	¢ 1.8	0	27.8
Salvage of channel evaporation	(147)	.1	0	0	0	0	0	0	.1
Replacement of native vegetation	(148)	4.2	0	0	0	0	0	0	4.2
Decreased losses from native growth change	(149)	1.3	0	0	0	0	0	0	1.3
Undepleted Gila River at Kelvin, Arizona	(150)	345.6	0	0	187.7	0	13.5	0	546.8
SANTA CRUZ RIVER FROM HEADWATERS IN ARIZONA THROUGH MEXICO TO GAGE NEAR NOGALES, ARIZONA									
Consumptive use upstream from Nogales	(151)	.8	0	0	0	0	8.2	0	9.0
Less replacement of native vegetation	(152)	.2	0	0	0	0	2.8	0	3.0
Net depletions upstream from Nogales	(153)	.6	0	0	0	0	5.4	0	6.0
Santa Cruz River near Nogales, Arizona	140	6.6	0	0	0	0	8.6	0	15.2
Undepleted Santa Cruz River near Nogales	(154)	7.2	0	0	0	0	14.0	0	21.2
SANTA CRUZ RIVER FROM GAGE NEAR NOGALES TO GAGE AT RILLITO, ARIZONA									
Estimated inflow, Nogales to Rillito	142	83.2	0	0	0	0	1.8	0	85.0
Undepleted volumes conveyed to Rillito	(155)	90.4	0	0	0	0	15.8	0	106.2
Historic channel losses	145	20.0	0	0	0	0	4.7	0	24.7
Virgin channel losses	(156)	$56.4	0	0	0	0	¢ 5.6	0	62.0
Salvage of channel evaporation	(157)	4.5	0	0	0	0	.9	0	5.4
Replacement of native vegetation	(158)	23.6	0	0	0	0	0	0	23.6
Decreased losses from native growth change	(159)	8.3	0	0	0	0	0	0	8.3
Undepleted Santa Cruz River at Rillito	(160)	34.0	0	0	0	0	10.2	0	44.2

Routing of Mean Virgin Runoff

Item No.

(150). Item (145) minus Item (146).

(151). Consumptive use of irrigation water by crops and noncropped areas in Arizona and Mexico in this stream section (see Table 12, San Rafael Ranch in Arizona, A-13-G, and Santa Cruz River in Mexico, M-2-G). The Santa Cruz River heads in Arizona, curves through northern Sonora, Mexico, and reenters Arizona near Nogales.

(152). Uses by native vegetation in cropped and noncropped areas in Arizona and Mexico in this river section under virgin conditions (see Table 14, Santa Cruz River upstream from Nogales gage).

(153). Item (151) minus Item (152).

(154). Item (153) plus Item 140.

(155). Item (154) plus Item 142.

(156). Channel losses in this river section were estimated to be 62,000 acre-feet a year under virgin conditions (see Table 14 for total). The estimated water surface evaporation from the channel was 5,400 acre-feet a year less for historical conditions as compared with virgin conditions and the salvage was credited as 4,500 acre-feet to Arizona and 900 acre-feet to Mexico on the basis of the respective undepleted volumes conveyed. Virgin channel losses apportioned to Mexico were considered as 900 acre-feet a year greater than for historical conditions or 5,600 acre-feet a year and the remainder of the virgin channel losses were apportioned to Arizona.

(157). This salvage was discussed under Item (156) (see Table 14 for total).

(158). Uses by native vegetation in cropped and noncropped areas in this river section under virgin conditions (see Table 14); all in Arizona.

(159). It was estimated that growth changes attributable to the influence of man decreased the uses by native vegetation in this stream section as compared with virgin conditions (see Table 14). As these changes occurred in Arizona, the decreased channel losses of 8,300 acre-feet a year were credited to Arizona.

Notes Accompanying Table 23

Item No.

(160). Item (155) minus Item (156).

(161). Consumptive use of irrigation water by crops and noncropped areas upstream from the gage on the Salt River near Roosevelt (see Table 12, the sum of A-17-G, A-18-G, A-19-G, and A-20-G); all in Arizona.

(162). Stream depletion by small reservoirs upstream from the gage on the Salt River near Roosevelt (see Table 8, Upper Salt River small reservoirs); all in Arizona.

(163). Uses by native vegetation in the cropped and noncropped areas upstream from the gage on the Salt River near Roosevelt under virgin conditions (see Table 14, Salt River above Roosevelt gage); all in Arizona.

(164). Item (161) plus Items (162) and 98 minus Item (163).

(165). Item (164) plus Item 147.

(166). Consumptive use of irrigation water by crops and noncropped areas upstream from the gage on Tonto Creek near Roosevelt (A-21-G in Table 12); all in Arizona.

(167). Uses by native vegetation in the cropped and noncropped areas upstream from the gage on Tonto Creek near Roosevelt under virgin conditions (see Table 14, Tonto Creek above Roosevelt gage); all in Arizona.

(168). Item (166) minus Item (167).

(169). Item (168) plus Item 148.

(170). Consumptive use of irrigation water by crops and noncropped areas upstream from the gage on the Verde River below Bartlett Dam (A-22-G plus A-23-G in Table 12); all in Arizona.

(171). Stream depletion by small reservoirs upstream from the gage on the Verde River below Bartlett Dam (see Table 8, Upper Verde River small reservoirs); all in Arizona.

Climatic Variability and Flood Frequency of the Santa Cruz River, Pima County, Arizona

United States
Geological
Survey
Water-Supply
Paper 2379

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

U.S. DEPARTMENT OF THE INTERIOR
March 3, 1849

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Climatic Variability and Flood Frequency of the Santa Cruz River, Pima County, Arizona

By ROBERT H. WEBB and JULIO L. BETANCOURT

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

U.S. GEOLOGICAL SURVEY WATER-SUPPLY PAPER 2379

U.S. DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, JR., Secretary

March 3, 1849

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CONTENTS

FIGURES

TABLES

METRIC CONVERSION FACTORS

Multiply inch pound unit	By	To obtain metric units
millimeter (mm)	0.03937	inch
meter (m)	3.2818	foot
kilometer (km)	0.6214	mile
square kilometer (km²)	0.3861	square mile
cubic meter per second (m³/s)	35.31	cubic foot per second
degree Celsius (°C)	°F=1.8(°C)+32	degree Fahrenheit (F°)

SEA LEVEL

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

Climatic Variability and Flood Frequency of the Santa Cruz River, Pima County, Arizona

By Robert H. Webb *and* Julio L. Betancourt

Abstract

Past estimates of the 100-year flood for the Santa Cruz River at Tucson, Arizona, range from 572 to 2,780 cubic meters per second. An apparent increase in flood magnitude during the past two decades raises concern that the annual flood series is nonstationary in time. The apparent increase is accompanied by more annual floods occurring in fall and winter and fewer in summer. This greater mixture of storm types that produce annual flood peaks is caused by a higher frequency of meridional flow in the upper-air circulation and increased variance of ocean-atmosphere conditions in the tropical Pacific Ocean.

Estimation of flood frequency on the Santa Cruz River is complicated because climate affects the magnitude and frequency of storms that cause floods. Mean discharge does not change significantly, but the variance and skew coefficient of the distribution of annual floods change with time. The 100-year flood during El Niño-Southern Oscillation conditions is 1,300 cubic meters per second, more than double the value for other years. The increase is mostly caused by an increase in recurvature of dissipating tropical cyclones into the Southwestern United States during El Niño-Southern Oscillation conditions. Flood frequency based on hydroclimatology was determined by combining populations of floods caused by monsoonal storms, frontal systems, and dissipating tropical cyclones. For 1930–59, annual flood frequency is dominated by monsoonal floods, and the estimated 100-year flood is 323 cubic meters per second. For 1960–86, annual flood frequency at recurrence intervals of greater than 10 years is dominated by floods caused by dissipating tropical cyclones, and the estimated 100-year flood is 1,660 cubic meters per second. For design purposes, 1,660 cubic meters per second might be an appropriate value for the 100-year flood at Tucson, assuming that climatic conditions during 1960–86 are representative of conditions expected in the immediate future.

INTRODUCTION

Statistical flood-frequency analysis is a commonly used method for assessing flood hazards and risks in the United States (Interagency Advisory Committee on Water Data, 1982; Thomas, 1985). This method uses the annual flood series, which is an array of the largest discharges that occur each year at a gaging station, to estimate discharges associated with various recurrence intervals, such as 10, 50, and 100 years. Certain recurrence-interval floods, such as the 100-year flood, are then used in engineering design of flood-plain structures or in managing flood plains for development. An example of the use of flood-frequency analysis is the National Flood Insurance Program, which is based primarily on the area of inundation caused by a 100-year flood (Federal Emergency Management Agency, 1986).

Flood-frequency analysis requires certain assumptions about the statistical properties of the annual flood series (Interagency Advisory Committee on Water Data, 1982). The annual flood series is assumed to be composed of random events and to be stationary in time; in other words, all floods were randomly generated from a single probability distribution with stable moments, such as the mean and variance. Thus, the floods that compose the annual flood series are assumed to be derived from the same population. Climate is assumed to be invariant, and the effects of watershed changes on flow conveyance must be negligible (Interagency Advisory Committee on Water Data, 1982). Climatic fluctuations, however, are a source of uncertainty and can lead to misjudgment and misuse of flood-frequency analyses (Dunne and Leopold, 1978, p. 311).

Many of the assumptions required for flood-frequency analysis are not routinely tested and thus could be violated. Obvious hydrologic changes commonly result from urbanization and other forms of intensified land use. Influence of climatic variability on flood frequency, however, may be subtle and more difficult to detect. Mixed populations of floods commonly occur, such as those caused by dissipating hurricanes and runoff from snowmelt. Even where this is demonstrably true, flood-frequency analysis has been used to operationally estimate flood-recurrence intervals.

The flood record for the Santa Cruz River at Tucson, Arizona (fig. 1), provides one example of an annual flood series (fig. 2; table 1) for which standard flood-frequency analyses yield inconsistent results. Past estimates of the 100-year flood for this river, using slightly different methods and lengths of record and assuming different statistical properties of the series, range from 572 to 2,780 m^3/s (table 2). The wide range of estimates stems partially from an extraordinary flood in October 1983 (Saarinen and others, 1984) that had an estimated recurrence interval greater than 100 years (Roeske and others, 1989) and is the largest flood since 1891. Another large flood in October 1977

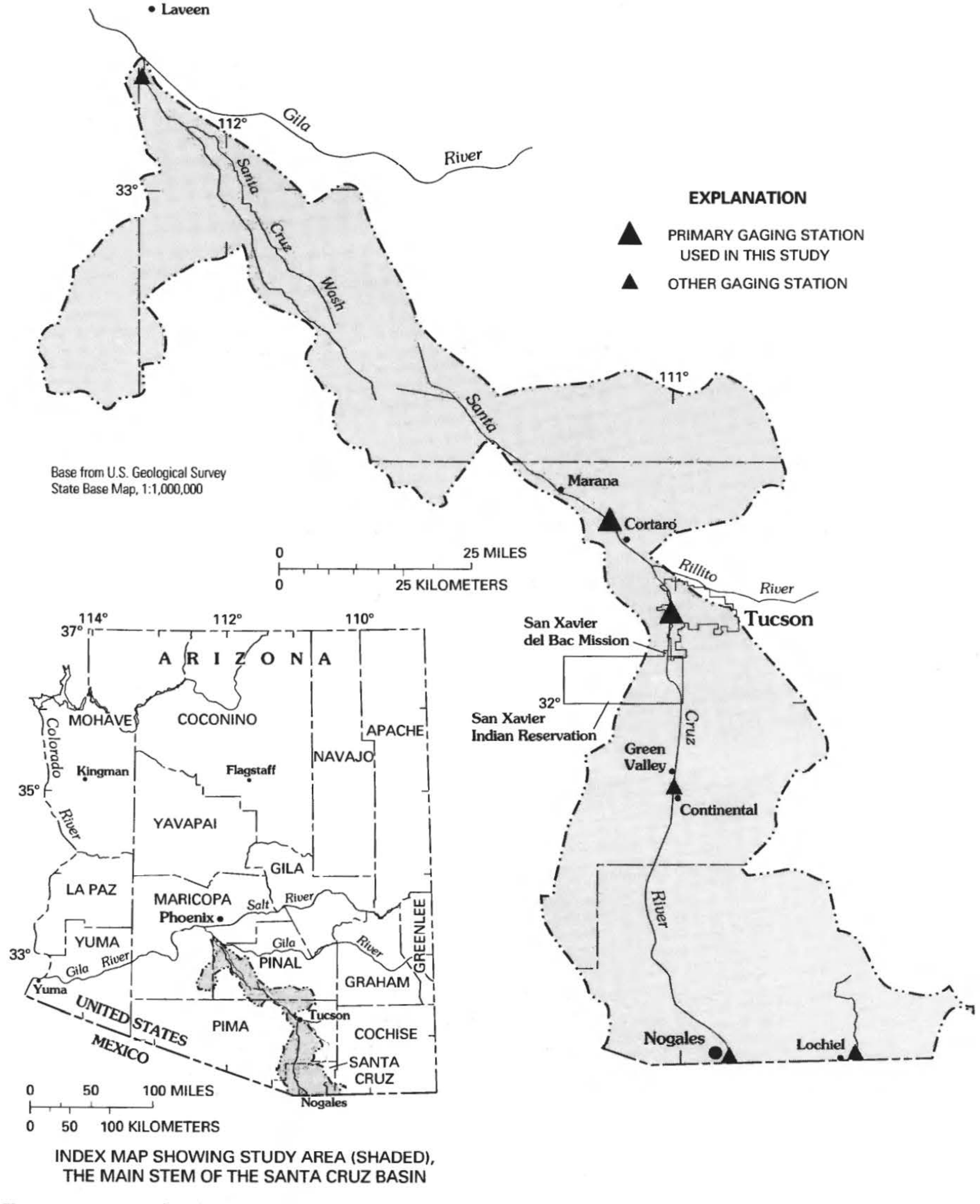

Figure 1. Location of study area (shaded).

(Aldridge and Eychaner, 1984) had a recurrence interval that, at the time, was estimated to be in excess of 100 years. Overall, six of the seven largest floods in the annual flood series (1915–86) occurred after 1960. After the 1983 flood, alternative methods for estimating design floods, including rainfall-runoff modeling, were proposed and used (Michael Zeller, Simons and Li Associates, written commun., 1984; Ponce and others, 1985).

The frequent occurrence of large floods in recent years has led several authors to assert that the annual flood series for the Santa Cruz River is nonstationary (Michael Zeller, Simons and Li Associates, written commun., 1984; Hirschboeck, 1985; Baker, 1984; Reich and Davis, 1985, 1986), thus violating the assumption that all floods are derived from the same statistical population. Changes in land use have been blamed for the alleged nonstationarity (Reich, 1984), but larger floods have also occurred in the headwaters of the Santa Cruz River, where land-use changes have been negligible. An alternative explanation is that low-frequency shifts in climate that occur on a time scale of decades have led to a change in the type, intensity, and (or) frequency of storms that cause floods. Changes in flood frequency on the Santa Cruz River coincide with apparent shifts in seasonality and magnitude of floods elsewhere in the Gila River basin.

Purpose and Scope

In 1988, the U.S. Geological Survey in cooperation with Pima County Department of Transportation and Flood Control District undertook a study of changing channel conditions and flood frequency of the Santa Cruz River. Part of this larger study is an assessment of the applicability of flood-frequency analysis in estimating the recurrence intervals of floods. Whereas much previous work addressed the influence of channel change on flood frequency, this report uses the hydroclimatic perspective of Hirschboeck (1985, 1987, 1988) to evaluate the link between low-frequency climatic variability and changes in flood frequency of the Santa Cruz River in Pima County, Arizona.

The hydroclimatology of the Santa Cruz River basin is examined with particular emphasis on storm types that cause floods. The extent of 20th-century climatic variability is analyzed using long-term records of sea-level pressure in the Pacific Ocean, upper atmospheric circulation patterns, and tropical-storm frequency. The time series of these climatic indices are compared with weather records from Tucson and streamflow records from the gaging station, Santa Cruz River at Tucson, to show the connection between climatic vari-

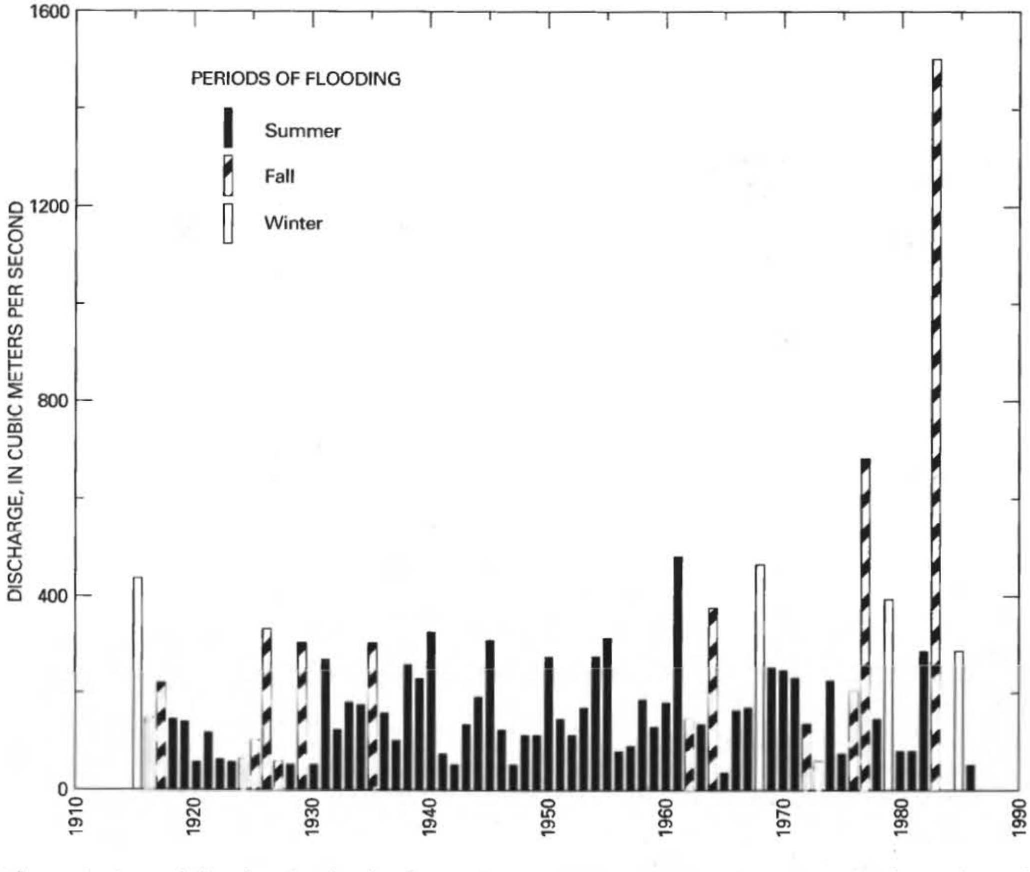

Figure 2. Annual flood series for the Santa Cruz River at Tucson, Arizona. Hydroclimatological year is November 1 to October 31.

Table 1. Annual flood series, Santa Cruz River at Tucson, Arizona

[Water year for annual flood series, November 1 to October 31]

Date	Discharge, in cubic meters per second	Date	Discharge, in cubic meters per second	Date	Discharge, in cubic meters per second
12-23-14	425	8-03-39	227	8-26-63	132
1-20-16	142	8-14-40	320	9-10-64	368
9-08-17	212	8-14-41	71	7-16-65	34
8-07-18	139	8-09-42	47	8-19-66	156
8-02-19	133	8-02-43	128	7-17-67	166
8-09-20	55	8-16-44	185	12-20-67	456
8-01-21	113	8-10-45	306	8-06-69	247
7-20-22	57	8-04-46	121	7-20-70	242
8-17-23	54	8-10-47	48	8-17-71	227
11-17-23	58	8-16-48	109	10-19-72	133
9-18-25	96	8-08-49	108	3-14-73	54
9-28-26	323	7-30-50	269	7-08-74	225
9-07-27	55	8-02-51	142	7-12-75	70
8-01-28	45	8-16-52	108	9-25-76	201
9-24-29	295	7-15-53	167	10-10-77	671
8-07-30	50	7-24-54	271	8-02-78	142
8-10-31	261	8-03-55	309	12-19-78	382
7-30-32	119	7-29-56	74	8-13-80	78
8-21-33	173	8-31-57	86	7-27-81	76
8-23-34	170	7-29-58	180	8-23-82	[1]283
9-01-35	292	8-20-59	125	10-02-83	1,493
7-26-36	153	8-10-60	174	12-28-84	283
7-10-37	93	8-23-61	470	7-21-86	54
8-05-38	255	9-26-62	141		

[1] Estimated.

ability and hydroclimatology of southern Arizona. Also examined is the influence of climatic variability on the frequency and severity of storm types that cause flooding in southern Arizona. Flood frequency is analyzed using several different methods and assumptions about the data that are based on the hydroclimatic analysis. A mixed-population analysis made on the basis of hydroclimatic segregation of floods and maximum-likelihood analysis is used to estimate flood frequency for floods caused by different storm types in different periods of the 20th century.

Acknowledgments

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Hydrologic Setting

The Santa Cruz River is primarily an ephemeral desert stream and drains 22,200 km^2 in southern Arizona and northern Mexico. From its headwaters in the mountains of southern Arizona, the river flows southward into Mexico and loops north to re-enter the United States just east of Nogales. The river flows 105 km from Nogales to Tucson (fig. 1). During major floods, the Santa Cruz River below Tucson flows another 155 km to join the Gila River near Phoenix; however, this reach is typically dry or contains treated sewage or irrigation-return flow. The headwaters of the Santa Cruz are at an altitude of 2,885 m above sea level, the confluence with the Gila River occurs at 310 m, and the average basin altitude above Tucson is 1,234 m above sea level (Roeske, 1978). The basinwide precipitation for the Santa Cruz River basin is 430 mm/yr. Several large historic floods

Table 2. Estimates of the 100-year flood on the Santa Cruz River at Tucson, Arizona, made by previous investigators after 1970

[———, no record]

Reference	Years of record	Method or probability distribution	100-year flood, in cubic meters per second
U.S. Army Corps of Engineers (1972)	———	(1)	1,280
Roeske (1978)	1915–75	(2)	575
	1915–75	(3)	640
Malvick (1980)	1915–78	(3)	1,810
Federal Emergency Management Agency (1982)	1915–78	(2)	850
Boughton and Renard (1984)	1915–79	(4)	572
	1915–79	(2)	666
	1915–79	(5)	2,180
Michael Zeller (Simons and Li Associates, written commun., 1984)	———	(6)	1,420
Eychaner (1984)	1915–81	(2)	626
	1915–81	(3)	657
Reich (1984)	1960–84	(2)	1,530
	1960–84	(7)	2,730
	1962–84	(2)	1,420
	1962–84	(7)	2,780
Ponce and others (1985)	———	[8]24	1,660
		[8]48	1,900
		[8]96	1,330
Hirschboeck (1985)	1950–80	(2)	736

[1] Curve, comparison with floods in other watersheds in southern Arizona.

[2] Log-Pearson type III distribution, method-of-moments fitting.

[3] Log-Pearson type III distribution plus regression analysis.

[4] Log-Pearson type III distribution plus envelope curve.

[5] Log-Boughton distribution, method-of-moments fitting.

[6] Rain, estimated from 100-year rainfall.

[7] Log-Extreme Value distribution, method-of-moments fitting.

[8] Model, estimated from rainfall-runoff model with 100-year, 24-, 48-, and 96-hour duration storms. This value is currently being used by Pima County for compliance with Federal Emergency Management Agency regulations.

on the Santa Cruz River have been described previously (Knapp, 1937; Lewis, 1963; Aldridge, 1970; Aldridge and Eychaner, 1984; Saarinen and others, 1984; Roeske and others, 1989).

Three long-term gaging stations have been maintained on the Santa Cruz River in Pima County. The gaging record for the Santa Cruz River at Tucson is the longest but is discontinuous because of a complicated station history. Although the first gaging station was installed in 1905 (Schwalen, 1942), the continuous gaging record began in 1915. The station was discontinued in 1981 and was re-established in 1986 (Wilson and Garrett, 1989). In this report, streamflow records for 1915-86 were evaluated, and annual peak discharges were measured or estimated for all years during 1915–86 (fig. 2; table 1). Peaks above a base discharge of 48 m^3/s (the partial-duration series) were measured for 1930–81; however, peaks above base discharge are not known for July and August 1984 or for water year 1985. The mean annual streamflow is 0.64 m^3/s at Tucson from a drainage area of 5,755 km^2 (Wilson and Garrett, 1989).

The gaging station, Santa Cruz River at Cortaro, Arizona (fig. 1), has a record from 1939–47 and 1950–84, after which the station was discontinued (White and Garrett, 1987). The drainage area above this gaging station is 9,073 km^2. Discharges for both the annual flood series (table 3) and the partial-duration series are available for all years of record. The base discharge for the partial-duration series is 76 m^3/s. A record from the gaging station, Santa Cruz River at Continental, Arizona, was not analyzed for flood frequency. Discharges for many floods at this gaging station are inaccurate because flow in an overflow channel around the gaging station was not measured (H.W. Hjalmarson, hydrologist, U.S. Geological Survey, oral commun., 1989).

Averages of monthly discharge for the Santa Cruz River at Tucson indicate that runoff occurs mainly from

Table 3. Annual flood series, Santa Cruz River at Cortaro, Arizona

[Water year for annual flood series, November 1 to October 31]

Date	Discharge, in cubic meters per second	Date	Discharge, in cubic meters per second
8-14-40	481	8-26-63	205
12-31-40	221	9-10-64	450
8-09-42	43	12-22-65	475
9-24-43	155	8-19-66	169
8-16-44	160	7-17-67	162
8-10-45	396	12-21-67	447
8-04-46	125	8-06-69	238
8-15-47	212	7-20-70	317
7-30-50	365	8-20-71	257
7-25-51	193	10-19-72	255
8-14-52	172	2-22-73	104
7-14-53	305	7-08-74	331
7-24-54	259	7-12-75	147
8-03-55	470	9-25-76	300
7-29-56	89	10-10-77	651
9-01-57	124	3-02-78	221
9-01-57	124	12-18-78	532
8-12-58	223	7-19-80	75
8-20-59	226	9-22-81	122
8-11-60	181	8-23-82	376
8-23-61	416	10-02-83	1,841
9-26-62	317	8-16-84	145

December through February and July through October (fig. 3). Variability in monthly streamflow is high, and coefficients of variation range from 1 to 6 (fig. 3). Because the normally defined water year of October 1 to September 30 artificially separates the fall runoff season, a hydroclimatic water year was defined for this report as November 1 to October 31. Redefinition of the water year, which satisfies the assumption of interannual independence in annual floods, shifts some floods that occur in October, such as the flood of October 1983, to the previous water year.

Precipitation in southern Arizona has distinct peaks in summer and winter (Sellers and Hill, 1974). Tucson has one of the longest precipitation records (1868–1989) in Arizona, although, like other long-term southwestern stations, it has a complicated station history (Durrenberger and Wood, 1979). The University of Arizona has maintained precipitation records since 1891, although the station has been moved to five locations within a 15-kilometer radius. There were major station moves in 1894, 1956, 1966, and 1968; the effect of these moves on the statistical properties of the time series has not been determined. Mean annual precipitation recorded at the University of Arizona in Tucson is 291 mm for the 119-year record. About 129 mm of rain falls between November and June, and 162 mm of rain falls between July and October.

The predominant land use is for livestock grazing, which has occurred for several centuries. Bottomlands are used for agriculture, primarily alfalfa and pecans. Copper is mined in several areas of the drainage basin, mainly near Green Valley, Arizona (fig. 1). Urbanization affects Nogales, Sonora, in Mexico; and Nogales, Green Valley, Tucson, and Marana in Arizona. Green Valley and Tucson incorporate flood-prone properties along the Santa Cruz River.

HYDROCLIMATOLOGY OF SOUTHERN ARIZONA

Recent hydroclimatological research in southern Arizona links various flood-producing storm types to large-scale atmospheric-oceanic interactions (Hansen and others, 1977; Maddox and others, 1980; Hansen and Schwarz, 1981; Hirschboeck, 1985, 1987; Smith, 1986). Three principal types of flood-producing storms and associated upper-atmospheric circulation patterns are described below.

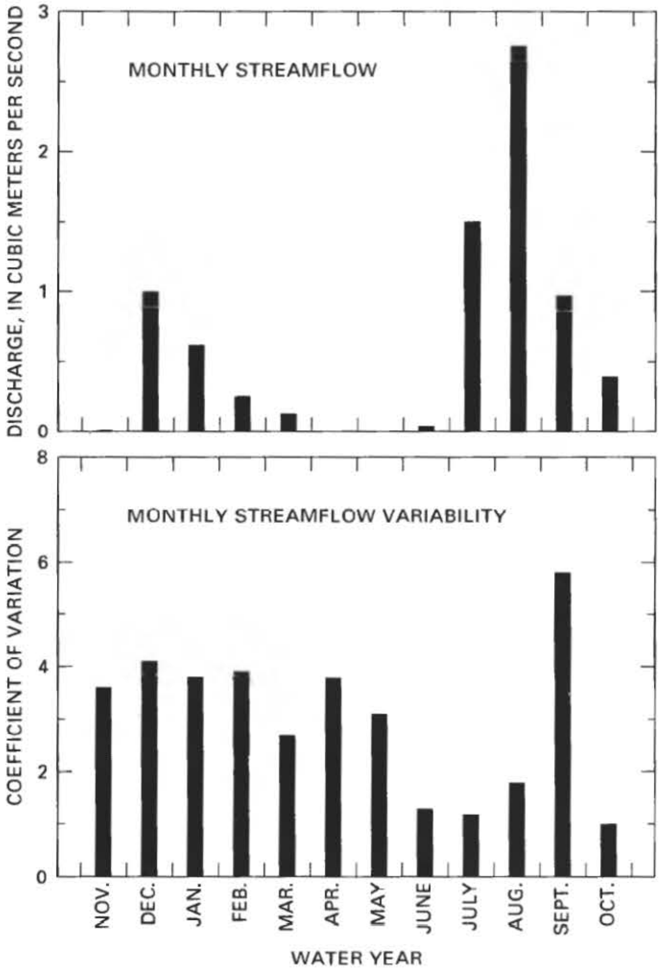


Figure 3. Average monthly streamflow and monthly streamflow variability, Santa Cruz River at Tucson, Arizona.

Frontal and Cutoff Low-Pressure Systems

Winter storms in southern Arizona originate from large-scale low-pressure frontal systems embedded in the westerly winds from the Pacific Ocean. The storm track moves southward in conjunction with seasonal expansion of a low-pressure cell, called the Aleutian Low, that occurs in the North Pacific. During dry winters, the westerlies follow a path around the north side of a ridge of high pressure off the west coast of North America and into the Pacific Northwest. In wet winters, this ridge is displaced westward, and a low-pressure trough develops over the Western United States. Storms then tend to follow the prevailing winds along the west coast and enter the continent as far south as San Francisco. An example of a frontal system that caused a flood on the Santa Cruz River is the storm of December 17–18, 1978 (fig. 4*A*, *B*). The rainfall during this storm ranged from 70 to 250 mm in central Arizona and caused widespread flooding (Aldridge and Hales, 1984).

When a high-pressure ridge in the Pacific is well developed, low-pressure systems can stagnate and form cutoff low-pressure systems (fig. 5). The atmospheric conditions that produce cutoff low-pressure systems are discussed in the section titled "Changes in Circulation of the Upper Atmosphere." Cutoff lows that affect Arizona typically form between latitude 30° N. and 45° N. and longitude 105° W. and 125° W. and have spring and fall maxima (fig. 6). Cutoff lows may intensify off the coast of California before moving inland into Arizona, where they can produce substantial rainfall (Sellers and Hill, 1974; Pyke, 1972; Hansen and Schwarz, 1981). In fall, cutoff low-pressure systems may stall over warm tropical waters and steer dissipating tropical cyclones inland, creating conditions for the idealized probable-maximum precipitation in Arizona (Hansen and Schwarz, 1981).

Dissipating Tropical Cyclones

Occasionally in late summer and early fall, widespread and intense rainfall occurs in southern Arizona because of northeastward penetration of tropical cyclones, which include hurricanes and tropical storms, from the tropical North Pacific Ocean. An average of 14.1 tropical cyclones are generated each year in the eastern North Pacific Ocean (fig. 7; Rosendal, 1962; Cross, 1988). July and August have the largest number of tropical cyclones—3.4 and 3.5 cyclones per month, respectively (fig. 6). The main area of cyclone generation is off the west coast of Mexico between latitude 10° and 15° N. and between longitude 95° and 100° W.; most tropical cyclones originate more than 300 km south of Cabo San Lucas, the southernmost point in Baja California (Eidemiller, 1978; Cross, 1988).

After leaving their area of origin, most tropical cyclones curve west-northwestward and may intensify into tropical storms or hurricanes. Farther north and west, the storms are dissipated by wind shear and colder water. Some tropical cyclones recurve toward the north and east, steered either by southerly winds ahead of a low-pressure trough, centered over the Pacific Northwest, by a weak trough between two subtropical high-pressure cells, or by circulation associated with a cutoff low-pressure system. These cyclones dissipate over Mexico and the United States, causing intense precipitation and regional flooding (Smith, 1986). Precipitation from dissipating tropical cyclones can range from several millimeters to more than 300 mm in 2 to 4 days (Smith, 1986).

Recurving cyclones that have affected southern Arizona were generated most frequently in September and October—72 percent—compared with July and August—27 percent (Smith, 1986). Between 1965 and 1984, an average of 1.4 tropical cyclones per year caused precipitation in the Southwestern United States (Smith, 1986). Tropical Storm Octave in late September and early October 1983 is an example of the interaction between a tropical cyclone and a cutoff low-pressure system (fig. 4*C*) that caused flooding on the Santa Cruz River (Roeske and others, 1989).

The disparity between seasonality of cutoff low-pressure systems and generation of tropical cyclones explains the greater incidence of recurvature during fall (fig. 6). Although generation of tropical cyclones is at a maximum in July and August, cutoff low-pressure systems have a maximum incidence in October. The greater incidence of recurvature in fall also is associated with the weakening and southern migration of the Pacific subtropical high and the more frequent appearance of midlatitude troughs at lower latitudes (Eidemiller, 1978). These two phenomena can behave synergistically, because dissipating tropical cyclones may contribute moisture to early fall extratropical cyclones from the North Pacific.

Monsoonal Storms

The summer rainy season in Arizona is preceded by strong zonal flow and aridity under direct influence of subsidence from the subtropical high-pressure cell in the eastern Pacific Ocean, which remains displaced to the south during spring and early summer. Near the end of June and early July, the subtropical high-pressure cells shift rapidly northward and induce advection of moist tropical air into Arizona. These synoptic-scale surges (Carleton, 1986) that abruptly break the early summer drought have been likened to monsoonal circulation elsewhere (Tang and Reiter, 1984). The resultant monsoonal storms are characterized by isolated or complex groups of thunderstorms that have a duration of less than several hours (Maddox and others, 1980; Hansen and Schwarz, 1981). Analyses of broad-scale patterns in precipitable water (Reitan, 1960), water-vapor flux

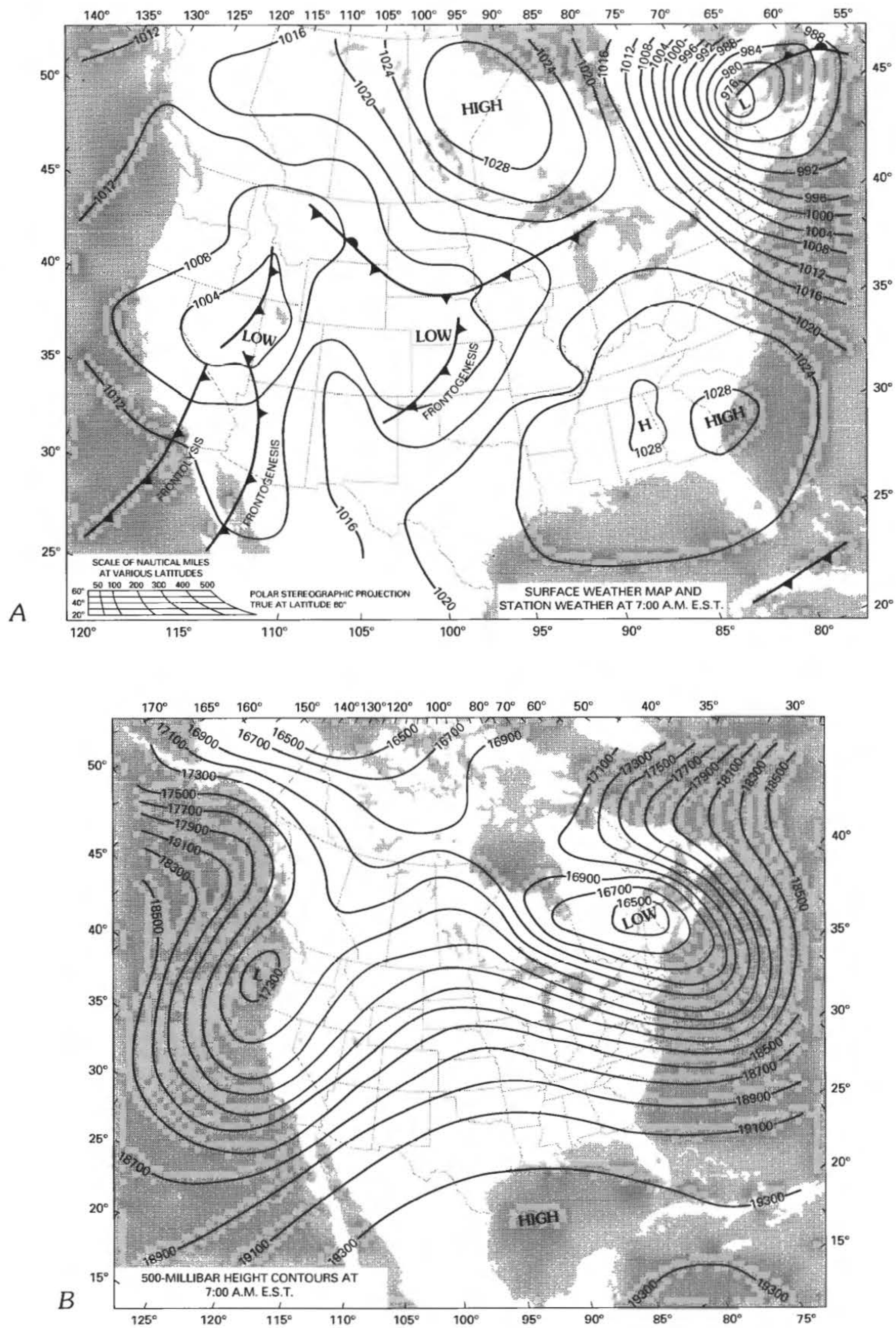
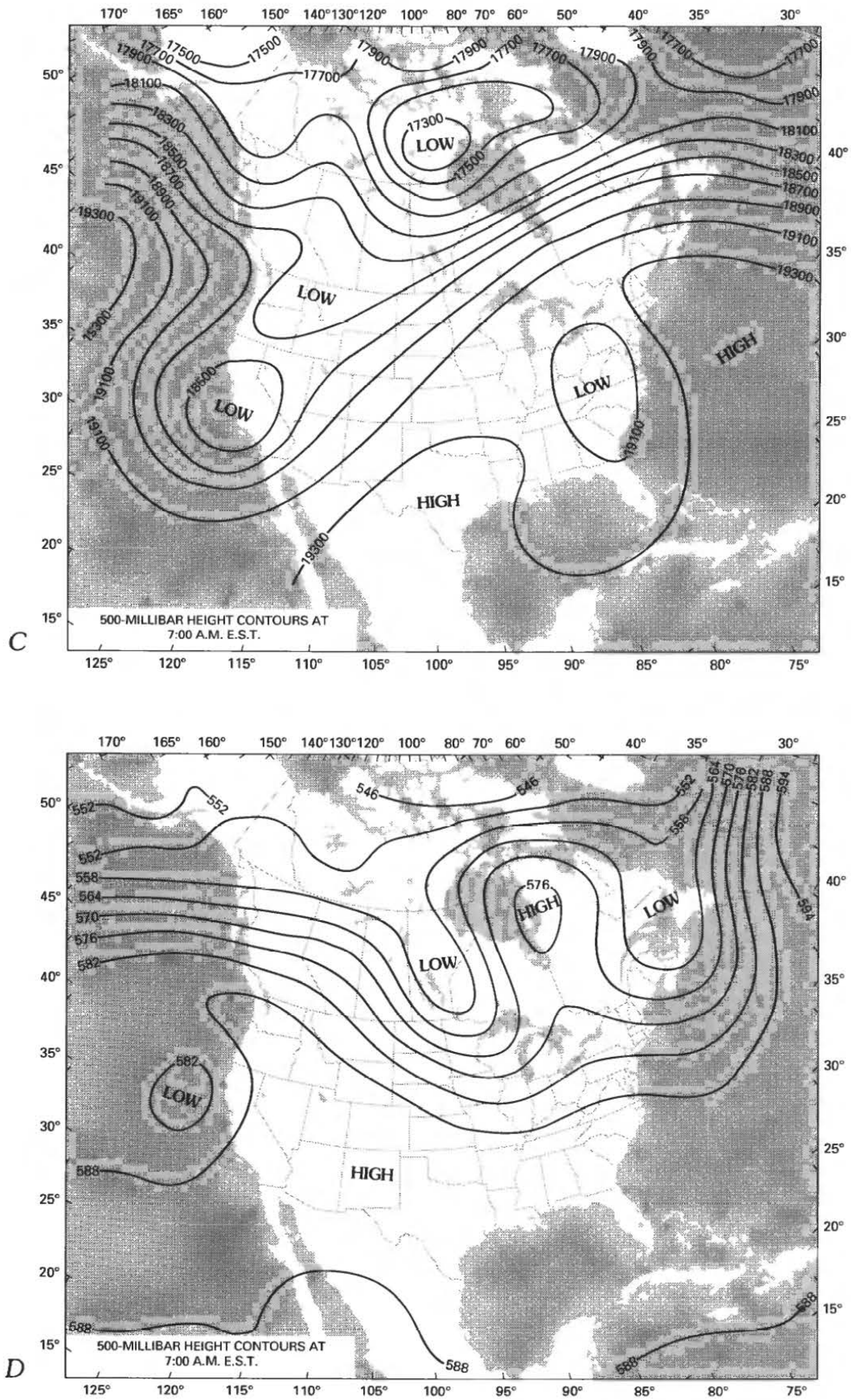
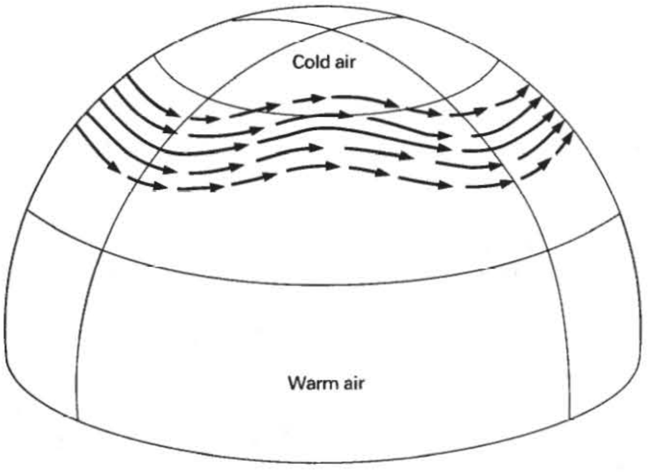


Figure 4. Meteorological conditions on days during which three example floods occurred on the Santa Cruz River at Tucson, Arizona. (Maps from the Daily Weather Map series of the National Oceanic and Atmospheric Administration, 1988.) *A*, A frontal system passed through Arizona on December 18, 1978. Contours in millibars. *B*, On December 18, 1978, a large low-pressure trough off the California coast was associated with the frontal system shown in *A*. Contours in feet above

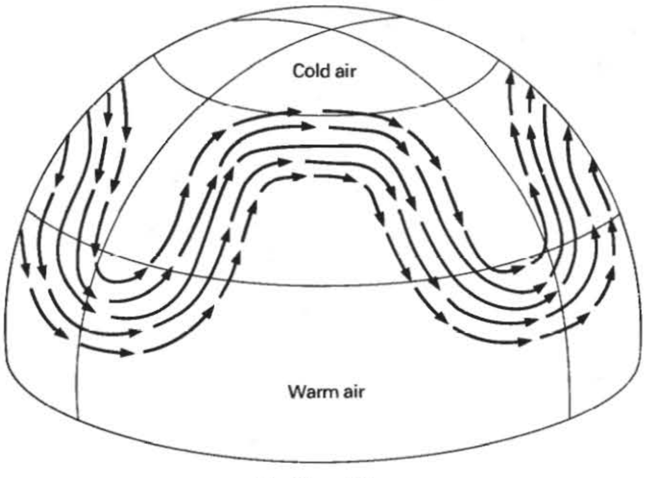


sea level. *C*, On October 1, 1983, a cutoff low-pressure system was over the California coast. At the same time, Tropical Storm Octave was off the southwestern tip of Baja California. Contours in feet above sea level. *D*, On August 23, 1988, generally weak upper atmospheric conditions were associated with monsoonal precipitation in Arizona. Contours in tens of meters above sea level.

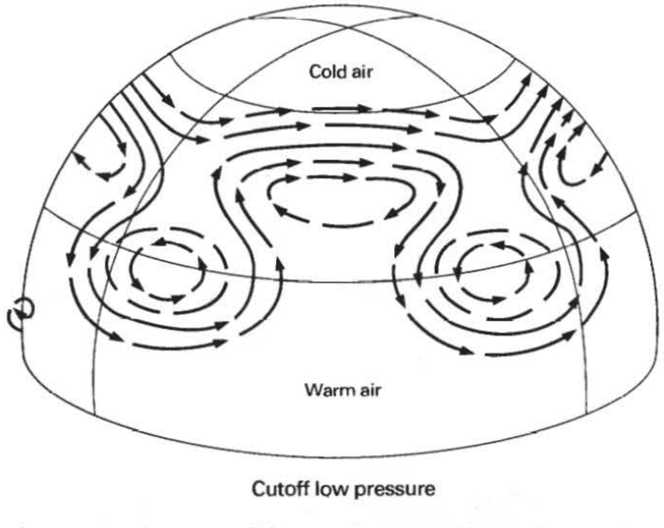
(Rasmusson, 1967), low-level winds (Tang and Reiter, 1984), and regional precipitation (Hales, 1974; Pyke, 1972) suggest that much of the moisture originates from the Pacific Ocean and Gulf of California. Hansen and Schwarz (1981) asserted that although the Gulf of Mexico may be the source for much of the day-to-day summer precipitation in the Southwest, it is not the source of moisture for extreme precipitation. Floods caused by monsoonal storms have occurred in almost every year of record for the Santa Cruz River. An example of the weak upper-atmospheric circulation of a typical monsoonal storm occurred on August 23, 1988 (fig. 4*D*). This storm dropped about 70 mm of rainfall in 1 hour in parts of southwestern Tucson.



Zonal flow



Meridional flow



Cutoff low pressure

Figure 5. Schematic definitions of general circulation flow types.

CLIMATIC VARIABILITY IN THE 20TH CENTURY

Large-scale climatic phenomena affect the hydroclimatology of southern Arizona and the watershed of the Santa Cruz River. Location of the watershed in a climatic transition zone between temperate and tropical latitudes contributes to distinct seasonal precipitation and streamflow. Streamflow may be a less ambiguous measure of climatic variability than precipitation because it integrates weather phenomena over space and time. In large watersheds such as the Santa Cruz River basin, floods often occur under a special set of climatic conditions that combine general circulation over North America and sea-surface temperatures in the Pacific Ocean (Hansen and others, 1977). Thus, floods can integrate climatic information that might be difficult to detect in more direct measurements of the climate system.

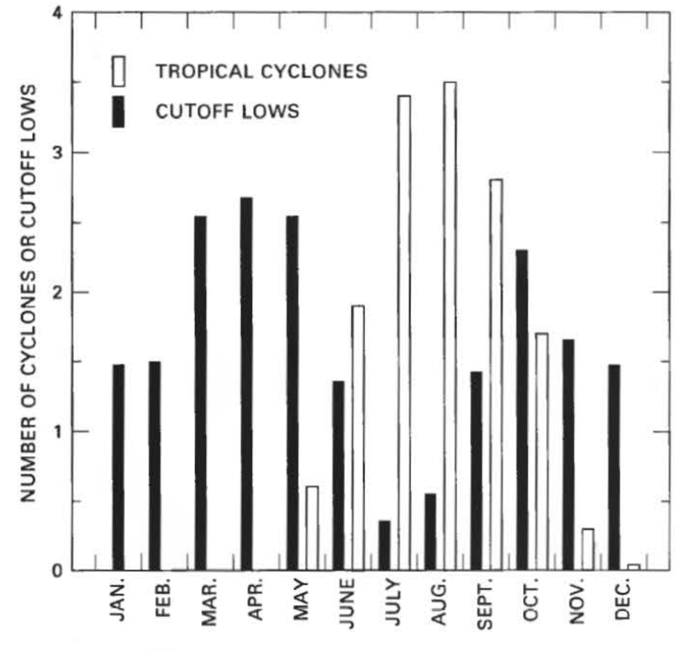


Figure 6. Seasonality of cutoff low-pressure systems over the Western United States (lat 20° to 45° N., long 100° to 140° W.) and generation of tropical cyclones in the tropical eastern North Pacific Ocean (lat 5° to 20° N., long 85° to 120° W.).

Teleconnections and 20th-Century Variability in Global Climate

Precipitation patterns in certain parts of the world are teleconnected, or related over long distances (Ropelewski and Halpert, 1986). For example, the Southwestern United States occasionally has abundant precipitation while the Northwestern United States undergoes drought (Lins, 1985). Similarly, the Southeastern United States and much of northern South America are negatively teleconnected. Propagation of teleconnections worldwide suggests that the same climatic process may control concurrent flooding in Arizona and Florida or in India and Australia.

Teleconnections provide a network for studying the worldwide propagation of low-frequency climatic fluctuations. Using precipitation as an example, summer rainfall in the positively teleconnected areas of India (Mooley and Parthasarathy, 1984), west Africa (Ojo, 1987), and the Sahel (Folland and others, 1986) was above normal for 1930–60 and below normal before and after 1930–60. Changes in ocean temperatures appear to precede the changes in precipitation. In the Atlantic Ocean, warming occurred in the Southern Hemisphere and cooling occurred in the Northern Hemisphere before about 1925 and after the late 1950's to early 1960's (Folland and others, 1986; Cayan, 1986). The Pacific Ocean also cooled after the early 1960's. This cooling coincided with anomalous upper-atmospheric pressure patterns in the central North Pacific Ocean and southward displacement of the winter storm tracks across western North America (Douglas and others, 1982; Balling and Lawson, 1982). Cumulative departures from mean temperatures for the United States (Diaz and Quayle, 1980) show significant breakpoints about 1921, 1930, 1952, and 1960. These studies suggest that the middle third of this century (about 1930–60) appears to be climatically distinct from periods before 1930 or after 1960.

Frequency of El Niño-Southern Oscillation Conditions in the 20th Century

The El Niño-Southern Oscillation (ENSO) involves the appearance every 3 to 5 years of anomalously warm water (El Niño) in the equatorial eastern and central

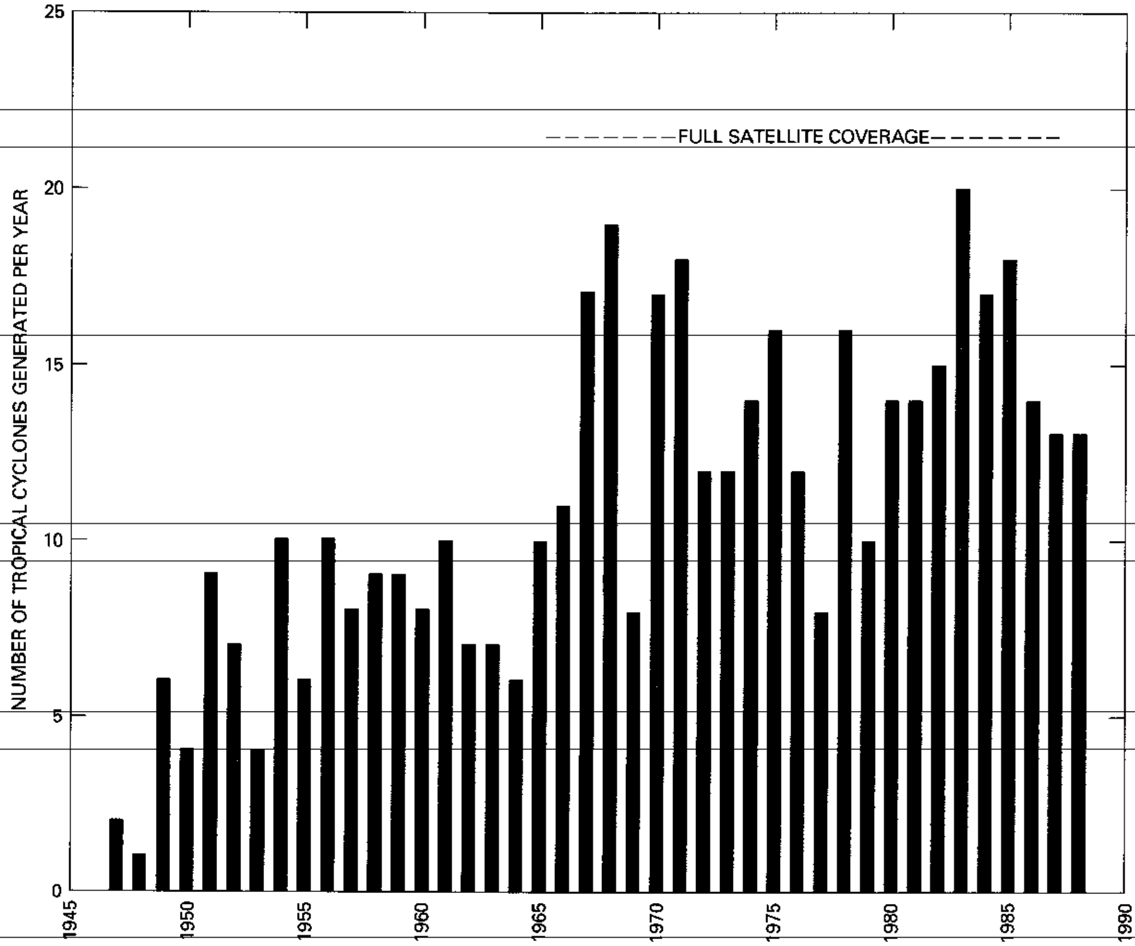


Figure 7. Variation in the number of tropical cyclones generated in eastern North Pacific Ocean between lat 5° N. and 20° N. and long 85° W. and 120° W. Tropical cyclones include hurricanes and tropical storms. Full detection began after 1965 with daily satellite coverage (data from Cross, 1988).

Pacific (Rasmusson, 1985; Enfield, 1989). During ENSO events, the sea-surface temperature anomalies are accompanied by unusually high sea-level pressure near Indonesia and unusually low sea-level pressure near the central equatorial Pacific Ocean (Rasmusson, 1984). The term "La Niña" refers to anomalous cooling in the equatorial Pacific (Bradley and others, 1987). ENSO affects various meteorological and oceanographic conditions worldwide. Teleconnections are particularly pronounced during ENSO conditions (Horel and Wallace, 1981; Elliott and Angell, 1988).

Several indices have been developed that indicate ENSO conditions. The difference in sea-level pressure between Darwin, Australia, and Tahiti (fig. 8) is commonly used to create an index of the Southern Oscillation. The pressure difference has a significant month-to-month persistence, as indicated by serial autocorrelation coefficients that are significantly different from zero for 8 months. Several variations of this index have been developed (Troup, 1965; Wright, 1984; Ropelewski and Jones, 1987). The most common, the Southern Oscillation Index (SOI), is the pressure difference between Darwin and Tahiti normalized to a mean of zero and a variance of one (Ropelewski and Jones, 1987). Negative values of the Darwin-Tahiti pressure difference indicate ENSO conditions.

Precipitation in the Line Islands of the equatorial Pacific Ocean (lat 0° to 10° N., long 160° W.) also has been used as an index of ENSO conditions. Distinct precipitation surges occur in these normally dry islands under ENSO conditions (Wright, 1984; Douglas and Englehart, 1984). Positive values of the index of Line Island precipitation (fig. 9) indicate ENSO conditions. This index is significantly autocorrelated for 7 months, similar to the Darwin-Tahiti pressure difference. Fewer surges of precipitation occurred in the Line Islands during 1930–63 (Reiter, 1983).

One of the problems in analyses of ENSO-related phenomena is the use of different criteria for identifying ENSO conditions, such as sea-surface temperatures in Peru, several versions of the SOI, or Line Island precipitation. When there is a high negative correlation between sea-surface temperature in the eastern Pacific Ocean and the SOI, strong ENSO years are easily defined. Differences arise when defining weaker ENSO years because warming occurs without a large reversal in sea-surface pressure. The Darwin-Tahiti pressure difference and the Line Island precipitation index were used to develop a chronology of 20th-century ENSO conditions (table 4). The chronology differs only slightly from existing chronologies of ENSO (table 4), does not have a denotation of strength, and gives the approximate beginning and ending times for ENSO conditions.

Using the classification in table 4, ENSO conditions recurred on the average of every 3.8 years for 1900–29, every 4.3 years for 1930–59, and every 3.8 years for 1960–86. The seasonality during which ENSO conditions are present has changed during the 20th century. For 1930–60, ENSO conditions often began in the early part of the year and ended in the late part of the year, and the interval between ENSO conditions was as long as 7 years (table 4). Between 1960 and 1986, ENSO conditions typically began in the middle of the year and lasted until the early or middle part of the following year, and the longest interval between ENSO conditions was 5 years (table 4).

Changes in the statistical properties of the Darwin-Tahiti pressure difference (fig. 8) reflect decadal changes in ENSO conditions. The mean pressure difference is 0.3 millibar (mbar) for 1930–59 and –0.2 mbar for 1960–86. Although the means are not significantly different, the intermonthly variance in sea-level pressure increased from 43 mbar during 1930–59 to 60 mbar after 1960. The increase in variance after 1960 is statistically significant at a 95-percent confidence level using the nonparametric Squared Ranks Test (Conover, 1971, p. 239–241). Elliott and Angell (1988) also found reduced variances in sea-level pressure at Darwin and Tahiti for about 1920–50. The increased frequency of ENSO conditions suggests an increased occurrence of high sea-surface temperatures, which may affect the occurrence and (or) intensity of frontal storms in the extratropical latitudes.

Precipitation in the Line Islands shows seasonal changes after 1960. Average precipitation from August through February increased after 1960. For September through December, the increases ranged from 12 to 23 percent. The mean for 1960–82 is only 6 percent greater than the record mean; however, the mean for 1976–82 of 127 percent of normal precipitation illustrates the persistent ENSO conditions during this period. This scenario is consistent with the virtual absence, without precedent in the 20th century, of La Niña conditions during 1975–87 (Bradley and others, 1987).

ENSO conditions affect the hydroclimatology of the southwestern United States, particularly Arizona (Andrade and Sellers, 1988; Douglas and Engelhart, 1984). Areas teleconnected with the equatorial Pacific Ocean, such as the Southwestern United States, have increased variability of precipitation (Nicholls, 1988). Winter frontal storms are more numerous and intense during certain ENSO years (Rasmusson, 1984, 1985) because of an intensified Aleutian low (Yarnal and Diaz, 1986). The probabilities for generation and recurvature of tropical cyclones change during ENSO conditions, but the advection of moisture needed to fuel monsoonal storms is reduced (Reyes and Cadet, 1988). Hypothetically, ENSO conditions could reduce the number of monsoonal storms but increase the number of frontal systems and tropical cyclones that affect Arizona.

ENSO affects the variability of tropical-cyclone generation. After 1965, all tropical cyclones generated in the eastern North Pacific Ocean were detected by weather satellites. On average, fewer tropical cyclones were generated under ENSO conditions (12.6 tropical cyclones per year) than under non-ENSO conditions (15.3 tropical cyclones per year). Analysis of variance, however, indicates a significant difference at the 95-percent confidence level between the variances of generation of tropical cyclones during ENSO and non-ENSO conditions. The incidence of

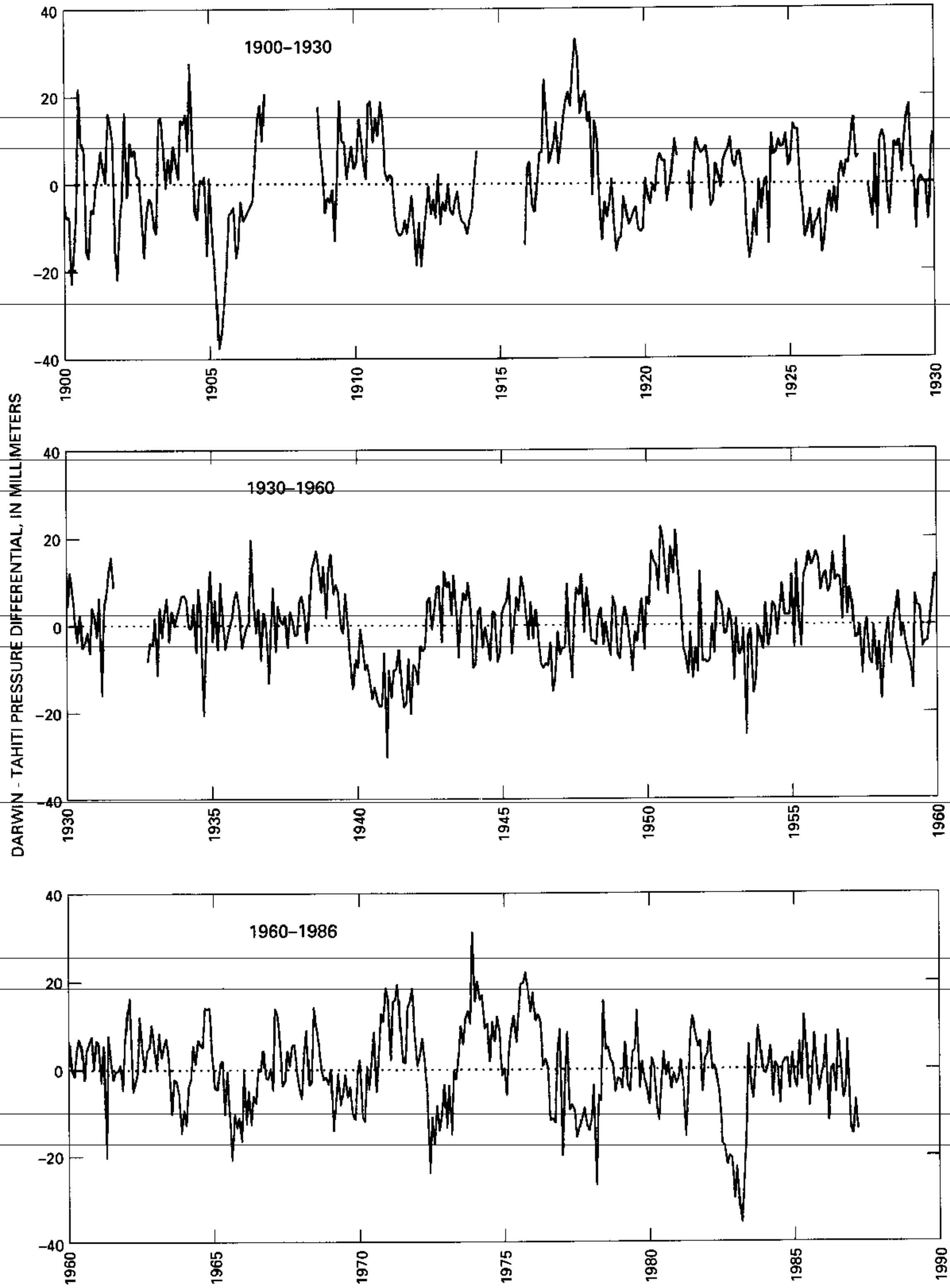


Figure 8. Difference in monthly sea-level pressure between Darwin, Australia, and Tahiti. Sea-level pressure difference is a measure of El Niño-Southern Oscillation conditions; negative values indicate warm El Niño-Southern Oscillation conditions.

tropical cyclones dissipating over Arizona increases during ENSO conditions. The largest numbers of dissipating tropical storms per year that affected the Southwestern United States occurred in the ENSO years of 1925–26, 1939, 1957–58, 1976–77, and 1982–83 (Smith, 1986). In September, the peak month for recurvature, 3.4 tropical cyclones

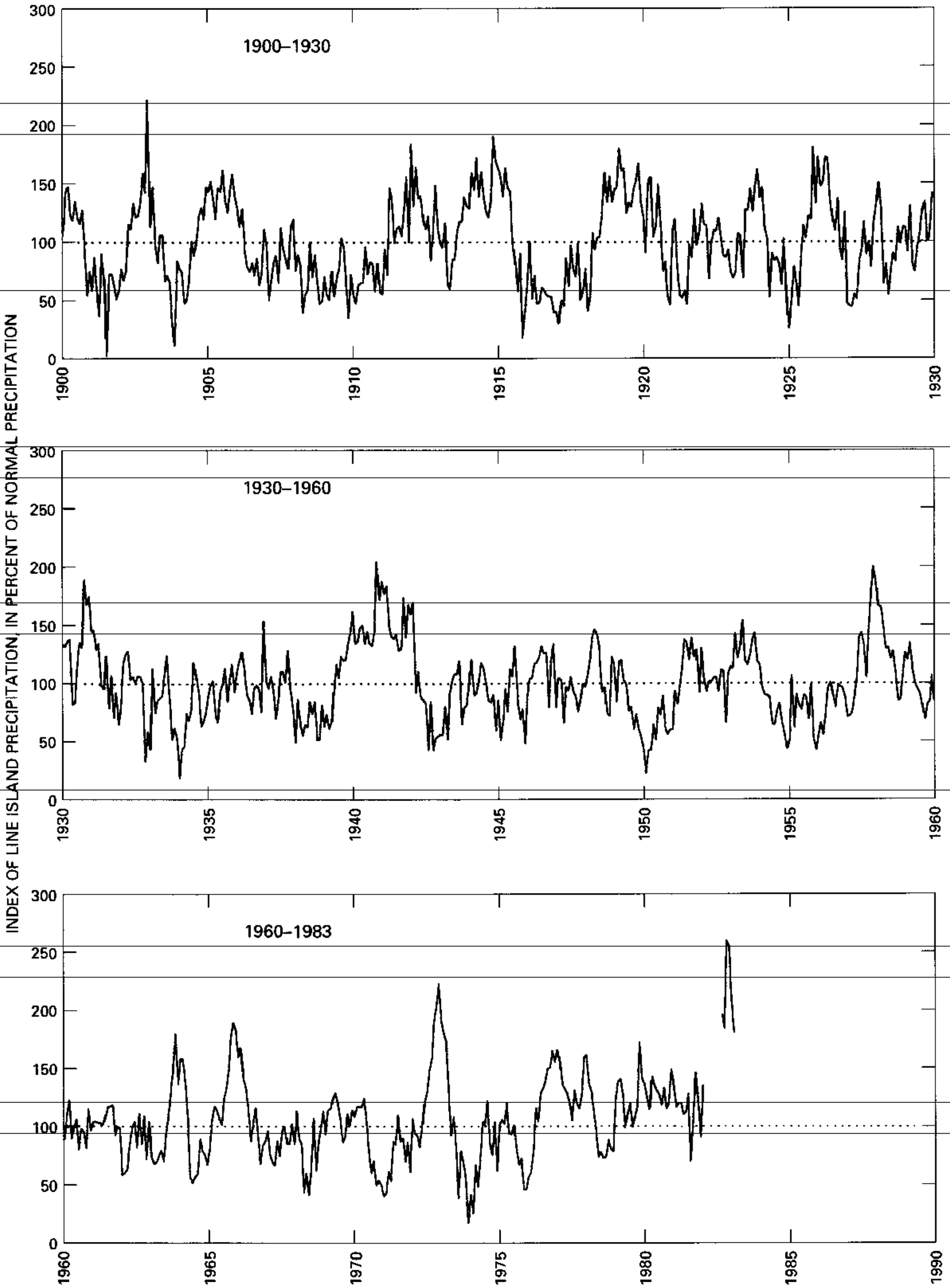


Figure 9. Index of Line Island precipitation (Wright, 1984), representing percent-of-normal precipitation for several stations. Sustained periods with values greater than 100 indicate El Niño-Southern Oscillation conditions.

Table 4. Approximate periods of El Niño-Southern Oscillation conditions in equatorial Pacific Ocean

[Note tendency for El Niño-Southern Oscillation conditions to begin in the early part of the calendar year between 1930 and 1960, compared to midyear before 1930 and after 1960]

Period of time		El Niño-Southern Oscillation conditions agree with			
From	To	Southern Oscillation Index	Line Island Precipitation Index	Quinn and others (1987)	Rasmusson (1984)
Late 1899	Mid-1900	Yes	Yes	Yes	Yes
Mid-1902	Early 1903	Yes	Yes	Yes	Yes
Early 1905	Mid-1906	Yes	Yes	Yes	Yes
Mid-1911	Mid-1912	Yes	Yes	Yes	Yes
Mid-1914	Mid-1915	Yes	Yes	Yes	Yes
Mid-1918	Late 1919	Yes	Yes	Yes	Yes
Mid-1923	Late 1923	Yes	Yes	Yes	Yes
Mid-1925	Mid-1926	Yes	Yes	Yes	Yes
Mid-1930	Early 1931	No	Yes	Yes	Yes
Early 1932	Late 1932	Yes	Yes	Yes	Yes
Mid-1939	Early 1942	Yes	Yes	Yes	Yes
Early 1946	Late 1946	Yes	Yes	No	Yes
Early 1951	Late 1951	Yes	Yes	Yes	Yes
Early 1953	Late 1953	Yes	Yes	Yes	Yes
Early 1957	Mid-1958	Yes	Yes	Yes	Yes
Mid-1963	Early 1964	Yes	Yes	No	Yes
Early 1965	Mid-1966	Yes	Yes	Yes	Yes
Early 1969	Late 1969	Yes	Yes	No	Yes
Mid-1972	Early 1973	Yes	Yes	Yes	Yes
Mid-1976	Early 1978	Yes	Yes	Yes	Yes
Mid-1982	Mid-1983	Yes	Yes	Yes	Yes
Mid-1986	Early 1987	Yes	—	Yes	—

per year were generated during ENSO years compared with 2.3 tropical cyclones per year during non-ENSO years. The annual number of tropical cyclones generated increased from 13.7 for 1965–70 to 16.4 for 1983–88 (fig. 7).

The different recurrences of ENSO during different periods of the 20th century possibly stem from trends in upper-atmospheric pressure over the Northern Hemisphere (Reiter, 1983). Namias (1986) observed that periods of high persistence in the westerly winds precede the Northern Hemisphere mature stage of ENSO by as much as 1 year, which implies that abnormal atmospheric circulation could induce ENSO conditions. Climatic variability on a decadal scale could be driven by long-term increases in the midtropospheric subtropical westerlies and in the frequency of ENSO conditions (Namias and others, 1988). Changes in general atmospheric circulation, therefore, need to be considered in concert with ENSO conditions for an explanation of decadal-scale variability on hydroclimatology in Arizona.

Changes in Circulation of the Upper Atmosphere

In the temperate latitudes, the upper atmosphere generally alternates between two different types of large-scale motion. Zonal flow occurs when winds in the upper atmosphere are predominantly westerly in direction (fig. 5) and usually results in fair weather in Arizona. Meridional flow occurs when winds follow an undulating, wavelike path across the Northern Hemisphere (figs. 4*B*, 5). Meridional flow creates ridges of high pressure and troughs of low pressure that may be stationary for long periods over North America. Meridional flow allows storms to intensify with tropical moisture and penetrate into the Southwest. The spatial distribution of precipitation in the Western United States depends on the axial position, orientation, amplitude, and wavelength of troughs and ridges (Granger, 1984). Meridional flow may break down in transition to zonal flow, and low-pressure eddies in troughs may become separated from the general circulation and become cutoff low-pressure systems (figs. 4*C*, 5; Douglas, 1974).

The long-term frequency of circulation patterns in the Northern Hemisphere has been addressed by Dzerdzeevskii (1969, 1970), Kalnicky (1974), Barry and others (1981), and Carleton (1987). Zonal flow was more common for 1930–60 than before or after (Dzerdzeevskii, 1969; Kalnicky, 1974; Balling and Lawson, 1982). Dzerdzeevskii (1970) classified Northern Hemisphere circulation for each day for 1899–1969 as zonal, meridional, or transitional (fig. 10). The Dzerdzeevskii circulation types shifted to a greater incidence of zonal flow around 1930 and back to a dominance by meridional flow beginning in the 1950's (fig. 10; Dzerdzeevskii, 1969). The greater incidence of meridional flow in the latter part of the series has continued into the 1980's (Balling and Lawson, 1982).

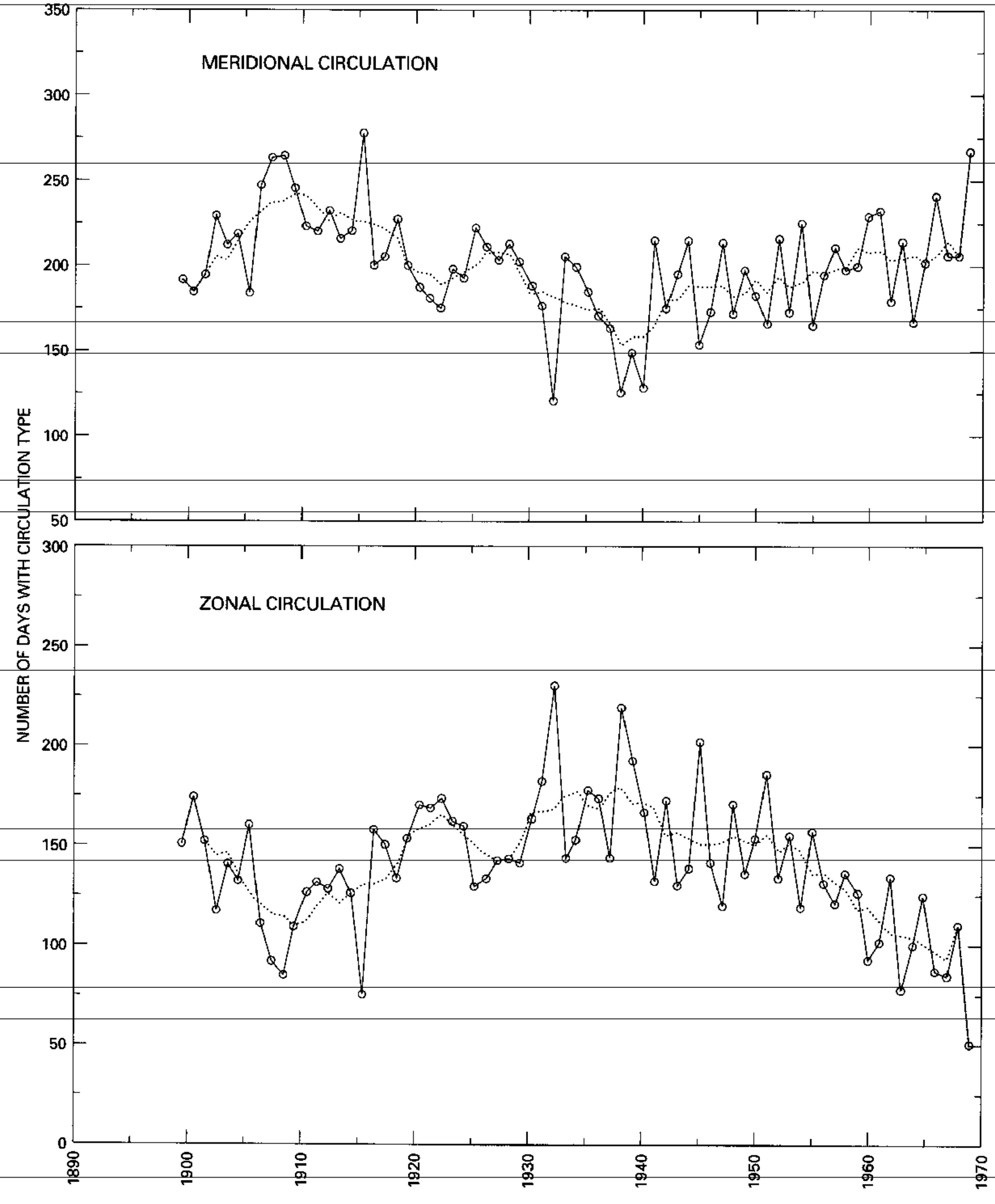


Figure 10. Time series of meridional and zonal flow in upper atmosphere from 1899 to 1970 (Dzerdzeevskii, 1970). Dotted lines represent the 6-year running mean.

The temporal incidence of cutoff low-pressure systems suggests another measure of fluctuations in general circulation. As noted previously, cutoff low-pressure systems evolve during the breakdown of meridional flow in the upper atmosphere. Generally, a low-pressure cell is present near latitude 55° N. and longitude 140° W., and low-pressure eddies move eastward from that area to produce precipitation across the United States. During meridional flow, some low-pressure eddies move as far southward as latitude 25° N. become detached from the westerly circulation pattern, and stagnate before slowly drifting eastward.

For 1945–59, the number of cutoff low-pressure systems that occurred over the continental and southwestern United States averaged 31.9 and 21.3 per year, respectively (fig. 11). For 1960–88, this number decreased to 29.3 per year over the continental United States and 19.2 per year over the Southwest. Concurrently, the variance decreased by about 60 percent in both cases, and the decrease is significant at the 95-percent confidence level using the Squared Ranks Test. These results suggest a greater continuity of meridional flow after 1960.

The incidence of cutoff low-pressure systems in certain months is significantly correlated with ENSO conditions. For example, the number of cutoff lows over the Southwestern United States is negatively correlated with the sea-level pressure difference in January ($r = -0.460$), March ($r = -0.316$), and November ($r = -0.474$). The average numbers of cutoff low-pressure systems are similar during ENSO and non-ENSO conditions; however, seasonally, the average numbers of cutoff lows increases slightly under ENSO conditions for the months of March, October, and November. For example, the average numbers of cutoff lows during March are 3.15 for ENSO conditions and 2.32 for non-ENSO conditions. The joint occurrence of a slight increase of cutoff low-pressure systems in the fall with a slightly increased generation of tropical cyclones suggests increased incidence of tropical cyclones that dissipate over Arizona during ENSO conditions.

El Niño-Southern Oscillation and Precipitation in Southern Arizona

Climate in southern Arizona is teleconnected with the equatorial Pacific Ocean. For example, correlations between SOI and seasonal precipitation for many Arizona stations are statistically significant and negative (Andrade and Sellers, 1988; Ropelewski and Halpert, 1986; and Douglas and Englehart, 1984). Andrade and Sellers (1988) found that precipitation in Arizona and western New Mexico is enhanced in the normally dry spring and fall during ENSO conditions. They suggested that warm sea-surface temperatures off the west coasts of Mexico and California (1) provide the necessary energy for the development of strong west coast troughs, (2) weaken the tradewind inversion and thus allow moist air to penetrate into the Southwest, and (3) cause stronger, more numerous Pacific tropical cyclones than usual. Douglas and Englehart (1984) found significant positive correlations between the index of Line Island summer precipitation and precipitation in the southwestern United States during October, November, and the following February and March (fig. 12). These months are also ones in which the incidence of cutoff low-pressure systems increased under ENSO conditions. Southern Arizona and southern California yield the highest positive correlations for each of these months for latitudes south of 40° N. (fig. 12).

For 1900–82, seasonal teleconnections are reflected in the correlation coefficients between monthly precipitation at the University of Arizona at Tucson station and the index of Line Island precipitation for the current and previous (lag 1) year. Significant positive correlations were obtained between precipitation in the Line Islands for all months from the previous June to the current April and precipitation at the University of Arizona from February to May (table 5). Significant correlations were also obtained between Line Island precipitation in summer and fall with precipitation at the University of Arizona between October and November (table 5). Some of these correlations imply a 4- to 6-month lag in the midlatitude atmosphere-ocean response to processes that occur at the equator. Significant relations between precipitation in the Line Islands and Tucson for the same month, however, suggest a more direct link to tropical cloud masses moving northeast from the central equatorial Pacific Ocean.

Betancourt (1990) analyzed the effect of ENSO conditions on Tucson precipitation using a 36-month period centered on June of an average year with ENSO conditions. Precipitation is significantly increased in most months during and 1 year after ENSO conditions; precipitation for April through June and October is significantly higher than for non-ENSO conditions. Significantly reduced precipitation in August, during ENSO conditions, indicates a suppression of summer monsoonal precipitation under ENSO conditions. Sellers (1960) found a negative correlation between September and July and August precipitation for 1898 to 1959 in Arizona. Under ENSO conditions, precipitation begins earlier in fall months in the southwestern United States (Kiladis and Diaz, 1989). Sellers (1960) and Betancourt (1990) suggested that atmospheric conditions that are conducive to monsoonal precipitation are somewhat exclusive of precipitation from dissipating tropical cyclones.

Hydrologic Variability in the Santa Cruz River Basin

Various indices and proxy records indicate shifts in climate around 1930 and 1960. Because Arizona's climate

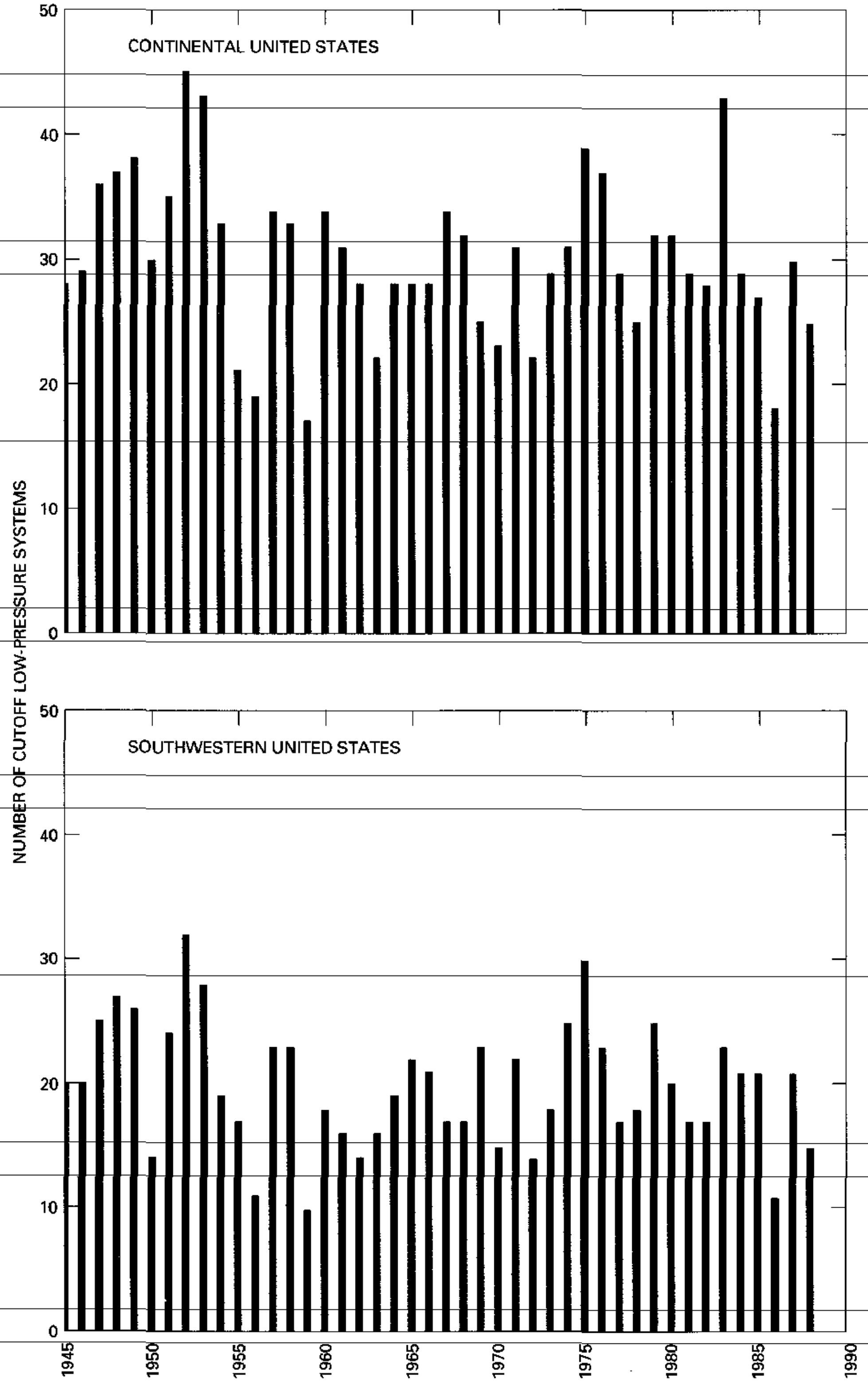
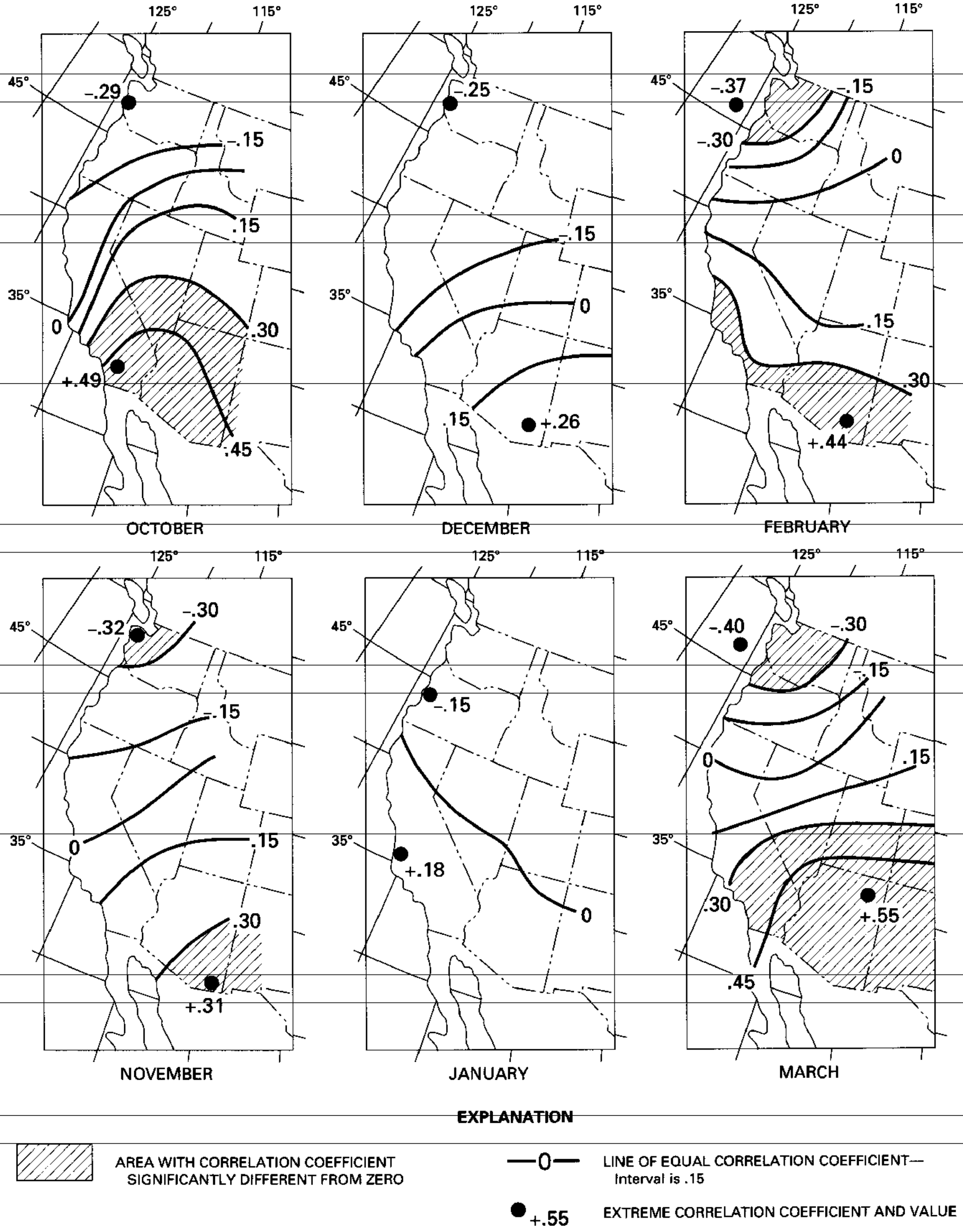


Figure 11. Annual frequency of cutoff low-pressure systems, which are defined as 2 days with one closed geopotential height on a 500-millibar height map (National Oceanic and Atmospheric Administration, 1988). Cutoff low-pressure systems occur over the Continental United States between lat 20° N. and 45° N. and long 65° W. and 140° W. and in the Southwestern United States between lat 20° N. and 45° N. and long 100° W. and 140° W.



OCTOBER

DECEMBER

FEBRUARY

NOVEMBER

JANUARY

MARCH

Figure 12. Correlations between the index of Line Island precipitation for the equatorial Pacific Ocean and precipitation in the Western United States (Douglas and Englehart, 1984).

Table 5. Matrix of correlation coefficients between Line Island monthly precipitation and Tucson monthly precipitation, 1900–82

[Comparison begins with Line Island precipitation in June of the previous year to check for lag effects on Tucson precipitation. Pearson correlation coefficients greater than or equal to 0.22 are significantly different from zero at the 95-percent confidence level. Significant values are underscored. Note that correlation coefficients greater than 0.28 are significantly different from zero at a 99-percent confidence level]

Tucson precipitation	Index of Line Island precipitation																			
	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Jan.	–0.11	–0.15	–0.13	0.03	–0.09	–0.08	–0.02	–0.01	–0.03	0.07	0.01	–0.05	0.04	0.02	–0.14	–0.03	0.02	–0.06	–0.02
Feb.	.22	.27	.26	.37	.34	.43	.33	.36	.27	.19	.21	.08	.12	–.01	.05	.08	.05	.03	.16
Mar.	.25	.28	.47	.42	.45	.47	.51	.38	.41	.31	.24	.19	.15	.04	–.07	.05	.00	.01	–.01
Apr.	.14	.16	.27	.27	.26	.20	.31	.33	.25	.24	.28	.21	.28	.14	.26	.19	.12	–.08	.10
May	.02	.11	.17	.14	.16	.22	.25	.17	.19	.22	.24	.11	.23	.06	.13	.29	.25	.18	.23
June	.02	.12	.12	.19	.14	.06	.09	.05	.06	.07	.00	–.01	.06	.06	.12	.11	.16	.14	.14
July	–.05	–.06	–.15	–.16	–.17	–.19	–.10	–.10	–.09	–.14	–.12	–.26	–.28	–.17	–.19	–.10	–.16	–.19	–.22
Aug.	–.01	.00	–.10	–.15	–.11	–.15	–.14	–.08	–.10	–.13	.10	–.15	.08	.05	–.07	–.06	.05	.05	.09
Sept.	.06	–.13	.08	.12	.14	.05	.04	.02	.03	.05	.14	.09	.12	.23	.18	.01	.06	.10	.16
Oct.	.00	–.17	.03	–.06	.06	–.13	.06	.03	.04	.14	.23	.30	.22	.34	.21	.21	.30	.29	.29
Nov.	–.01	–.20	.22	.16	.17	.13	.19	.17	.20	.17	.17	.13	.33	.25	.37	.29	.34	.27	.24
Dec.	.02	.04	.06	–.06	.10	.04	.08	.09	.11	.15	.15	.08	.16	.11	.15	.19	.20	.24	.07

is linked with these climatic processes, some differences in climatic and hydrologic regimes would be expected for different periods of the 20th century. The periods of 1900–29, 1930–59, and 1960–86 were chosen for comparison because they represent approximately equal numbers of years. The intensity and amount of precipitation at the University of Arizona at Tucson station changed after 1960. Extreme precipitation events of 1- to 7-day duration increased significantly after 1954 for September to October and January to February (Kenneth Young, University of Arizona, written commun., 1985). Likewise, the frequency of days with more than 25 mm of rainfall during the summer months increased significantly in the 1950's (Betancourt, 1990). Heavy rains were also frequent in the late 1800's, when large floods initiated the arroyo that now marks the course of the Santa Cruz River.

Streamflow in the Santa Cruz River also has changed during the 20th century. The seasonality of annual floods changed after about 1960 (fig. 2). The amount of seasonal runoff, in accordance with the annual flood series, varies significantly during the 20th century. Seasonal cumulative departures from mean streamflow (fig. 13) indicate that below-average runoff occurred during 1920–60 in winter and fall. Streamflow in winter and fall increased episodically in the mid-1960's, late 1970's, and early 1980's (fig. 13). The graphs in figure 13 reflect changes in the annual flood series (fig. 2). Conversely, summer runoff increased from 1949 to the late 1950's and then steadily decreased until 1985.

Duration analyses of daily streamflow at the gaging station, Santa Cruz River at Tucson, reveal marked changes with time. Daily discharges in summer months that were exceeded less than 2 percent of days were much higher for 1930–59 than for 1915–29 or for 1960–81 (fig. 14). Conversely, daily discharges in fall months that were exceeded less than 2 percent of days were much less for 1930–59 than before or after. Cumulative-departure curve patterns and duration-analysis results reflect the enhancement of fall and winter precipitation and the suppression of summer precipitation during periods of increased frequency of ENSO conditions before 1930 and after 1960.

FREQUENCY ANALYSIS OF ANNUAL FLOODS IN THE SANTA CRUZ RIVER

Previous Estimates of the 100-Year Flood

The flood of October 1983 on the Santa Cruz River heightened public awareness of flood-frequency estimates. Even before the flood of October 1983, estimates of the 100-year flood for the Santa Cruz River at Tucson were controversial (Michael Zeller, Simons Li and Associates, written commun., 1984). Knapp (1937) first estimated the 100-year flood to be 355 m³/s from a record length of 20 years. Schwalen (1942) estimated the 100-year flood to be 450 m^3/s from a record length of 27 years. Recent estimates range from 572 to 2,780 m^3/s (table 2) and were derived by applying different methods and assumptions to varying lengths of record both before and after the 1983 flood (table 2).

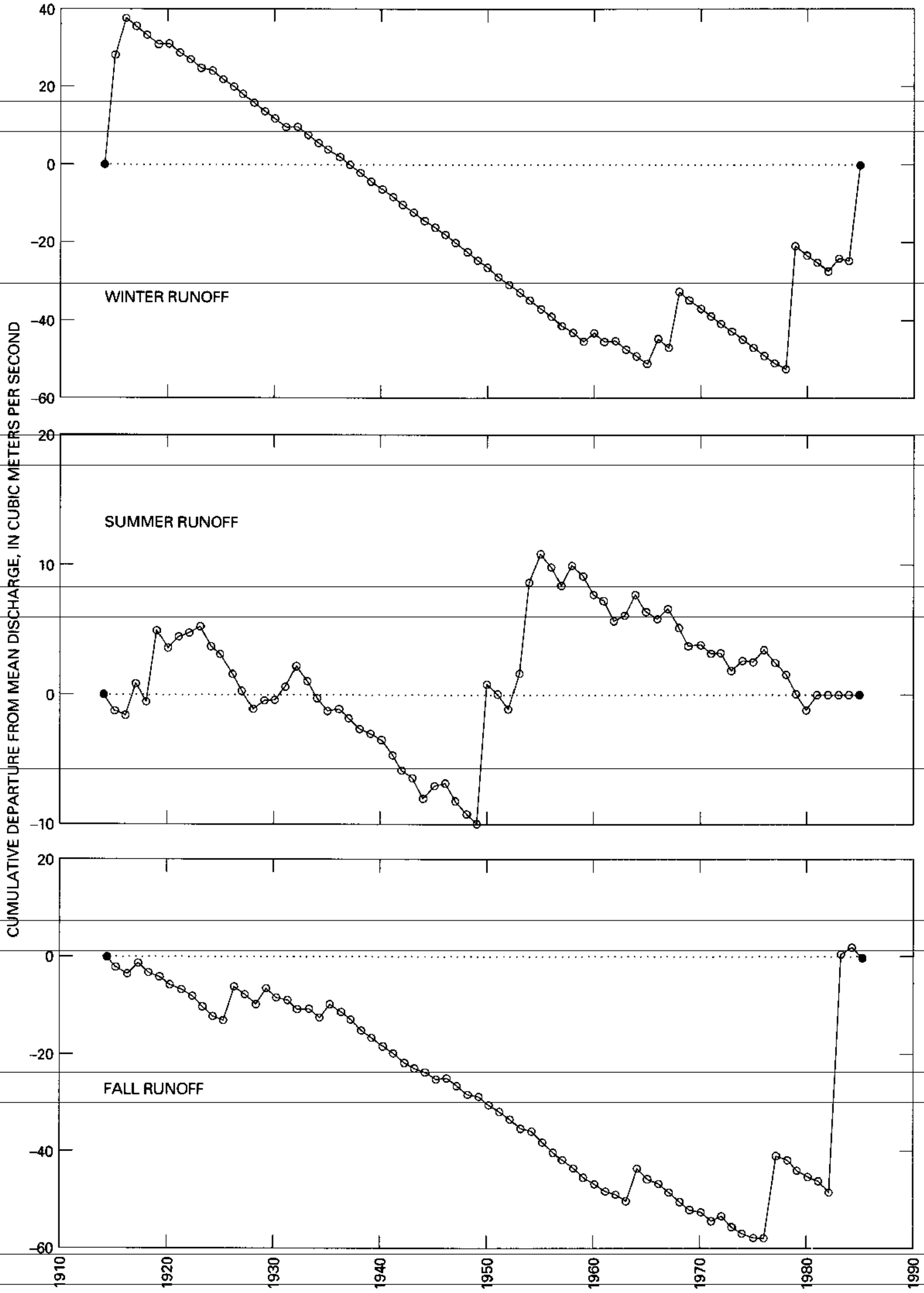


Figure 13. Seasonal cumulative departures from mean discharge, Santa Cruz River at Tucson, Arizona.

After the flood of 1983, local authorities reacted to discrepancies in the 100-year flood estimates by commissioning studies and amending existing flood-plain legislation. A deterministic hydrologic simulation model using 100-year-frequency rainfall of 24-hour, 48-hour, and 96-hour durations was used in one study (Ponce and others, 1985). The model was calibrated by hindcasting the runoff hydrograph of the flood of October 1983.

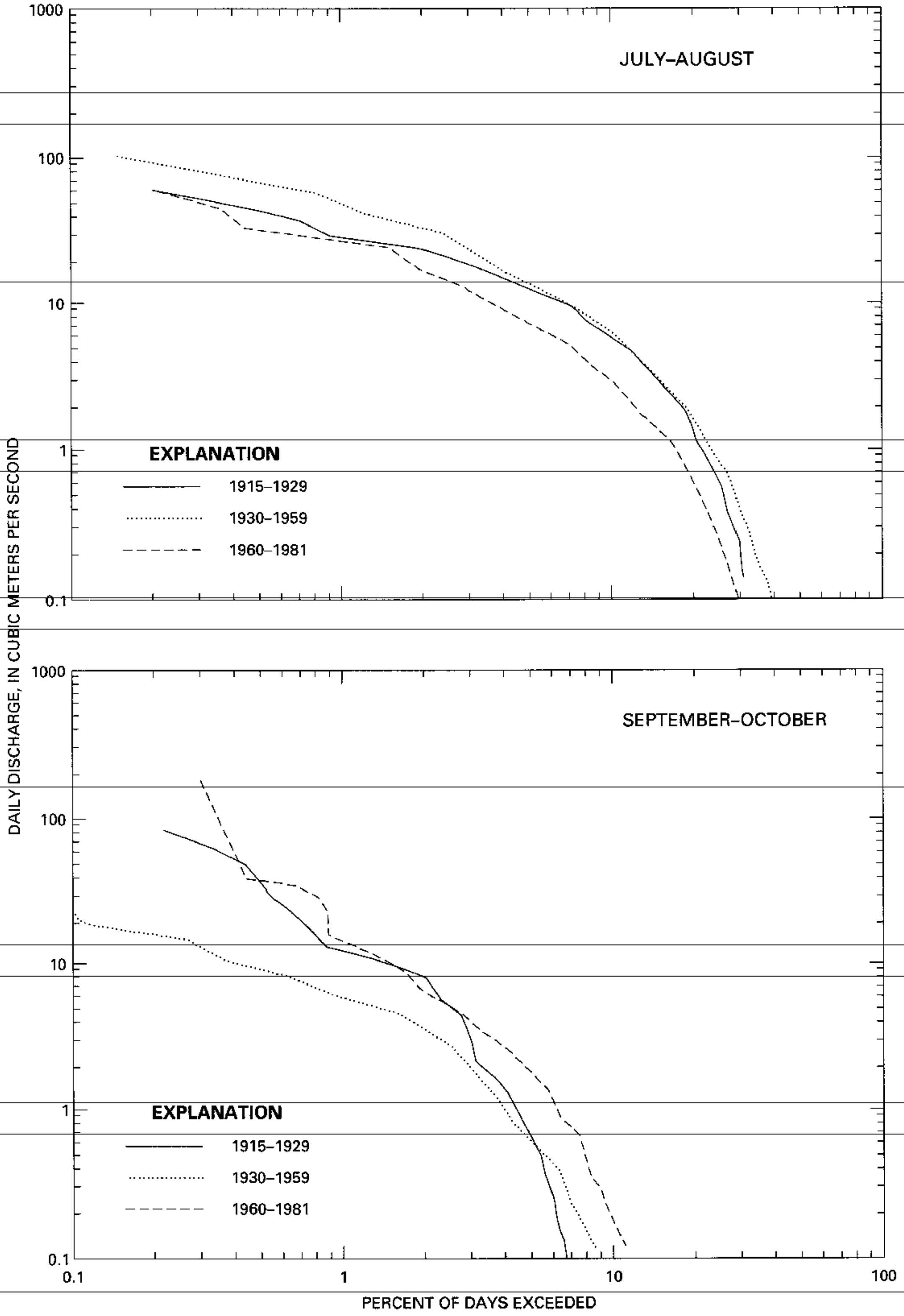


Figure 14. Duration analyses of daily discharge for two periods, Santa Cruz River at Tucson, Arizona.

Some of the assumptions relating to tributary inflow during the flood of October 1983 have been questioned (Hjalmarson, 1987). On the basis of the rainfall-runoff model, both Pima County and the city of Tucson adopted a "regulatory flood" of 1,700 m^3/s and a "design flood" of 1,980 m^3/s in 1985 for the reach between the San Xavier del Bac Mission and the confluence with the Rillito River (fig. 1). The regulatory flood is used for compliance with the National Flood Insurance Program, whereas the design flood is used for design of bridges and other flood-plain structures.

Effects of Land Use and Channel Change

Reich (1984), Michael Zeller (Simons Li and Associates, written commun., 1984), and Reich and Davis (1985, 1986) attributed the change in flood frequency to increased channelization, improved channel conveyance, and reduced channel storage upstream from Tucson since establishment of the gaging station, Santa Cruz River at Tucson, in 1915. Changes in channel topography, such as those that evolved from arroyo-cutting along the Santa Cruz River (Cooke and Reeves, 1976; Betancourt and Turner, 1988; Betancourt, 1990), are known to alter conveyance of flood waves (Burkham, 1981). The result would be an increase in the peak discharge downstream for the same volume of runoff.

The Santa Cruz River did not have an entrenched channel near the south boundary of the San Xavier Indian Reservation (fig. 1) in 1915, when the gaging station was established at Tucson. In the reservation, the channel deepened 3 to 5 m between 1915 and the late 1930's and another 2 to 3 m since then. The channel bottom at Tucson incised 3 to 5 m after 1946 (Aldridge and Eychaner, 1984) apparently because of encroachment of the channel by landfills and highway construction. Hypothetically, the flood in December 1914, which produced a peak discharge of 425 m^3/s, would yield a much higher peak if routed through the modern incised channel. Conversely, the peak discharge of 1,490 m^3/s in October 1983 might have been much less if it had flowed through the discontinuous arroyo system that existed in 1915. Preliminary results using a flow-routing model, however, yielded only an approximate 15- to 20-percent decrease in discharge by routing the flood of 1983 through the 1915 channel (H.W. Hjalmarson, hydrologist, U.S. Geological Survey, oral commun., 1989). Local channel erosion, therefore, is not the sole reason for changes in the annual flood series.

Annual floods have increased in size at all gaging stations on the Santa Cruz River (fig. 15). At Lochiel, a flood in August 1984 was larger than the flood of October 1983 (fig. 15*A*). No significant change in land use has occurred upstream from the gaging station at Lochiel. At Nogales (fig. 15*B*), where land use in Mexico could have altered flow conveyance, five of the six largest floods occurred between 1968 and 1983. The annual flood series for other gaging stations on the Santa Cruz River also show an increase in annual peaks (fig. 15*C*, *E*, *F*). At Tucson, six of the seven largest floods occurred after 1960 and five of these occurred in fall or winter (table 1; fig. 15*D*).

Although land use and changes in channel conveyance undoubtedly have increased flood discharges to some unknown extent, climatic effects are the only common link among the six gaging stations on the Santa Cruz River. Only the very largest floods, as in October 1983, are sustained from the headwaters to the juncture with the Gila River near Laveen. At Lochiel, flows in the Santa Cruz River could not have been affected significantly by land use, yet peak discharges have increased since 1960 (fig. 15*A*). The August 1984 flood at Lochiel, the peak of record, was larger than the October 1983 flood, which indicates that the apparent changes are not caused by a few isolated large floods. Changes in the hydroclimatology of the basin are reflected by a shift in the seasonality of annual flood peaks, which is also the most striking symptom of the underlying climatic control of flood frequency.

Seasonality of Annual Floods

The annual flood series of the Santa Cruz River at Tucson shows a lack of uniformity in the seasonality of flood peaks (table 1, fig. 2; Keith, 1981; Hirschboeck, 1985; Betancourt and Turner, 1988) that may partly account for the increase in annual peaks since 1960. Floods in July and August accounted for 75 percent of the annual peaks for 1915–86, and summer had the largest and least-variable monthly discharges (fig. 3). For 1915–29 and 1960–86, however, 53 percent and 39 percent, respectively, of the annual flood peaks occurred in fall (September to October) or winter (November to February). For 1930–59, only 3 percent of the peaks occurred in fall or winter. Seven of the eight largest peaks in the flood series were produced by fall or winter storms, and five of these occurred in 1960–86. Whereas most of the annual floods at Nogales occurred in summer (fig. 15*B*), four of the six largest floods occurred in fall or winter. These changes indicate that seasonality of flooding is not stationary or random on the Santa Cruz River.

The change in seasonality of annual flood peaks after 1960 is not unique to the Santa Cruz River but also occurs on other streams in southern and central Arizona that have drainage areas larger than about 2,000 km^2. Rillito Creek (Slezak-Pearthree and Baker, 1987), San Francisco River (Hjalmarson, 1990), and the Gila and San Pedro Rivers (Roeske and others, 1989) are some examples. The largest floods on these rivers commonly occur in fall and winter, although annual peaks also occur in summer. The storm types that are responsible for these floods are dissipating tropical cyclones, cutoff low-pressure systems, and frontal systems.

The change in seasonality of annual floods indicates low-frequency climatic variability as the principal reason for increased flood frequency on the Santa Cruz River. Al-

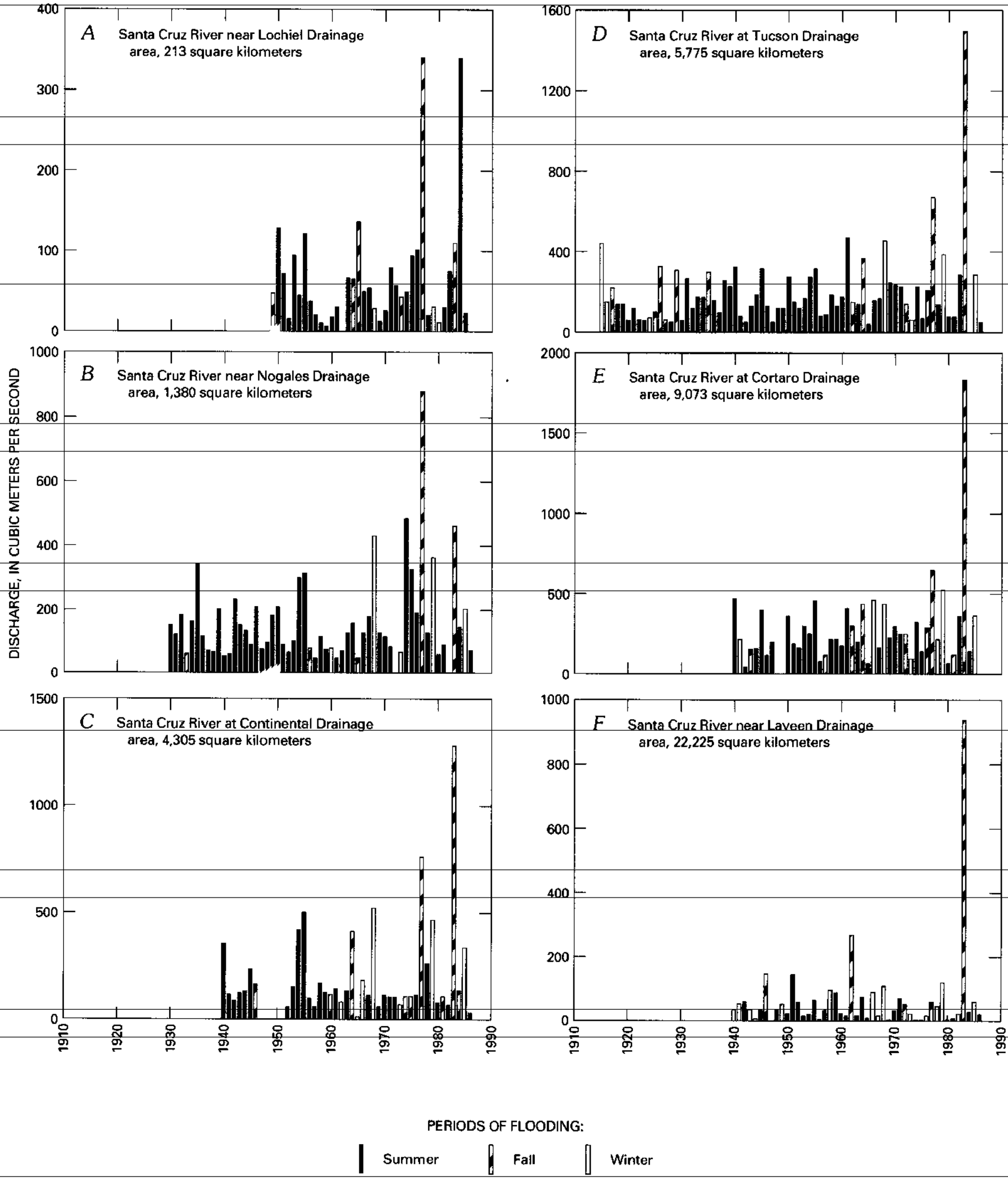


Figure 15. Annual flood series for six gaging stations, Santa Cruz River, southern Arizona. Hydroclimatological year, November 1 to October 31.

though land-use practices may have produced a modest increase in discharges, climatic variability is the only possible reason for changes in the seasonality of flooding. As will be shown, the best explanation for the change in seasonality is a shift in the type of storms that cause floods. Storms in fall and winter after 1960—related to dissipating tropical cyclones, cutoff low-pressure systems, and frontal systems—caused floods that were larger than floods between 1930 and 1959.

Estimates of 100-Year Discharges Using Method of Moments, 1970–85

The stability of 100-year flood estimates is one indication of stationarity in an annual flood series. In 1970, the length of the annual flood series for the gaging station, Santa Cruz River at Tucson, was 55 years. By using the method of moments and assuming a log-Pearson type III distribution, addition of successive annual floods after 1970 affected 100-year flood estimates (fig. 16; Interagency Advisory Committee on Water Data, 1982). The 100-year flood estimates increased 16 percent or 90 m^3/s for 1970–82. The influence of the flood of October 1983 is apparent in the 50-percent increase in 100-year flood estimates—from 577 to 872 m^3/s—for 1971–86. The 100-year flood estimated from annual peaks for 1915–86 is larger than the band between the 10- and 90-percent confidence intervals for the value estimated from peaks for 1915–71 (fig. 16).

Changes in the standard deviation and skew coefficient of the log-Pearson type III distribution (fig. 17) indicate the statistical cause for changes in estimates of the 100-year flood. Although the mean and variance do not change significantly with addition of successive annual floods, the skew coefficient increases from –0.29 to 0.30 for 1971–86 (fig. 17) because of the preponderance of large floods. Despite the moderating effect of weighting the sample skew coefficient with a generalized skew coefficient of –0.2 (Interagency Advisory Committee on Water Data, 1982), the larger skew coefficient underlies the increase in discharge for the 100-year flood.

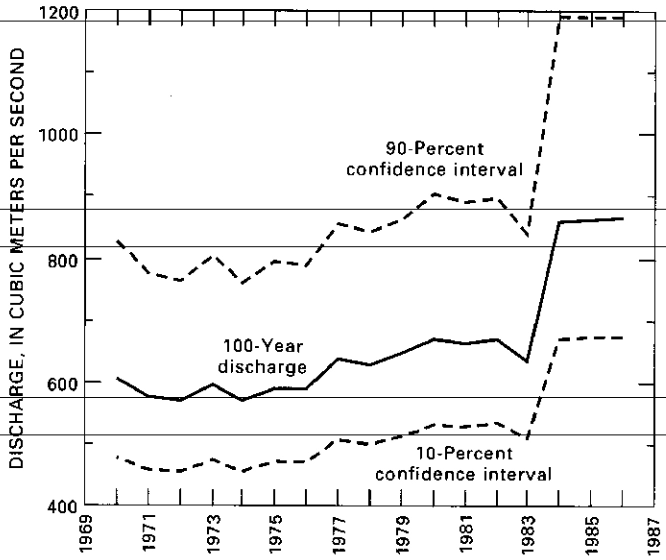


Figure 16. Chronology of 100-year flood estimates for the Santa Cruz River at Tucson, Arizona, 1970–86. The skew coefficient is weighted using a generalized skew coefficient of –0.2 with a mean-squared error of 0.302.

Trend Analysis of the Annual Flood Series

According to Reich (1984), the annual flood series changed about 1960 to a regime of increased flood size. Using a Kruskal-Wallis nonparametric test (see Conover, 1971, p. 229) on data from the gaging station, Santa Cruz River at Tucson, Reich (1984) concluded that annual floods for 1915–59 were derived from a different population than annual floods for 1960–84. H.W. Hjalmarson (U.S. Geological Survey, written commun., 1985) detected a positive trend in the annual flood series for 1915–84 using Pearson product-moment correlation analysis and moderate trends using other nonparametric tests. The Pearson product-moment correlation results were highly influenced by the 1983 flood, whereas the nonparametric tests were not. Hjalmarson's results also suggest that annual floods were larger after 1960.

Although the means for 1915–29, 1930–59, and 1960–86 are not significantly different, the mean of the annual flood series is 147 m^3/s for 1915–29 and 267 m^3/s for 1960–86 (table 6). The variances for 1915–29 and 1930–59 are significantly less than the variance for 1960–86 at a 95-percent confidence level using the Squared Ranks Test (Conover, 1971). These results suggest that the annual flood series at Tucson may result from weak stationarity of order 1—the mean is time invariant although the variance and skew coefficient change with time (Box and Jenkins, 1971, p. 30). The annual flood series at Cortaro yields similar results because the correlation coefficient between the two series is 0.938 ($r = 0.785$ without the flood of 1983).

Trend analysis was performed on the annual flood series using two nonparametric tests. Kendall's tau-b (Conover, 1971) and Spearman rank-correlation analyses were used to detect any significant trends in the annual flood series and (or) segments of the flood series. Most of the analyses did not yield significant trends at the 95-percent confidence level (table 6). Kendall's tau-b analyses indicate no significant trends in or between any of the periods. Using the Spearman rank correlation, only floods for 1915–29 had a significantly negative trend (table 6). Lack of significant trends for most periods could be explained by a lack of significant differences among the mean annual floods of the various periods, which trend analysis is designed to detect. Changes in the variance and skew apparently are not large enough to yield significant trends in or between the periods. The absence of significant trends within periods suggests that, with the possible exception of 1915–29, each of the three segments of the annual flood series may have arisen from a homogeneous population.

Flood Frequency During El Niño-Southern Oscillation Conditions

The annual flood series of the Santa Cruz River is also affected by ENSO conditions. Four of the five largest and six of the ten smallest annual floods at Tucson occurred during ENSO conditions. For ENSO conditions, the mean discharge and standard deviation for 27 annual floods at Tucson are 226 and 288 m^3/s. For non-ENSO conditions, the mean and standard deviation for 44 annual floods are 181 and 111 m^3/s. The means of the respective series are not significantly different, but the variance during ENSO years is significantly increased. Using the nonparametric Squared Ranks Test statistic (Conover, 1971, p. 239–240), the variance for ENSO years is significantly greater than that for non-ENSO years at the 95-percent confidence level.

Flood frequency was estimated using procedures given in Interagency Advisory Committee on Water Data (1982) for ENSO and non-ENSO years (fig. 18). A tenuous assumption of stationarity over the period of record is required for the frequency analysis. A generalized skew coefficient of –0.2 was used to weight the station skew. The estimated 100-year floods for ENSO and non-ENSO years are 1,300 and 628 m^3/s, respectively, at Tucson (table 7). The frequency relations begin to diverge substantially above about a 25-year recurrence interval (fig. 18). At Cortaro, the estimated 100-year floods for ENSO and

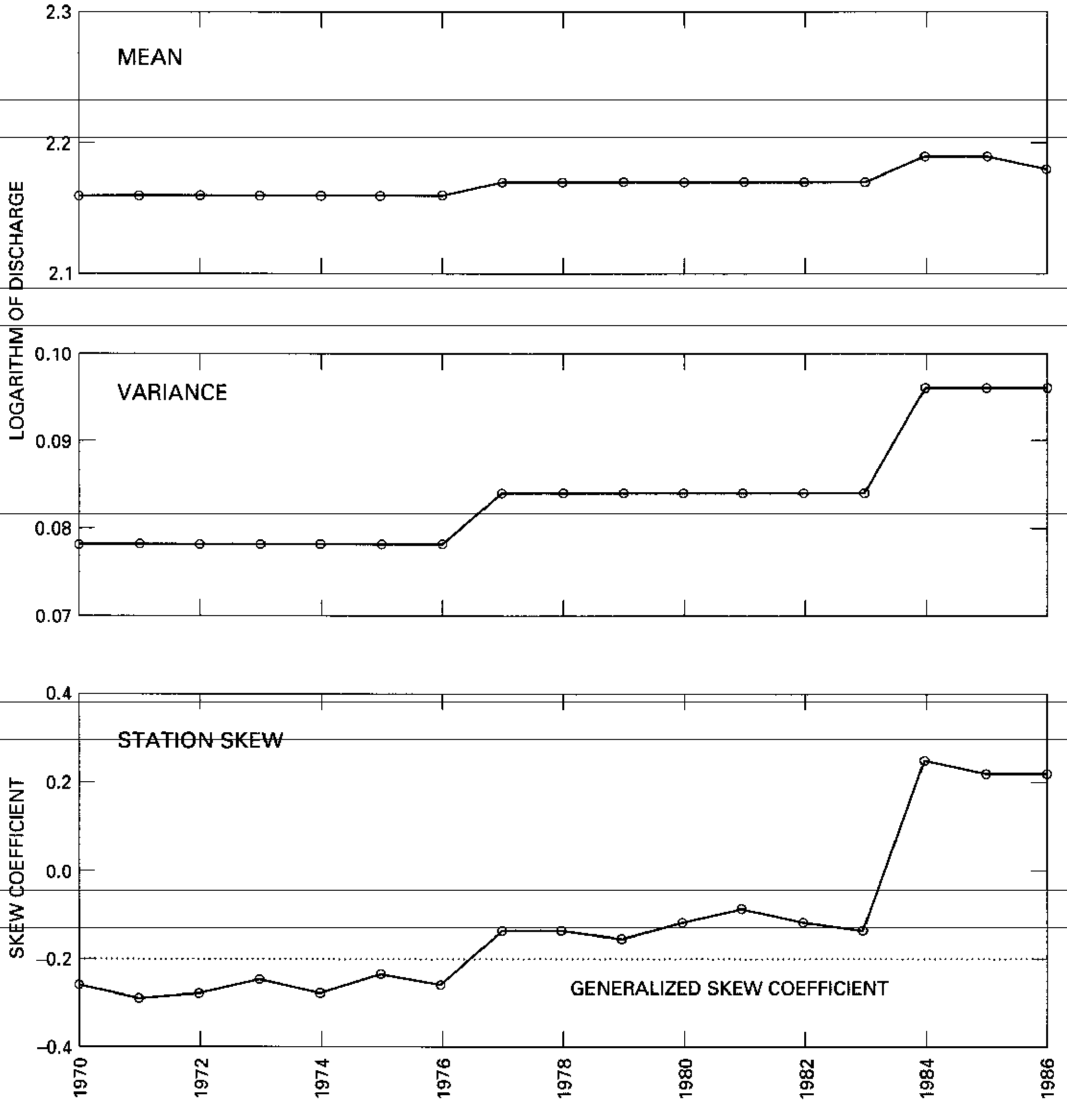


Figure 17. Chronology of moments of the log-transformed annual flood series of the Santa Cruz River at Tucson, Arizona, 1970–86. Values were estimated using U.S. Water Resources Council (1981) methods and a generalized skew coefficient of –0.2 with a mean-squared error of 0.302.

Table 6. Statistical properties and trend-analysis results for five periods of the annual flood series, Santa Cruz River at Tucson, Arizona

Period	Number of years	Mean discharge, in cubic meters per second	Standard deviation, in cubic meters per second	Mean logarithm of discharge	Standard deviation of log discharge
All	71	199	198	2.17	0.319
1915–29	15	147	117	2.05	.321
1930–59	30	166	85	2.16	.248
1960–86	26	267	292	2.27	.371
ENSO years	27	226	288	2.18	.368
Non-ENSO years	44	181	111	2.17	.288

	Kendall's tau-b		Spearman rank correlation	
Period	Tau-b	Probability of significance[1]		Probability of significance[1]
1915–29	–0.36	0.067	–0.64	[2]0.014
1930–59	–.01	.96	–.051	.79
1960–86	–.01	.98	.019	.98
1915–86	.13	.12	.19	.12
1930–86	.09	.34	.12	.38

[1] Probability of significance refers to the probability level at which the null hypothesis of no significant slope can be rejected.

[2] A significant trend was determined at the 95-percent confidence level.

non-ENSO years are 1,620 and 746 m³/s, respectively. Whether or not ENSO conditions occur has an important effect on flood frequency regardless of fluctuations in 20th-century climate.

HYDROCLIMATIC FLOOD-FREQUENCY ANALYSIS OF THE SANTA CRUZ RIVER

Analyses of oceanic and atmospheric processes that lead to storms and subsequent flooding in Arizona suggest that the 20th century has at least three distinct hydroclimatic periods—1900–29, 1930–59, and 1960–86. Transitions between these periods appear to be gradational instead of abrupt. The increased frequency of ENSO conditions after 1960 has apparently enhanced the generation of tropical cyclones in the eastern North Pacific Ocean, and the relation of increased incidence of cutoff low-pressure systems with ENSO conditions suggests an increased probability for recurvature of tropical cyclones into North America. Frontal storms are enhanced by an increase in meridional circulation, a deepened Aleutian low, and greater moisture availability from the North Pacific Ocean. The duration of the period that began about 1960 is unknown, but the period appears to have been stable until at least 1986.

These results pose a challenge for statistical flood-frequency analysis of rivers in Arizona. Certain storm types that cause floods are enhanced before 1930 and after 1960, whereas other storm types may occur less frequently. The low-frequency temporal shifts in hydroclimatology support the empirical observation that changes in annual flood series are caused by temporal changes in variance and (or) skew coefficient, instead of the mean. Larger floods caused by frontal systems and tropical cyclones could be offset by a decrease in incidence of the more common floods caused by monsoonal storms. This possible offset suggests that annual flood series, such as the one for the Santa Cruz River at Tucson (fig. 2), are weakly stationary and have a changing variance and (or) skew coefficient.

One means of estimating annual flood frequency for a river such as the Santa Cruz might be to consider floods caused by different storm types as independent populations. Although the sampling properties of these populations probably are continuous functions of time, floods caused by different storm types may be stationary for 1930–60 and 1960–86. Because no partial-duration series is available before 1930 and the length of the period is only 15 years, this period was not considered separately. Samples from the separate periods can be fitted to probability distributions with different assumptions concerning the expected effects of the shifts in oceanic and atmospheric processes on their statistical properties. The separate populations can then be combined using mixed-population analysis to estimate annual flood-recurrence intervals.

Separation of Floods by Storm Types

Hirschboeck (1985) analyzed the hydroclimatology of floods for 1950–80 in the Gila River basin of which the Santa Cruz River basin is a part. She identified populations of floods caused by snowmelt and eight types of storms and classified all floods for 30 gaging-station records, including Santa Cruz River at Tucson and Santa Cruz River at Cortaro, in the partial-duration series. Storm types were identified using various data sources including daily weather maps (National Oceanic and Atmospheric Administration, 1988), 700- and 500-millibar heights, tropical cyclone reports, and precipitation data (Hirschboeck, 1985).

Hirschboeck's (1985) classification scheme cannot be applied to floods before 1945 because of the absence of 700- and 500-millibar height data. To obtain consis-

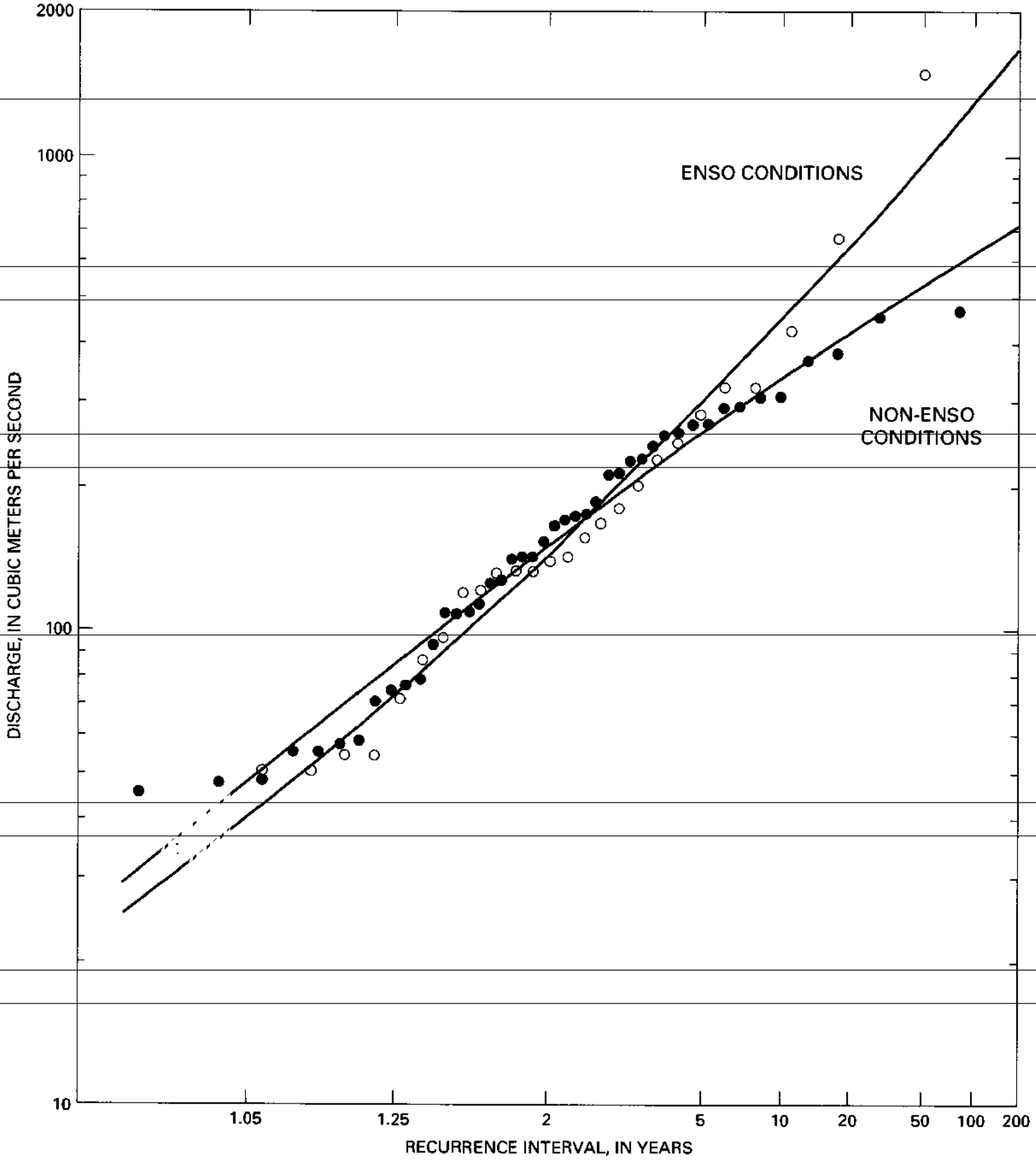


Figure 18. Flood frequency for years with and without El Niño-Southern Oscillation conditions, Santa Cruz River at Tucson, Arizona. The skew coefficient is weighted using a generalized skew coefficient of –0.2, with a mean-squared error of 0.302.

Table 7. Estimates of the 100-year flood for the Santa Cruz River calculated using different methods and based on different assumptions

[Methods: MM, procedures specified in Interagency Advisory Committee on Water Resources (1982) and a generalized skew coefficient of –0.2; ML, maximum-likelihood analysis of type I censored data (Stedinger and others, 1988); MP, mixed-population analysis of floods caused by monsoonal storms, frontal systems, and dissipating tropical cyclones. Assumptions: A, data are strictly stationary in time; B, discharge for 1983 flood is not considered as a historic peak; C, data are weakly stationary but are considered stationary for the indicated period, and future flood potential is similar with conditions in the period; D, floods caused by different storm types are assumed to be independent]

Years	Method	Assumptions	100-year discharge, in cubic meters per second	
			At Tucson	At Cortaro
All ----------------	MM	A,B	872	1,150
ENSO ------------	MM	A,B	1,300	1,620
Non-ENSO -------	MM	A	628	746
All ----------------	ML,MP	A,B,D	1,050	1,610
1930–59 ----------	ML,MP	C,D	323	——
1960–86 ----------	ML,MP	B,C,D	1,660	2,030

tent storm types for the period of record on the Santa Cruz River, Hirschboeck's (1985) storm types were combined for this study into the three categories of monsoonal storms, synoptic-frontal systems, and dissipating tropical cyclones. Hirschboeck's (1985) monsoonal-local, monsoonal-widespread, and monsoonal-frontal types are classified simply as monsoonal storms. Widespread synoptic, fronts, and cutoff-low types are classified as synoptic-frontal systems. The tropical-storm type was redefined as a dissipating tropical cyclone using criteria of Smith (1986). Floods for 1915–86 were classified using these criteria independent of Hirschboeck's (1985) classification. Several discrepancies in the classification of floods caused by dissipating tropical cyclones occurred, mainly because the primary reference on tropical cyclones (Smith, 1986) was not available when Hirschboeck did her classification. The largest annual flood was then determined for each storm type.

A potential problem with dependence among storm types occurs because incursions of dissipating tropical cyclones are often associated with cutoff low-pressure systems. Cutoff low-pressure systems, which are lumped with synoptic-frontal systems, cannot be detected without 500-millibar height data. The chronology of tropical cyclones that is now available (Smith, 1986; Jose Arroyo Garcia and others, Circuito Exterior, Ciudad Universitaria, Mexico City, written commun., 1989), however, permits an unambiguous classification of floods caused by this storm type.

Patterns present in the time series of annual floods at Tucson caused by three storm types (fig. 19, table 8) indicate the cause for the shift in magnitude and seasonality of annual floods (fig. 2). The magnitude of floods caused by dissipating tropical cyclones and frontal systems increased after 1960 (fig. 19). The decadal frequency of floods above base discharge caused by dissipating tropical cyclones did not change after 1960 (2.9 per decade for 1960–84 compared with 3.0 per decade for 1930–59). Decadal frequency of floods above base caused by frontal systems, however, nearly doubled from 2.0 per decade in 1930–59, to 3.8 per decade in 1960–84. Although the magnitude of floods caused by monsoonal storms does not appear to change (fig. 19), the frequency decreases from 9.7 per decade in 1930–59 to 7.3 per decade after 1960. These results illustrate the inverse relation between the occurrence of floods caused by monsoonal storms and floods caused by dissipating tropical cyclones and frontal systems. Also, floods caused by different storm types in 1960–84 should be considered as populations distinct from those in 1930–59.

Methods of Flood-Frequency Analysis

Annual floods caused by different storm types can be analyzed as type I censored data. Censored data arise when a known number of observations are missing from a sample population (Cohn, 1986). Type I censoring occurs when all values larger than a fixed threshold, or censoring level, are observed and all values less than the censoring level are not (Cohn, 1986). The partial-duration series is determined by selecting a base discharge above which all discharges are determined. Therefore, a series that consists of the largest annual floods above base discharge and caused by a single storm type is, by definition, type I censored and independent data from a single population.

Plotting positions are assigned to the data using a generalized equation developed by Hirsch and Stedinger (1987) (Stedinger and others, 1988). Consider the case of one censoring level with record length (h) and number of floods (n) that exceed the censoring level (base discharge). Discharges that exceed the censoring level are ranked from largest to smallest by $i=1,2,3,\ldots,n$. The probabilities of discharges exceeding the censoring level are given by

$$p_i=(n/h)[(i-a)/(n+1-2a)],\ i=1,2,3,\ldots,n. \qquad (1)$$

In this report, we use a = 0.44 for Gringorten plotting positions (see Hirsch, 1987). The choice of plotting position is inconsequential because the differences among plotting position types are small compared with their sampling variability (Hirsch and Stedinger, 1987). The recurrence interval, T, for a flood is the inverse of p calculated with equation 1.

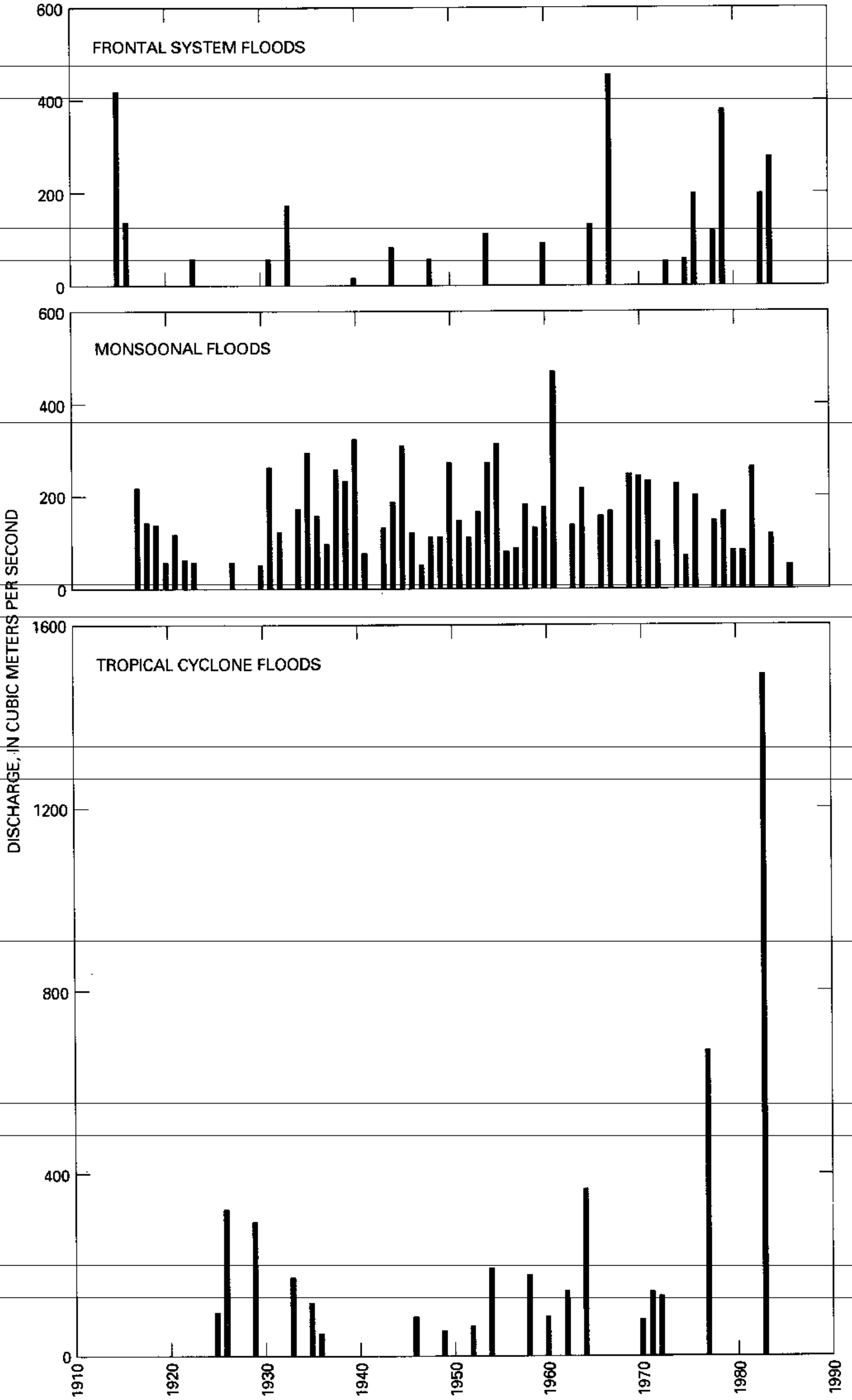


Figure 19. Largest annual floods at or above base discharge (48 m^3/s) on Santa Cruz River at Tucson caused by frontal systems, monsoonal storms, and dissipating tropical cyclones.

Table 8. Floods above base discharge, by storm type, Santa Cruz River at Tucson, Arizona

[Base discharge, 48 m^3/s. Hydroclimatic water year, November 1 to October 31]

Floods caused by									
Frontal storms		Dissipating tropical cyclones		Monsoonal storms					
Date	Discharge, in cubic meters per second	Date	Discharge, in cubic meters per second	Date	Discharge, in cubic meters per second	Date	Discharge, in cubic meters per second	Date	Discharge, in cubic meters per second
12-23-14	425	9-18-25	96	9-08-17	212	8-14-41	71	8-10-60	174
1-20-16	142	9-28-26	323	8-07-18	139	8-02-43	128	8-23-61	470
11-17-23	58	9-24-29	295	8-02-19	133	8-16-44	185	8-26-63	132
2-16-31	58	9-21-33	173	8-09-20	55	8-10-45	306	7-24-64	214
8-21-33	173	8-24-35	117	8-01-21	113	8-04-46	121	8-19-66	156
9-15-44	87	8-08-36	49	7-22-22	57	8-10-47	48	7-17-67	166
9-27-48	55	10-01-46	84	8-17-23	54	8-16-48	109	8-06-69	247
9-24-54	114	9-10-49	56	9-07-27	55	8-08-49	108	7-20-70	242
1-12-60	91	9-20-52	64	8-07-30	50	7-30-50	269	8-17-71	227
12-23-65	137	7-20-54	191	8-10-31	261	8-02-51	142	7-15-72	98
12-20-67	456	7-29-58	180	7-30-32	119	8-16-52	108	7-08-74	225
3-14-73	54	9-10-60	84	8-23-34	170	7-15-53	167	7-12-75	70
9-13-75	60	9-26-62	141	9-01-35	292	7-24-54	271	9-25-76	201
9-25-76	201	9-10-64	368	7-26-36	153	8-03-55	309	8-02-78	142
10-21-78	118	9-05-70	81	7-10-37	93	7-29-56	74	8-15-79	163
12-19-78	382	8-12-71	142	8-05-38	255	8-31-57	86	8-13-80	78
2-04-83	1200	10-19-72	133	8-03-39	227	7-29-58	180	7-27-81	76
12-28-84	283	10-10-77	671	8-14-40	320	8-20-59	125	8-23-82	[1]260
		10-02-83	1,493					8-14-84	113
								7-21-86	50

[1] Estimated.

The censored data for each hydroclimatic type of flood on the Santa Cruz River (table 9) were fit to the three-parameter log-Pearson type III distributions using maximum-likelihood analysis. The method of moments was not used because reliable estimates of the mean, variance, and skew of censored data are more efficiently made using maximum-likelihood analysis (Pollard, 1977, p. 245–246). Techniques used to fit type I censored data to probability distributions using maximum-likelihood techniques were presented by Stedinger and Cohn (1986, 1987). Stedinger and Cohn (1986) developed a maximum-likelihood function, L, for the combination of conventional gage and historical data. Because no historical data are used for the Santa Cruz River at Tucson, the likelihood function has to be slightly modified from those given in Stedinger and Cohn (1986) and Stedinger and others (1988). The likelihood function, L_N, for nonexceedances of base discharge is

$$L_N(\mu,\sigma,\gamma) = [F(X_b)]^{(h-n)}, \tag{2}$$

where

μ = population mean,
σ = population standard deviation,
γ = the population skew coefficient,
$F(X_b)$ = the cumulative-density function, and
X_b = logarithm (base 10) of the base discharge.

The likelihood function for discharges that exceed base discharge is

$$L_N\left(\mu,\sigma,\gamma\right) = \prod_{i=1}^{n}\left[f\left(x_i\right)\right], \tag{3}$$

where

$f(x_i)$ = the probability-density function, and
x_i = an array of the logarithms of floods that exceed base discharge.

The total likelihood function is

$$L(\mu,\sigma,\gamma) = L_N \bullet L_E. \tag{4}$$

Because equation 4 is maximized over μ, σ, and γ and the maximum of the logarithm of the likelihood function, $\ln L$, occurs at the same place as the maximum for the likelihood function, L, equation (4) becomes

$$\ln L\left(\mu,\sigma,\gamma\right) = \left(h-n\right)\ln\left[F\left(X_b\right)\right] + \sum_{i=1}^{n}\ln\left[f\left(x_i\right)\right]. \tag{5}$$

Table 9. Floods above base discharge, by storm type, Santa Cruz River at Cortaro, Arizona

[Base discharge, 76 m³/s. Hydroclimatic water year, November 1 to October 31]

Floods caused by									
Frontal storms		Dissipating tropical cyclones		Monsoonal storms					
Date	Discharge, in cubic meters per second	Date	Discharge, in cubic meters per second	Date	Discharge, in cubic meters per second	Date	Discharge, in cubic meters per second	Date	Discharge, in cubic meters per second
12-31-40	482	7-16-54	173	8-14-40	482	8-12-58	224	7-12-75	147
9-16-44	122	7-29-58	206	8-08-41	170	8-20-59	227	9-25-76	300
9-10-46	79	9-26-62	317	9-24-43	156	8-11-60	182	9-10-77	133
3-23-54	143	9-10-64	450	8-16-44	160	8-16-84	146	8-02-78	79
1-09-57	78	9-06-70	136	8-10-45	397	8-23-61	416	7-25-81	118
10-28-59	79	10-19-72	255	8-04-46	126	8-26-63	205	8-23-82	377
1-12-60	176	10-10-77	651	8-15-47	213	9-06-64	203	8-07-83	176
12-22-65	476	10-02-83	1,841	7-30-50	365	7-16-65	77		
12-21-67	448	9-06-84	83	7-25-51	193	8-19-66	169		
2-22-73	104			8-14-52	173	7-17-67	163		
3-02-78	222			7-14-53	306	8-06-69	238		
12-18-78	533			7-24-54	259	7-20-70	317		
9-22-81	122			8-03-55	470	8-20-71	258		
9-11-82	190			7-29-56	89	8-12-72	200		
2-04-83	216			9-01-57	125	7-08-74	331		

Equation 5 is iteratively maximized by finding the point where $\partial(\ln L)/\mu$, $\partial(\ln L)/\partial\sigma$, and $\partial(\ln L)/\partial\gamma$ equal zero (Stedinger and others, 1988). Details of the numerical methods used to maximize equation 5 are given in Stedinger and Cohn (1986), Cohn (1986), and Stedinger and others (1988).

Mixed-population analysis is a method used to combine different populations of floods that may occur in a gaging record to estimate annual recurrence intervals for that river (Kite, 1988, p. 6–7). Distinct populations can be combined in several ways. One approach for estimating the cumulative density function, F_T, from m separate cumulative density functions, F_i, is given by Waylen and Woo (1982) as

$$F_T\left(X \le x\right) = \prod_{i=1}^{m} F_i\left(X \le x\right). \qquad (6)$$

This approach is difficult using maximum-likelihood analysis, because F would have to be differentiated and substituted into equations 2, 3, and 5 for solution. A similar method given by Kite (1988) and Crippen (1978) simply uses the assumption of independence of the populations to estimate the exceedance probability of occurrence. For two populations, the composite exceedance probability, P_T, is estimated using

$$P_T(X \ge x) = P_1(X \ge x) + P_2(X \ge x) - P_1P_2, \qquad (7)$$

where $P_1(X \ge x)$ and $P_2(X \ge x)$ are the exceedance probabilities of the independent populations. Jarrett and Costa (1988) showed an example of two-population mixed-population analysis for Colorado. A third population can be introduced to produce

$$P_T(X \ge x) = P_1 + P_2 + P_3 - P_1P_2 - P_1P_3 - P_2P_3 + P_1P_2P_3 \qquad (8)$$

By substituting $1/T$ for P and rearranging, the annual recurrence interval for the mixed population, T_a, can be estimated as three populations described by T_1, T_2, and T_3 from

$$T_a = \frac{T_1T_2T_3}{(T_1T_2 + T_1T_3 + T_2T_3 - T_1 - T_2 - T_3 + 1)} \qquad (9)$$

Frequency of Floods Caused by Different Storm Types

Three scenarios of flood frequency were analyzed for the Santa Cruz River at Tucson. First, probability distributions were fit to all data for annual floods caused by each storm type (fig. 19). The moments of the fitted distribution are given in table 10. Flood-frequency relations (fig. 20) show the relative importance of each storm type to annual flood frequency. Floods caused by monsoonal storms dominate flood frequency for recurrence intervals of less than 10 years. Floods caused by tropical cyclones dominate flood frequency at recurrence intervals above 20 years. Although the frequency of floods caused by frontal systems never dominates (fig. 20), it parallels that for tropical cyclones up to the 10-year recurrence interval, at which point the two relations diverge. The relation for the Santa Cruz River at Cortaro is similar.

The relations shown in figure 20 do not represent an accurate statistical analysis of flood frequency on the Santa Cruz River. As is apparent for floods caused by tropical cyclones and frontal systems, the frequency of floods caused by storm types is dependent on the period of record that is considered (fig. 19). Use of data from all periods for each storm type violates the assumption that a homogeneous population is being analyzed. The annual flood frequency for this scenario (fig. 20) is probably meaningless because flood frequency appears to exhibit weak stationarity of order 1. For comparative purposes, the 100-year flood estimated from a mixed-population analysis is 1,050 m^3/s at Tucson and 1,610 m^3/s at Cortaro.

To obtain stationary series for analysis, the assumption was made that populations of floods caused by frontal systems, dissipating tropical cyclones, and monsoonal storms are derived from different populations for 1930–59 and 1960–86. At Cortaro, only flows for 1960–84 were analyzed because only 18 years of data are available before 1960. The relations for floods at Tucson caused by different storm types that occurred after 1960 appear in figure 21. The same general relations occur as in figure 20, but discharges for given recurrence intervals are larger for the post-1960 relations (fig. 21). Comparison of the estimated mean, standard deviation, and skew coefficients

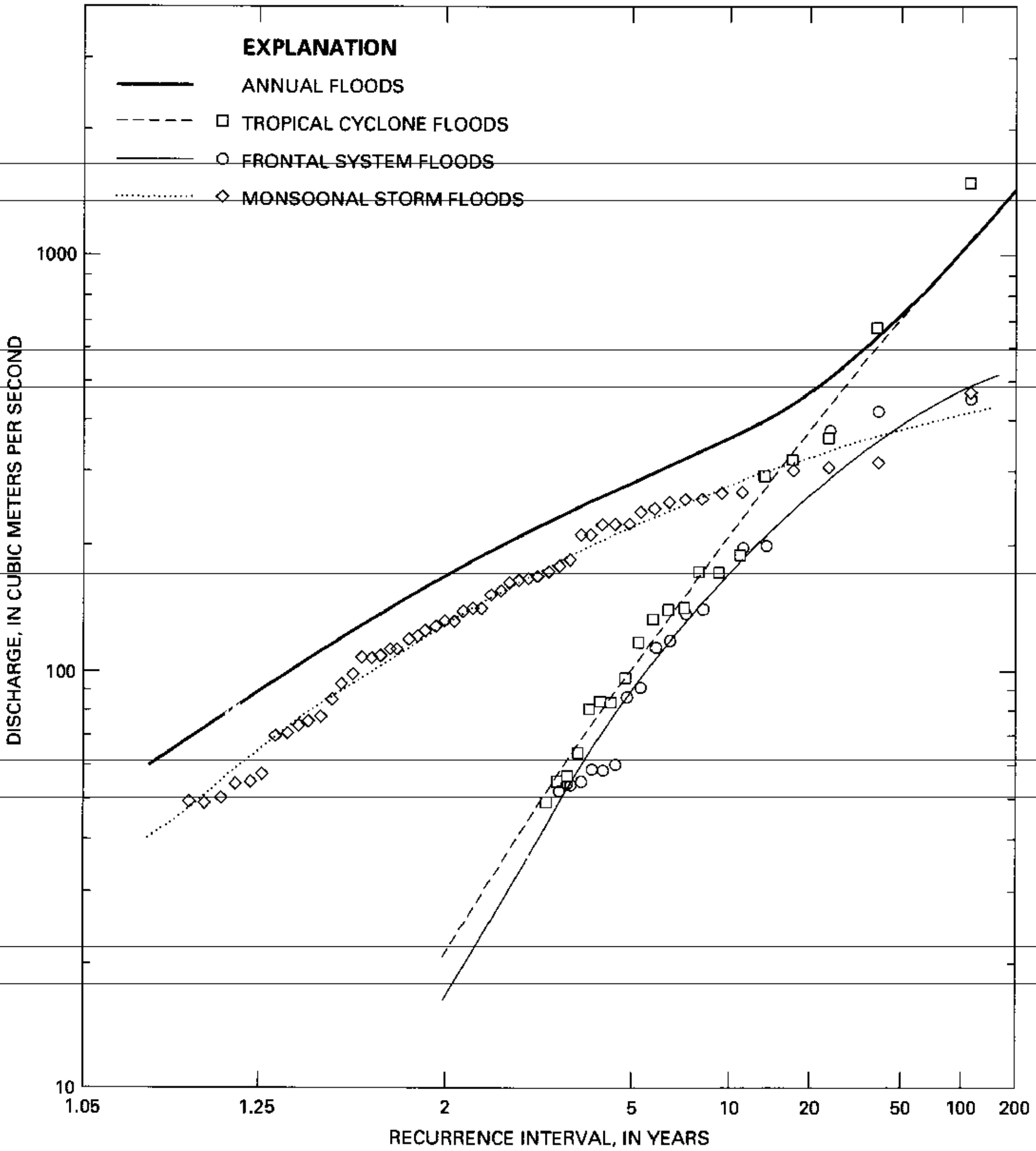


Figure 20. Mixed-population analysis of floods caused by different storm types between 1915 and 1986, Santa Cruz River at Tucson, Arizona. Probability distributions were fit using invalid assumptions; curves are presented for illustrative purposes only.

for post-1960 floods with those estimated for the entire record (table 10) suggests the reason for the increase. Although the mean discharge decreases for post-1960 floods at Tucson caused by tropical cyclones and monsoonal storms, the variances for all types increase. The skew coefficient becomes more negative (table 10), but because it is poorly estimated, changes in the skew coefficient are not considered significant. From mixed-population analysis, the annual 100-year flood for Santa Cruz River at Tucson is 1,660 m^3/s after 1960 (fig. 21). At Cortaro, the annual 100-year flood is 2,030 m^3/s after 1960. Both estimates are strongly affected by the large flood of October 1983.

Results for floods at Tucson for 1930–59 caused by tropical cyclones and frontal systems (fig. 22) contrast with the post-1960 results; floods caused by monsoonal storms dominate flood frequency. Although the means for floods caused by tropical cyclones and frontal systems are similar for 1930–59 and post-1960 (table 10), the standard deviations are much less for 1930–59 than post-1960. For 1930–59, the annual 100-year flood is 323 m^3/s and is essentially the frequency of floods caused by monsoonal storms (fig. 22).

The results of the hydroclimatic flood-frequency analysis underscore the cause for the increased flood frequency on the Santa Cruz River. The probability for floods caused by dissipating tropical cyclones, frontal systems, and, to a lesser extent, monsoonal storms changed in the 20th century. The greatest difference among the distributions estimated for 1930–59 and 1960–86 is the increased

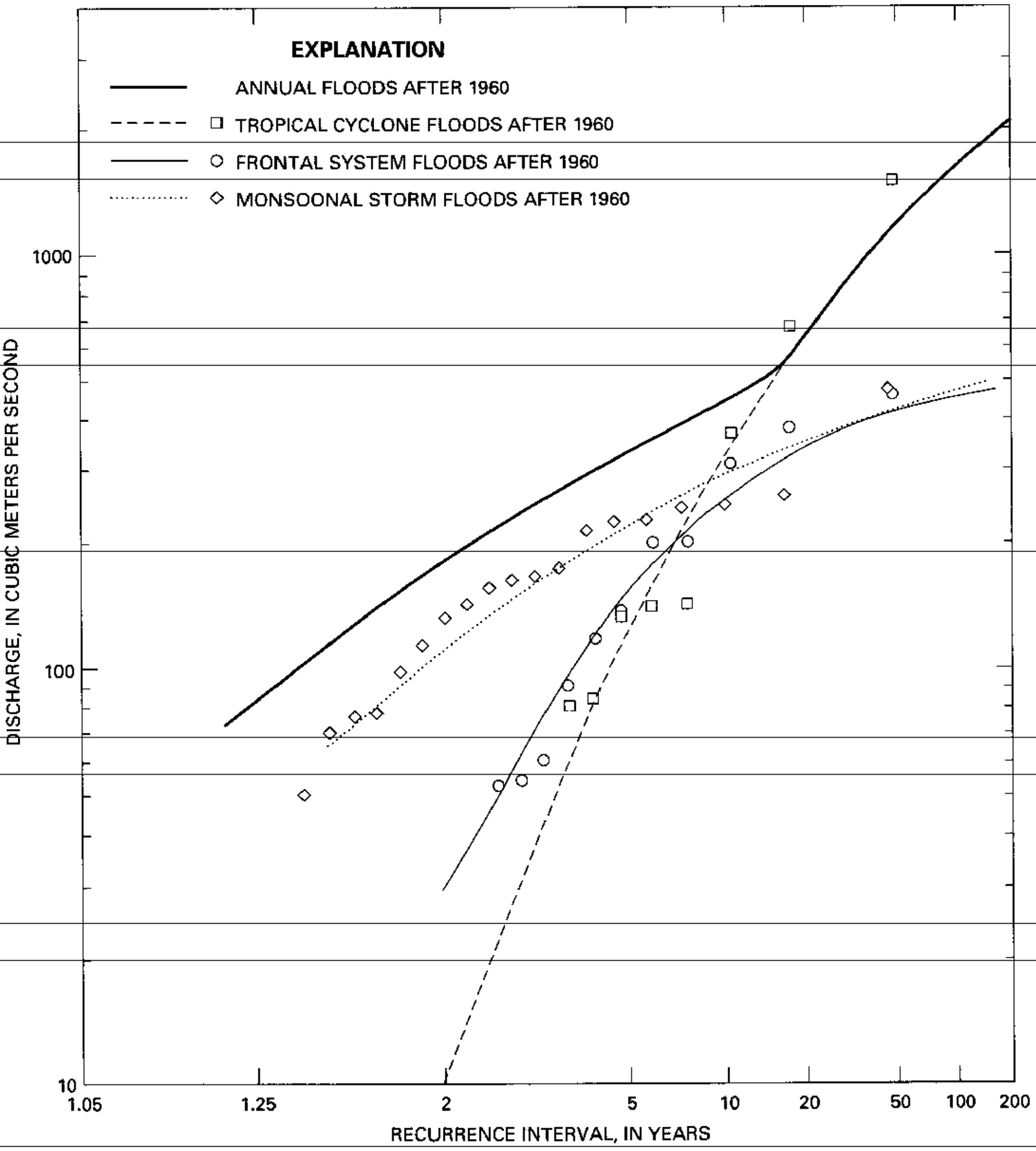


Figure 21. Mixed-population analysis of floods caused by different storm types between 1960 and 1986 for the Santa Cruz River at Tucson, Arizona.

Table 10. Statistics for annual series of floods caused by three storm types for the Santa Cruz River at Tucson and Cortaro, Arizona

[Statistics were generated by fitting floods above base discharges of 48 and 76 m³/s for the Tucson and Cortaro stations, respectively, using maximum-likelihood analysis]

Floods caused by storm type	Mean logarithm of discharge	Standard deviation of log discharge	Coefficient of skew of log discharge
Santa Cruz River at Tucson, Arizona			
All tropical cyclones	1.264	0.865	–0.400
All frontal systems	1.007	1.118	–1.133
All monsoonal storms	2.068	.327	–.865
Tropical cyclones after 1960	.730	1.596	–1.040
Frontal systems after 1960	1.133	1.297	–1.639
Monsoonal storms after 1960	1.979	.423	–.948
Tropical cyclones, 1930–59	.586	1.442	–1.639
Frontal systems, 1930–59	.800	1.002	–1.501
Monsoonal storms, 1930–59	2.130	.298	–1.401
Santa Cruz River at Cortaro, Arizona			
All tropical cyclones	.523	1.651	–.948
All frontal systems	2.427	.884	–1.112
All monsoonal storms	2.214	.313	–1.080
Tropical cyclones after 1960	.778	1.675	–1.112
Frontal systems after 1960	1.218	1.296	–1.639
Monsoonal storms after 1960	2.147	.335	–1.174

variance and, in the case of floods caused by tropical cyclones and monsoonal storms, more negative skew coefficients. Because estimates of long-recurrence interval floods are heavily influenced by higher-order moments, the 100-year flood estimate for 1960–86 is more than four times larger than that for 1930–59 for the Santa Cruz River at Tucson.

The main problem with the hydroclimatic flood-frequency analysis is the inability to assign uncertainty estimates to discharges at given recurrence intervals. A method is not available for estimating standard errors or confidence limits for cumulative-distribution functions using mixed-population analysis. Variances for the floods caused by different storm types, however, are high, and the maximum length of a stationary period is only 30 years. For example, the uncertainty in the 100-year flood estimates from hydroclimatic-frequency analyses would be expected to be higher than for frequency analyses using a longer period of record, such as the 71-year annual flood series for Santa Cruz River at Tucson (fig. 2).

A second problem results from the assumption that floods during periods are derived from a stationary population. Climatic information suggests that transitions among periods may have been gradual instead of abrupt (fig. 10). The assumption of stationarity within periods is required to obtain estimates of population parameters, and no compelling evidence indicates problems with stationarity within the periods.

Finally, use of the hydroclimatic flood-frequency analyses requires an assessment of which period best represents future climatic conditions. Although no evidence was found to suggest that the conditions for 1960–86 have changed, the maximum length of periods examined in this study is only 30 years. The question of whether future conditions will be similar to 1930–59 or 1960–86 is impossible to answer at this time. It is also questionable that a meaningful 100-year discharge can be estimated from an annual flood series of only 30 years.

SUMMARY AND CONCLUSIONS

The effects of climatic variability on the annual flood series and flood-frequency estimates were evaluated for the Santa Cruz River at Tucson and Santa Cruz River at Cortaro. Previous estimates of the 100-year flood at Tucson, calculated using different techniques and assumptions, ranged from 572 to 2,780 m³/s. This discrepancy has been attributed to increasing flood magnitudes caused by channelization and land-use changes in the last two decades. The magnitude of the 100-year flood for Santa Cruz River at Tucson, calculated from a log-Pearson type III distribution using the method of moments, increased from 577 to 872 m³/s when annual peak discharges between 1970 and 1986 were included in the calculations. Flood-frequency estimates for the Santa Cruz River are strongly influenced by an extraordinary flood in October 1983, but it is also true that six of the seven largest floods at Tucson occurred after 1960. In addition, the seasonality of annual floods changed significantly after 1960; whereas floods in summer accounted for 97 percent of annual peaks between 1930 and 1959, floods in summer accounted for 61 percent of annual peaks between 1960 and 1986. Although changes in land use and channelization may have affected the magnitude of annual floods, climatic variability is identified as the main cause for the change in flood frequency.

The annual flood series at Tucson exhibits weak stationarity of order 1. Analyses for 1915–29, 1930–59, and 1960–86 showed that the mean does not change significantly; however, the variance and skew coefficient change significantly with time. Trend analyses revealed no trends in the annual flood series or among periods of the series. Trend analyses, however, are intended to detect changes in the mean instead of the variance. Changes in variance, which were detected in nonparametric tests, exert a heavy influence on estimates of long-recurrence interval floods such as the 100-year discharge.

In southern Arizona, fluctuations in large-scale oceanic and atmospheric processes are reflected in the seasonal distribution of precipitation and increased probability of large floods. Twentieth-century climatic variability stems from decadal trends in atmospheric circulation over the Northern Hemisphere and in the frequency of El Niño-Southern Oscillation (ENSO) phenomena in the equatorial Pacific Ocean. Before 1930 and after 1960, westerly winds on average followed a more meridional path, and ENSO conditions occurred more frequently and with greater variability in the equatorial Pacific. By contrast, the westerlies followed a more zonal flow, and ENSO conditions occurred less frequently with less variability between 1930 and 1960. Meridional circulation and the climatology associated with ENSO conditions enhance Tucson precipitation in the winter, spring, and fall and possibly reduce summer rainfall.

Seasonal discharge on the Santa Cruz River is similarly related to climatic variability. Winter and fall floods account for 53 percent of annual peaks before 1930, only 3 percent from 1930 to 1959, and 39 percent after 1960. Changes in flood frequency on the Santa Cruz River are attributed to the changing probabilities of floods caused by certain storm types. In particular, the joint occurrence of cutoff low-pressure systems and tropical cyclones increases the probability for large floods along the Santa Cruz River. This joint occurrence tends to occur more frequently during ENSO years and during 1960–86.

Using procedures of the Interagency Advisory Committee on Water Data (1982), flood frequency at Tucson was estimated for the entire record using years with ENSO conditions and years with non-ENSO conditions. Climatic analyses suggest that the flood-producing mechanisms are not strictly stationary in the 20th century; therefore, analyses that require the assumption of stationarity may be invalid. Assuming stationarity for the entire record, the

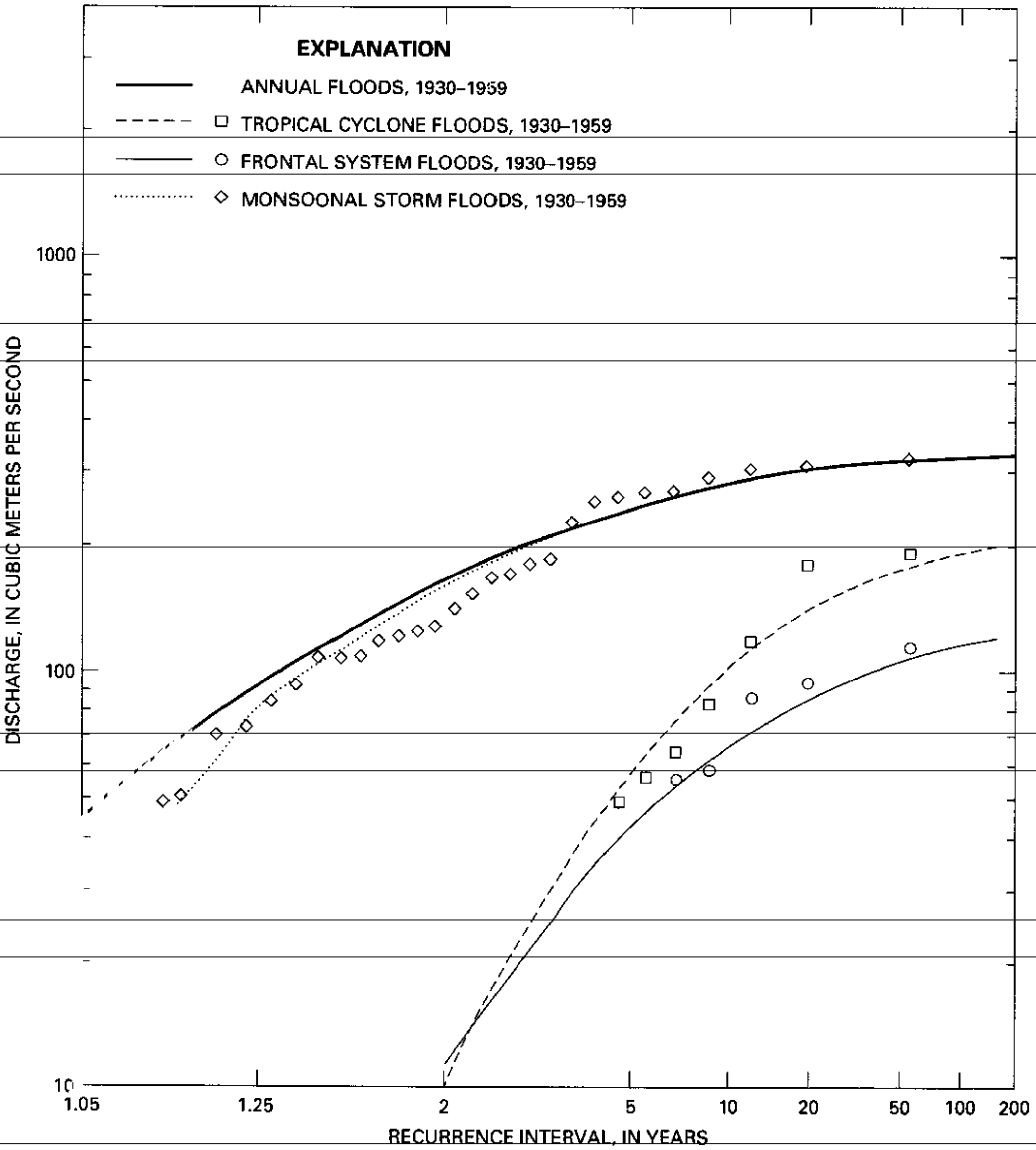


Figure 22. Mixed-population analysis of floods caused by different storm types between 1930 and 1959 for the Santa Cruz River at Tucson, Arizona

100-year flood is estimated to be 872 m^3/s. Assuming stationarity, the 100-year floods for years with ENSO and non-ENSO conditions are estimated to be 1,300 and 628 m^3/s, respectively. The frequency analysis for the entire record and for ENSO years is strongly affected by the unusually large flood of October 1983.

The frequency of floods caused by the three general storm types—summer monsoonal storms, frontal systems, and dissipating tropical cyclones—was estimated using maximum-likelihood analysis and the log-Pearson type III distribution. Annual flood frequency was estimated by assuming independence of the three types of floods and using a three-population mixed-population analysis. Floods caused by dissipating tropical cyclones determine the annual flood frequency at recurrence intervals greater than about 20 years for all years and for 1960–86. For 1930–59, floods caused by monsoonal storms dominate flood frequency for all recurrence intervals. Assuming stationarity, which analyses of climate suggest is invalid, the 100-year flood for all years is 1,050 m^3/s (table 7). The 100-year flood for 1960–86 is estimated to be 1,660 m^3/s and was strongly affected by the flood of October 1983. Likewise, the 100-year flood for 1930–59 was estimated to be 323 m^3/s (table 7). These analyses do not have an estimated uncertainty; however, the uncertainty is expected to be high because of short record length and high variance.

The results of flood-frequency analyses presented in this study raise questions about the validity of applying statistical flood-frequency analysis to the Santa Cruz River. Frequency analysis requires the assumptions of interannual independence and stationarity, neither of which are totally valid for the Santa Cruz River. Separation of the record into ENSO and non-ENSO conditions creates two independent populations but does not solve the problem of a variance that changes with time. Separation of floods by storm type assumes three independent, stationary populations, although long-recurrence-interval floods are estimated from stationary records of 30 years or less. Also, judicious use of the mixed-population results requires an assessment of future climatic conditions, which is questionable. Finally, separation of periods requires the assumption that climatic shifts are abrupt, whereas the climatic data presented in this report indicate that shifts may be gradual. Inclusion of the flood of October 1983 also adds to the complexity of the problem. Although this flood was the largest since at least 1891 and ordinarily would have been treated as a historic peak (Interagency Advisory Committee on Water Resources, 1982), considerations of stationarity prevented extension of a historical record length for this flood.

Flood-frequency estimates for the Santa Cruz River need to be used cautiously in design applications. Other methods, such as rainfall-runoff models (Ponce and others, 1985), may be appropriate alternatives to flood-frequency analysis. Frequency analysis, however, is appropriate in certain circumstances. For example, because ENSO conditions demonstrably affect flood frequency on the Santa Cruz River, flood plains could be managed for a specified recurrence interval of floods during ENSO conditions. Therefore, an appropriate estimate of the 100-year flood would be 1,300 m^3/s at Tucson. A similar scenario could be developed for floods caused by dissipating tropical cyclones. However, the period of record would have to be selected that best represents future or design conditions.

Perhaps the best estimate for the 100-year flood is obtained by assuming that future climate may be similar with that of 1960–86. This assumption may be valid for the immediate future but is tenuous when conditions for several decades into the future are considered. Given this assumption, an appropriate magnitude for the 100-year flood is 1,660 m^3/s at Tucson (table 7).

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