Channel Change Along the Rillito Creek System of Southeastern Arizona 1941 Through 1983

Implications for Flood-Plain Management

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by Marie Slezak Pearthree and Victor R. Baker

Special Paper 6
1987

Arizona Bureau of Geology and Mineral Technology Geological Survey Branch

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Preface

One of Arizona's most damaging geologic hazards has been water runoff from normally dry desert lands. Processes associated with this phenomenon are especially troublesome in the lowlands of the Basin and Range province, where more than 90 percent of the State's rapidly expanding population resides. Runoff intensity can range from low flows contained within erodible banks to overbank flooding onto adjacent flood plains. Less attention has been given to the management problems associated with shifting banks during "low" flows than to those caused by classic flooding.

This publication is primarily a result of research conducted by Marie Slezak Pearthree as part of her graduate studies at the Department of Geosciences, University of Arizona. The work was supported by the Arizona Bureau of Geology and Mineral Technology because it promised to help fill a void in the understanding of problems associated with desert runoff processes.

Because of his special knowledge about the dramatic runoff event of October 1983, Dr. Victor Baker, Professor of Geosciences, University of Arizona, joins Marie as coauthor.

The Arizona Bureau of Geology and Mineral Technology, Geological Survey Branch, is pleased to publish Special Paper 6. It is the Bureau's hope that this contribution will further basic research into the natural processes that could have increasingly damaging impacts as Arizona's desert population expands.

H. Wesley Peirce
Principal Geologist Emeritus
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and Mineral Technology

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The National Research Council supported the study of the Tucson October 1983 flow event through its Committee on Natural Disasters, Commission on Engineering and Technical Systems. Historical aerial photographs were provided by the Office of Arid Lands Studies of the University of Arizona, the Pima County Planning and Development Services Department, and the Arizona Bureau of Geology and Mineral Technology. The Laboratory for Remote Sensing and Computer Mapping of the University of Arizona supplied the Zoom Transfer Scope. The particle-size analyses were done in the Sedimentation Laboratory in the Department of Geosciences, University of Arizona. The U.S. Geological Survey in Tucson was an invaluable source of data, as were the Pima County Department of Transportation and Flood Control District and the Tucson Urban Study Office of the U.S. Army Corps of Engineers.

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Abstract

Lateral bank erosion and channel instability along the ephemeral streams of the Rillito Creek system have posed greater hazards to the Tucson metropolitan area than has overbank flooding. The historical behavior of this alluvial stream system has been investigated to document and evaluate past channel variability, determine potential sites of bank erosion and lateral channel migration, and suggest flood-plain management alternatives to Federal regulations currently applied to semiarid regions.

Rillito Creek and its main tributaries, Pantano Wash and Tanque Verde Creek, were mapped from Houghton Road to the mouth of Rillito Creek using aerial photographs taken between 1941 and 1983. These maps, in conjunction with streamflow and channel composition data, detail channel change within this stream system. In 1941 the Rillito Creek system exhibited braided plan-view patterns. By the early 1950's, single-channel patterns with greatly decreased channel widths had developed. From 1941 to late 1979, Pantano Wash primarily narrowed as its depth increased, whereas Tanque Verde Creek and Rillito Creek widened extensively in 1965 and 1978 during prolonged winter flows and narrowed during intervening periods dominated by low-magnitude summer flows. Local bank erosion also occurred, however, during periods of channel narrowing. In October 1983, spectacular channel change and pronounced channel-bank erosion were produced throughout the Rillito Creek system by an extreme flow event associated with a tropical storm.

The greatest amounts of bank erosion and collapse have occurred on the outer concave banks of channel bends and at locations where the silt-clay content of the banks and the density of riparian vegetation have been the least. During the October 1983 flow event, severe bank erosion also occurred immediately downstream from numerous channel reaches that had been protected with soil cement. Noncontinuous bank-protective works apparently concentrate areas of bank erosion along adjacent unprotected channel reaches.

In compliance with Federal regulations, management of the flood plains of the Rillito Creek system has focused mainly on those areas subject to inundation by the 100-year flood. Channel migration during flows smaller than or equal to the 100-year flood, however, has presented a greater hazard to property than has flooding. Zones of potential channel migration can be delineated based on (1) past erosional sites, (2) historical channel positions, (3) present stream-channel patterns, (4) channel composition data, and (5) locations of existing and planned bank-protective works. Flood plains of the Rillito Creek system and other ephemeral-stream systems of the semiarid Southwest can therefore be managed to minimize the potential hazards from lateral channel migration and bank erosion, as well as from flooding.

Introduction

PURPOSE OF STUDY

In the southwestern United States, frequent changes in the morphology and position of alluvial ephemeral-stream channels create uncertainties for flood-plain management. These stream channels are developed within unconsolidated, fluvially deposited sediments and convey flows resulting from direct precipitation or snowmelt (Gary and others, 1974; Maddock, 1976b). The channels are usually dry for long periods or carry only occasional low flows. Infrequent high flows may exceed channel capacities and locally inundate adjacent flood plains (Condes de la Torre, 1970). A flood plain is geologically defined as the nearly level land adjacent to a stream channel that is constructed by the stream and is subject to flooding (Gary and others, 1974).

It is conceptually important to distinguish between flood and flow events in the semiarid Southwest. Much confusion has arisen because of a lack of appreciation for the contrasting processes involved in these two types of runoff events. A flood occurs when the capacity of an active channel to contain the flow is exceeded. In other words, a true flood refers to distinct overbank flow. If there is no flooding, the runoff event is simply a flow event. Flooding may locally occur, but elsewhere along the same stream channel, runoff may be totally contained within well-defined banks. Flooding is an unusual condition, whereas confined flow is the norm.

Federal flood-plain management regulations, formulated by the U.S. Congress in response to past and potential loss of life and property from flooding, form the basis for local flood-plain management. These regulations, however, do not take into account regional differences in stream-channel behavior. The Federal regulations mainly address in-channel and overbank inundation produced by a 100-year flood, which has a 1 percent chance of occurring in any given year (U.S. Code Congressional and Administrative News, 1968). The limits of the resulting 100-year flood plain generally occur within the geologic flood plain.

Land-use restrictions are mandated within the regulatory flood plain, which currently consists of the 100-year flood plain, by Federal regulations for communities that want to participate in the National Flood Insurance Program. In the southwestern United States, however, channel-bank erosion often presents an equal or greater hazard to property than does flooding. This additional hazard is not addressed in the Federal regulations, nor is it often brought to the attention of communities enacting flood-plain management programs.

Changes in channel morphology (cross-sectional channel shape and plan-view patterns) and position, including both abrupt and long-term bank erosion, have modified the limits of 100-year flood plains. The computational methods generally used to predict the water-surface level of a 100-year flood along a stream, and thus determine the limits of its 100-year flood plain, assume that neither the morphology nor the position of the channel will change significantly before or during the flood (Burkham, 1972). This assumption is often invalid when applied to the alluvial channels of ephemeral streams in semiarid regions. Such streams frequently alter the positions of their channel banks and elevations of their streambeds during flows of lesser magnitude and greater frequency than the 100-year flood. Temporal variability of 100-year flood-plain limits makes land-use zoning based on nationally mandated regulatory procedures invalid in the semiarid Southwest. It is crucial in terms of land use to determine if property near a stream channel is potentially subject to bank erosion, flooding, or both. There is, therefore, a need to modify Federal flood-plain management regulations in semiarid regions to include the effects of channel change on the extent of the regulatory flood plain and the potential erosional damage associated with both flood and nonflood flows. If the definition of the regulatory flood plain were to take into account (1) past channel positions and (2) potential sites of bank erosion and lateral channel migration, regulatory flood plains would be less dependent upon present stream-channel morphologies and positions, and thus less prone to short-term fluctuations. Accordingly, for management purposes, the concept of the regulatory flood plain should be amended to include both historical channel positions and river margins potentially subject to erosion or flooding. Flood-plain management, as advocated in this paper, includes management of the stream channels and their margins, as well as the flood plains.

The Rillito Creek system of southeastern Arizona was studied to determine the behavior of alluvial ephemeral-stream channels in semiarid regions and thus encourage more effective

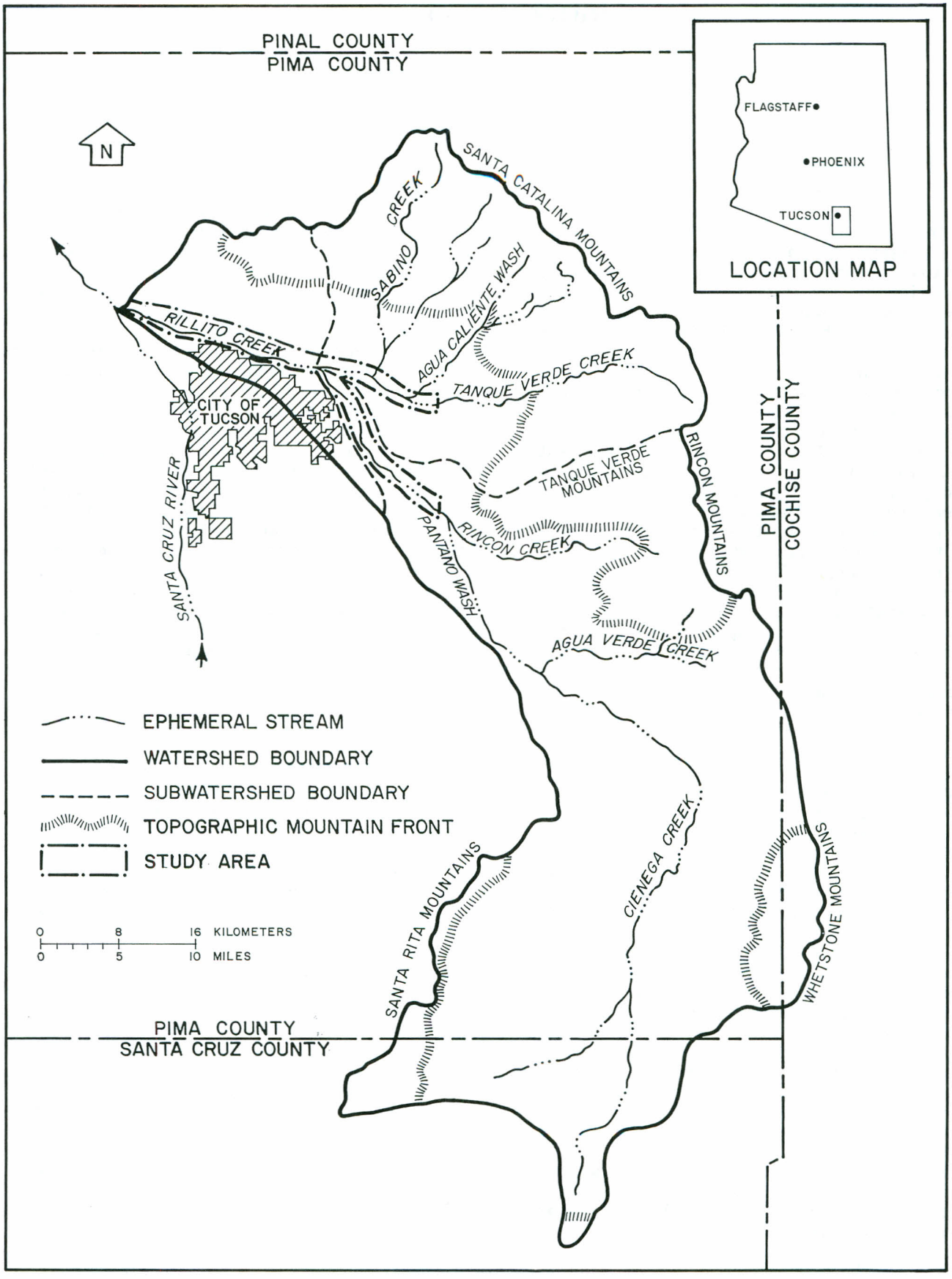


Figure 1. *Map of the Rillito Creek watershed (after U.S. Army Corps of Engineers, 1973).*

flood-plain management in the semiarid Southwest (Figure 1). This stream system was chosen because severe bank erosion and lateral channel migration have occurred during the past few decades within the rapidly expanding Tucson metropolitan area in Pima County. The study area lies within the Tucson basin primarily to the north and east of the current city limits (Figure 1). Population growth, exemplified by the influx of approximately 195,000 persons into Pima County between 1965 and 1985, has created substantial pressure to urbanize the stream margins of this drainage system (Pima County Planning and Development Services, oral commun., 1985). An understanding of the nature of this system is therefore required for setting development restrictions.

The behavior of the Rillito Creek system was investigated primarily by mapping Tanque Verde Creek, Pantano Wash, and Rillito Creek from aerial photographs generated between 1941 and 1979. From these photos, channel-width measurements were obtained at selected locations along each stream channel and comparisons were made of channel plan-view patterns and positions through time. In addition, historical observations of channel change were gathered from newspaper accounts. Longitudinal profiles from the Pima County Department of Transportation and Flood Control District provided insight into fluctuations in streambed elevations. This investigation was subsequently updated using aerial photographs to include the effects of the flow event of October 1983.

The results of this study are organized to provide an understanding of (1) the nature of channel change within ephemeral-stream systems in semiarid regions and (2) the management problems that such change creates. A general review of channel cross-sectional shapes and plan-view patterns is followed by a more specific discussion of the Rillito Creek system. Observed variations in channel morphology and position have been evaluated with respect to streamflow history and bank compositions. The U.S. Geological Survey provided the streamflow data. Channel-bank and streambed compositions were estimated by particle-size analysis. The effects of in-channel sand-and-gravel extraction on channel morphology have also been considered.

Federal flood-plain management regulations are presented through a survey of the legislation that led to the establishment of the National Flood Insurance Program. Pima County and City of Tucson flood-plain management ordinances are also outlined. Applicability of Federal regulations to ephemeral-stream systems in semiarid regions is discussed, using the Rillito Creek system as an example. Recommendations are then made for more effective flood-plain management in such regions.

THE RILLITO CREEK SYSTEM

Geologic Setting

The section of the Rillito Creek system analyzed in this study extends westward from Houghton Road to the confluence of Rillito Creek and the Santa Cruz River and includes about 6.6 miles (10.6 km) of Tanque Verde Creek, 10.2 miles (16.3 km) of Pantano Wash, and the entire 12-mile (19.3-km) length of Rillito Creek (Figure 1). This ephemeral-stream system drains 934 square miles (2,419 sq km) within the Basin and Range physiographic province of southeastern Arizona. The Rillito Creek watershed consists of large basin areas partially surrounded by mountain ranges and can be divided into three subwatersheds associated with Pantano Wash, Tanque Verde Creek, and Rillito Creek (Figure 1). The historical behavior of these three stream channels is the primary focus of this investigation.

Pantano Wash begins as Cienega Creek, whose source area includes the Canelo Hills and the Santa Rita, Whetstone, and Empire Mountains southeast of Tucson. Cienega Creek flows to the northeast across the Sonoita basin, then becomes Pantano Wash as it turns to the northwest and flows across the eastern margin of the Tucson basin. Upstream from the study area, Agua Verde Creek and Rincon Creek drain the southern and western flanks of the Rincon Mountains and form the main tributaries to Pantano Wash. Elevations within the 608-square-mile (1,582-sq-km) subwatershed range from 9,453 feet (2,881 m) at Mount Wrightson in the Santa Rita Mountains to 2,500 feet (762 m) at the confluence of Pantano Wash and Tanque Verde Creek. Approximately three-fourths of the subwatershed is composed of loosely to firmly consolidated gravels, sands, and silts. The mountainous areas consist of sedimentary, volcanic, metamorphic, and intrusive igneous rocks (Wilson and others, 1969; Davidson, 1973).

Tanque Verde Creek heads in the northwestern flank of the Tanque Verde Mountains and flows in a westward direction towards Tucson (Figure 1). Its main tributaries, Sabino Creek and Agua Caliente Wash, drain the Santa Catalina Mountains and join Tanque Verde Creek from the north. An aerial view of a portion of the Tanque Verde Creek subwatershed is shown in Figure 2. Elevations within this 241-square-mile (627-sq-km) subwatershed range from 2,500 feet (762 m) at the confluence of Tanque Verde Creek and Pantano Wash to 9,157 feet (2,791 m) at the top of Mount Lemmon, the highest point in the Santa Catalina Mountains.

Rillito Creek flows approximately 12 miles (19.3 km) in a west-northwest direction from the confluence of Tanque Verde Creek and

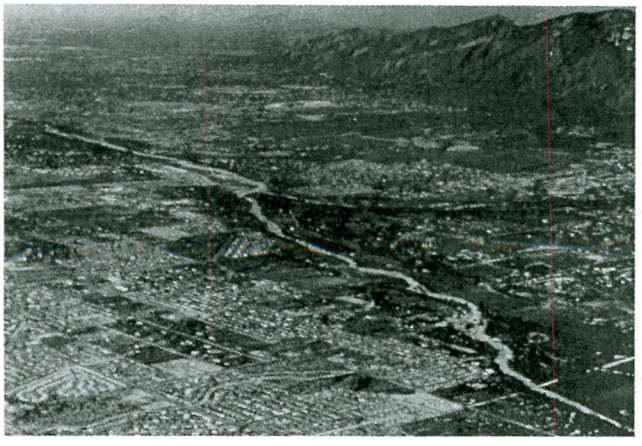


Figure 2. *Aerial view of a portion of the Tanque Verde Creek subwatershed bounded by the Santa Catalina Mountains. Tanque Verde Creek (middle and foreground) is joined by Sabino Creek (right center). Photo by Peter L. Kresan.* ©

Pantano Wash to the Santa Cruz River (U.S. Army Corps of Engineers, 1973; Figure 1). Because of its proximity to Tucson, Rillito Creek receives more urban runoff than either Tanque Verde Creek or Pantano Wash. Elevations within this subwatershed, which measures 85 square miles (220 sq km) in area, range from 2,200 feet (671 m) at the confluence of Rillito Creek and the Santa Cruz River to more than 9,100 feet (2,774 m) in the Santa Catalina Mountains.

These mountains, as well as the adjacent Tanque Verde and Rincon Mountains, consist of metamorphic and intrusive igneous rocks (Wilson and others, 1969; Davidson, 1973). The mountains have been incorporated into the Coronado National Forest and have been maintained in a fairly pristine state. The lower elevation portions of the Rillito Creek and Tanque Verde Creek subwatersheds are mainly composed of sedimentary units that range from semiconsolidated gravels, sandstone, and mudstone to unconsolidated stream and flood-plain alluvial deposits (Davidson, 1973).

Climate and Vegetation

The climate of southeastern Arizona is generally considered semiarid. In most semiarid regions, precipitation varies greatly from one season to another and from one year to the next (Durrenberger and Wood, 1979). Precipitation in southern Arizona occurs during two distinct seasons, summer and winter, that are separated by short dry periods. At the Tucson National Weather Service office, more than 50 percent of the annual amount of precipitation usually falls between July 1 and September 15, and more than 20 percent falls from December through March. July and August are normally the wettest months of the year (Table 1).

Table 1. *Normal monthly precipitation values for the Tucson area (from Durrenberger and Wood, 1979).*

Month	Precipitation (inches)	Precipitation (millimeters)
Jan.	0.77	19.56
Feb.	0.70	17.78
March	0.64	16.26
April	0.35	8.89
May	0.14	3.56
June	0.20	5.08
July	2.38	60.45
Aug.	2.34	59.44
Sept.	1.37	34.80
Oct.	0.66	16.76
Nov.	0.56	14.22
Dec.	0.94	23.88

Summer storms are of convective origin and result from surges of moist tropical air that originate in the Gulf of Mexico and the Pacific Ocean off the west coast of Mexico (Sellers and Hill, 1974; Durrenberger and Wood, 1979). Beginning in June, high-level thunderstorms start abruptly with high-intensity precipitation, then slowly taper off after less than 30 minutes (Sellers and Hill, 1974). Ninety percent of their total rainfall is yielded in as little as 2 hours (Baker, 1977; Strahler and Strahler, 1978). The spatial occurrence of these rains is essentially random (McDonald, 1956), although precipitation increases with altitude, particularly on the windward slopes of mountain ranges (Sellers and Hill, 1974). Remnants of tropical hurricanes also drift northward into Arizona in August, September, and early October, and occasionally produce very large amounts of precipitation and sizable floods (Durrenberger and Wood, 1979).

The winter rainfall season usually begins in November and lasts through March. Precipitation during this season originates from surface- and upper-level low-pressure systems and cyclonic storms that travel across the western United States from the Pacific Ocean (Durrenberger and Wood, 1979). In contrast to summer storms, whose diameters typically measure 6 to 12 miles (9.7 to 19.3 km), winter storms often cover most of the Tucson basin, which is approximately 1,000 square miles (2,590 sq km): 50 miles (80 km) long, 15 to 20 miles (24 to 32 km) wide in the southern and central parts, and 4 miles (6 km) wide at the northwest outlet (Davidson, 1973). Although these storms tend to display less spatial variability, they are more temporally random than summer storms (McDonald, 1956; Sellers, 1960a; Fogel and Duckstein, 1969). Winter rains are also generally less intense than summer rains, but are of longer duration.

Mean annual precipitation received by the Rillito Creek watershed ranges from approximately 10.5 inches (267 mm) near Tucson to 37.5 inches (953 mm) at the highest elevations within the Santa Catalina, Rincon, and Santa Rita Mountains (Grove, 1962). Vegetation varies from the creosote bush and desert saltbush communities of the Sonoran Desert, found within and around Tucson, to evergreen forest at the highest elevations (Schwalen, 1942; Turner, 1974; Table 2). In addition, grassland and oak woodland grow in the Sonoita basin portion of the Pantano Wash subwatershed, and deciduous riparian forest consisting of saltcedar, mesquite, cottonwood, willow, and other species thrives in numerous areas along Tanque Verde Creek, Sabino Creek, and Agua Caliente Wash (Turner, 1974).

Table 2. *Correlation between vegetation and elevation in the watershed of the Rillito Creek system (from Schwalen, 1942).*

Vegetative Types	Elevation Above Mean Sea Level (feet)	(meters)
Creosote bush, cacti, desert shrubs and grasses; cottonwood and other trees along stream channels and on bottom lands	2,000-3,000	610-914
Cacti, paloverde, other desert shrubs and grasses	3,000-4,000	914-1,219
Grasses and some chaparral	4,000-5,000	1,219-1,514
Oak, pinon pine, juniper, and grasses	5,000-6,000	1,514-1,829
Arizona pine and Douglas fir	6,300-9,000	1,920-2,743

Channel Morphologies and Patterns

An overview of the fluvial processes that shape the widths, depths, positions, and patterns of stream channels will aid the reader in interpreting variations in channel geometries mapped from the aerial photographs used in this study. The processes discussed in this section were chosen for their relevance to historical channel change observed along the Rillito Creek system.

The cross-sectional shapes and plan-view patterns of alluvial stream channels are produced by erosional and depositional processes that vary in space, time, and magnitude. These processes occur in response to the frequency, magnitude, and duration of streamflow and to the amount and type of sediment in transport. For simplicity, sediment load is defined here as the sum total of sediment transported on or very near the streambed (bed load) and sediment carried in suspension (suspended load).

CHANNEL-BANK EROSION

The cross-sectional shape of an alluvial stream channel is usually described qualitatively as narrow and deep or wide and shallow. The response of a stream channel to large flow events is often an increase in channel cross-sectional area caused by channel entrenchment (degradation), channel widening through bank erosion and collapse, or a combination of both. Channel enlargement is also promoted by low sediment loads.

At a more detailed level, channel width is primarily a function of bank resistance and shear along banks during flow events. Bank resistance is a function of the size, shape, and degree of cementation of materials and the density of vegetation. Shear depends upon discharge, sediment load in transport, and resistance of banks to flow (Renard, 1972). Bank erosion occurs when the applied stress exceeds bank resistance. Erosion may result from a combination of high flow velocities, eddies that form downstream from irregularities in the banks or streambed, and deflection of flow against the banks by boulders, debris, or sediment deposits. Bank erosion may also be promoted by specific channel patterns, which will be discussed in detail in a later section.

Bank erosion in the Rillito Creek system has often included bank caving, which is the slumping or sliding of bank materials from erosional undercutting (Gary and others, 1974; Figure 3). Bank undercutting and subsequent collapse is a process that can occur during low- as well as high-level flows within the Rillito Creek system.

Figure 3. *Bank caving along Rillito Creek near Country Club Road, December 1978. The ragged edge of the bank is the result of collapse after undercutting by a flow estimated to occur once every 20 years in Rillito Creek. The person on the right is pointing to a tension crack in the bank, a precursor to the next collapse episode. Note in the background the fill material and debris that have been dumped over the banks. Photo by H. Wesley Peirce.*

PLAN-VIEW PATTERNS

Plan-view patterns of alluvial stream channels are usually classified as straight, meandering, or braided (Leopold and Wolman, 1957; Figure 4). "Straight" is a relative term, as some irregularity or sinuosity is commonly found in channels described as straight (Leopold and others, 1964). Gradations exist among these patterns, and more than one pattern may be found along the length of a stream channel. The Rillito Creek system exhibited braided patterns in the 1940's that were mainly succeeded by sinuous ("straight") single-channel patterns seen in the 1960's.

Throughout the history of the Rillito Creek system, bars, consisting of sediment deposits, have played a major role in the formation of plan-view patterns and associated cross-sectional channel shapes. Bar growth, therefore, is discussed within the context of

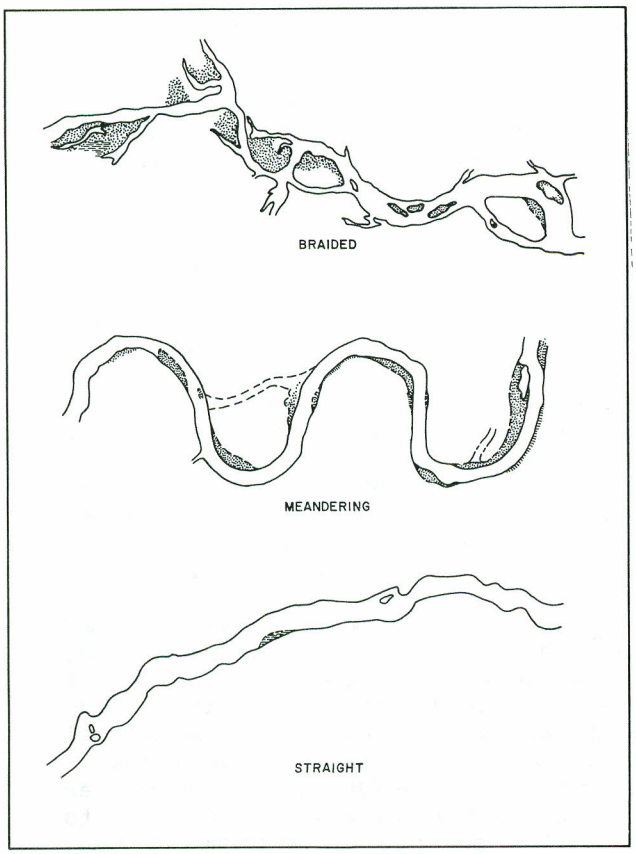


Figure 4. *Plan-view patterns of stream channels: braided, meandering, and straight (after Leopold and Wolman, 1957).*

channel sinuosity, braiding, and narrowing, each of which the Rillito Creek system has exhibited.

Development of Channel Sinuosity

Maddock (1969) has described the process by which bars develop within a channel and their influence on sediment distribution and flow patterns. Bars form from pulses of bedload sediment that migrate downstream during flows with high peak discharges and low sediment loads, which can occur, for example, when streamflow is augmented by snowmelt (Figure 5). Within a fairly straight channel, bars frequently alternate from one channel bank to the other at a wavelength of approximately 2 pi ( ) times the width of the channel (Figure 5a). These bars are termed alternate bars. If streamflow declines rapidly, as is common in southeastern Arizona and other semiarid regions, the bars remain above the water surface as relicts of the higher discharges. These bars become subject to erosion as subsequent low flows meander around them. Sediment supplied to the low flows by bar erosion is distributed locally, with little sediment transported downstream.

Channel-bank erosion and collapse tend to occur at locations where meandering flow impinges on the banks, regardless of bank height. Bank erosion is also promoted when the resistance of the banks to flow is less than that of adjacent bars (Figure 5b). Alluvial stream channels thus have a tendency to migrate laterally and develop sinuous courses whose wavelengths approximate 10 to 12 times their widths. Once established, channel bends tend to migrate downstream because of erosion and collapse of the outer concave banks of bends where flow velocities are maximized. Deceleration of flow at the inner edge of a channel bend induces sediment to accumulate as a point bar along the inner convex bank, slightly downstream from the bend axis (Morisawa, 1968; Figure 5b).

The rate of lateral cutting and point-bar deposition within a sinuous stream channel depends upon the rate (discharge), duration, and frequency of flows, and bank resistance. In a sinuous stream channel that has adjusted to frequent discharges and sediment loads,

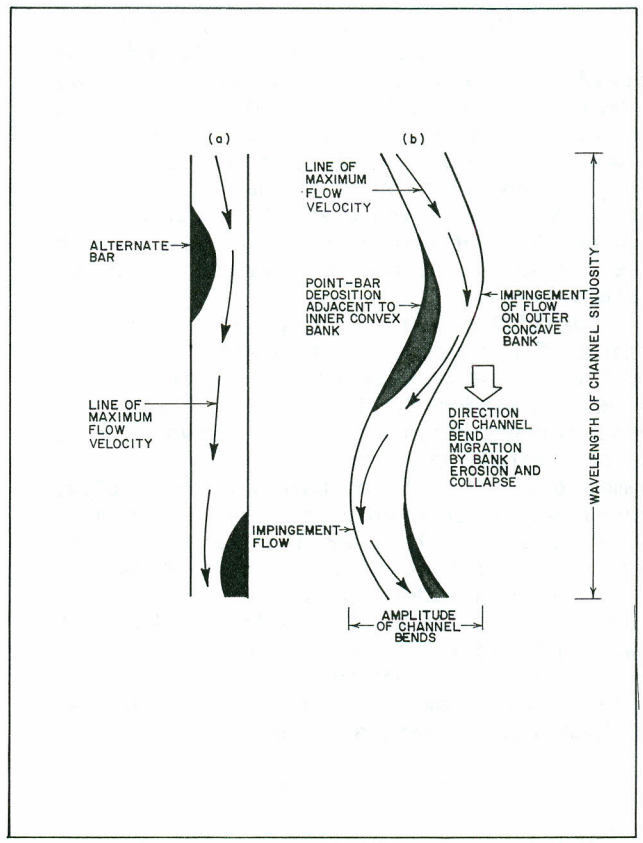


Figure 5. *Diagrammatic sketches showing (a) low- to moderate-magnitude flows reworking sediment deposits left by higher discharges; and (b) sinuous stream channel with locations of outer-bank erosion and point-bar deposition. The plan-view pattern of channel (b) will frequently develop from that of channel (a) in an unstabilized channel.*

outer-bank erosion is often compensated by corresponding deposition of sediment along inner banks as channel bends migrate downstream. In such a stream channel, a characteristic channel width and sinuosity are maintained; however, the entire system remains free to shift its position.

In contrast, high-level flows of low frequency tend to travel straight downvalley. At such times, turbulent forces develop along banks, and channel change occurs. Vegetation is uprooted, banks are eroded, and channel bends shift downstream. A wider and cleaner stream channel results that is more conducive to rapid conveyance of large flows. Such widening and channel-bend migration were observed in Rillito Creek and Tanque Verde Creek during relatively high flow events in 1965, 1978, and 1983. These changes will be discussed in greater detail in later sections on historical channel change within the Rillito Creek system.

Braided Patterns

Braided patterns are characterized by a network of channels that are divided by islands or bars and that successively join and redivide (Leopold and others, 1964). A study of these patterns by Leopold and Wolman (1957) revealed that braided channels are often wider and shallower and have steeper gradients than comparable undivided stream channels. Erodible banks, large volumes of bed load, and frequent fluctuations in discharge are thought to be necessary for the development of braids (Ritter, 1978).

A braided pattern develops after a coarse portion of the bed load is deposited during high-level flow because of an existing local channel condition (Ritter, 1978). Continued deposition produces a bar that grows in size and increasingly restricts the channel, which becomes too narrow to contain the total flow. Channel banks are then eroded as flow is deflected around the bar, and the bar itself may be eroded and the channel slightly deepened. The result is a wider channel capable of conveying a given discharge at a lesser depth of flow. Braided streams are not necessarily overloaded with sediment, however, as the braided pattern may actually be in equilibrium with incoming discharges and sediment loads.

CHANNEL NARROWING

Natural reconstruction of the eroded portions of a channel, or channel recovery, typically involves decreases in channel width that result from the interaction of sediment deposition and vegetative growth in the absence of large flows. Low flows usually do not have the hydraulic competence to transport incoming sediment downstream, and vegetation generally stabilizes newly formed bars by acting as a sediment trap. In the case of a midchannel bar, the flow path between the bar and the closest channel bank often gradually fills with sediment, and the bar eventually becomes attached to the bank through growth of additional vegetation. The mature bar thus restricts the width of the active channel, defined below. This process is referred to as bar maturation and continues until the bar is eroded by a sizable flow. Bar formation and growth of vegetation on newly formed bars are major factors in the channel narrowing seen time and again in the Rillito Creek system.

The channels of the Rillito Creek system have also been known to narrow locally from deposition of sediment where tributary streams enter the main stream channels (Thomas Maddock, Jr., University of Arizona, oral commun., 1981). This process also continues until one or more large flows in the main channel erode the deposited sediment and transport it downstream.

Because of the episodic construction and destruction of bars within alluvial channels, a distinction must be made between the active or low-flow channel, which conveys the majority of flows, and the larger stream channel necessary for conveyance of the more infrequent high-magnitude flows. The banks of an active stream channel may be cut from its geologic flood plain or may be formed by vegetated bars (Figure 6). In this study, the density of vegetation present on a bar was used to judge if the bar formed part of the active channel because vegetative cover is indicative of local, average flow conditions.

Figure 6. *Typical location of an active or low- to moderate-flow channel within a larger stream channel, Pantano Wash. The critical factor in distinguishing the active channel within a stream system is the distribution of vegetation within the larger channel.*

Channel areas that frequently convey flows are not likely to be covered with dense vegetation; therefore, low to moderately vegetated bars were considered in this study as part of the active channel, whereas densely vegetated bars were not. The latter are probably covered with water only during major flows.

Characteristics of the Rillito Creek System

CHANNEL SHAPES

To gain an understanding of the cross-sectional shapes currently exhibited by the channels of the Rillito Creek system, the primary author measured bank heights and channel-floor widths at seven sites each along Rillito Creek and Tanque Verde Creek and at five sites along Pantano Wash (Plate 1; Tables 3 to 5). The sites were selected in channel segments (reaches) that displayed uniform bank heights and channel-floor widths and that had retained a nearly natural state of vegetation along the banks. Channel-bank position was classified as left or right when viewed from downstream. The Water Resources Division of the U.S. Geological Survey previously selected and analyzed four of the sites along Rillito Creek (H. W. Hjalmarson, U.S. Geological Survey, Tucson, written commun., 1980; Table 5). At these sites, bank heights and channel widths were determined during the course of a Flood Insurance Study (Federal Emergency Management Agency, 1981). At the remaining sites that were analyzed by the primary author, bank heights were measured on each side of the active channel from the streambed to the top of the first surface above the bed, either a densely vegetated bar if present or the level of the geologic flood plain.

A report by Smith (1910) states that in 1858 the channel of Rillito Creek consisted of a continuous swath of trees and grasses obstructed by beaver dams. This report further states that by the 1890's, Rillito Creek had altered to a wide channel with vertical banks because of cutting of flood-plain grasses, overgrazing by cattle, concentration of runoff in cattle trails, and summer floods. In addition to Rillito Creek, Tanque Verde Creek and Pantano Wash currently display wide channels with nearly vertical banks, although considerable variation in bank height, bank slope, and riparian vegetation is found.

The highest banks, steepest slopes, and sparsest vegetation are often found on the outer concave banks of channel bends, where velocities of flow and consequent erosion are generally greatest (Figure 5b). Conversely,

Table 3. *Particle-size distributions of sediment samples collected from the banks and streambed of Tanque Verde Creek at seven cross-section locations, and corresponding channel measurements, 1980. (See Plate 1 for cross-section locations.)*

LOCATION			STREAMBED				RIGHT BANK				LEFT BANK									
CROSS SECTION	With Respect to Street	Miles Above Mouth	Gravel (%)	Sand (%)	Silt-Clay (%)	Median Grain Size D_{50} (mm)	Gravel (%)	Sand (%)	Silt-Clay (%)	Median Grain Size D_{50} (mm)	Gravel (%)	Sand (%)	Silt-Clay (%)	Median Grain Size D_{50} (mm)	CHANNEL-FLOOR WIDTH (m)	(feet)	MEAN CHANNEL DEPTH (m)	(feet)	BANKFULL WIDTH-DEPTH RATIO (F)
T.A.	320 Ft. (98 m) upstream from Craycroft Rd.	.06	23	77	0.4	1.77	1	57	42	0.10	10	66	24	0.50	57	187	2.6	8.5	21
T.B.	2,450 Ft. (747 m) downstream from Sabino Canyon Rd.	1.56	27	73	0.2	2.0	1	77	22	0.25	27	65	9	1.1	63	206	1.4	4.6	41
T.C.	1,200 Ft. (366 m) upstream from Sabino Canyon Rd.	2.27	18	80	2	1.41	31	67	2	1.40	0	74	26	0.13	95	312	2.2	7.1	45
T.D.	1,910 Ft. (582 m) upstream from Tanque Verde Rd.	3.77	13	87	0.5	1.23	2	53	45	0.09	9	75	16	0.55	45	146	1.9	6.1	24
T.E.	5,440 Ft. (1,658 m) upstream from Tanque Verde Rd.	4.71	19	78	3	1.45	23	72	5	1.33	0	56	44	0.09	60	198	2.0	6.4	33
T.F.	410 Ft. (125 m) downstream from Harrison Rd.	5.30	24	75	1	1.85	0	39	61	0.06	3	86	10	0.20	44	143	0.5	1.8	72
T.G.	40 Ft. (12 m) upstream from Houghton Rd.	6.48	19	81	0.1	1.68	0	50	50	0.07	0	50	51	0.07	30	97	0.7	2.3	49

Table 4. *Particle-size distributions of sediment samples collected from the banks and streambed of Rillito Creek at seven cross-section locations, and corresponding channel measurements, 1980. (See Plate 1 for cross-section locations.)*

LOCATION			STREAMBED				RIGHT BANK				LEFT BANK									
CROSS SECTION	With Respect to Street	Miles Above Mouth	Gravel (%)	Sand (%)	Silt-Clay (%)	Median Grain Size D_{50} (mm)	Gravel (%)	Sand (%)	Silt-Clay (%)	Median Grain Size D_{50} (mm)	Gravel (%)	Sand (%)	Silt-Clay (%)	Median Grain Size D_{50} (mm)	CHANNEL-FLOOR WIDTH (m)	(feet)	MEAN CHANNEL DEPTH (m)	(feet)	BANKFULL WIDTH-DEPTH RATIO (F)
R.A.	310 Ft. (94 m) upstream from confluence of Rillito & Santa Cruz Rivers	.06	5	93	2	0.81	4	72	24	0.16	9	74	16	0.84	40	132	2.7	9	15
R.B.	740 Ft. (226 m) downstream from Highway Dr.	1.36	10	90	1	1.00	4	75	20	0.50	0	62	38	0.19	36	117	3.2	10.4	12
R.C.*	800 Ft. (244 m) downstream from Flowing Wells Rd.	4.04	7	91	3	0.77	34	56	10	1.85	30	63	7	1.60	91	300	2.4	8	38
R.D.*	100 Ft. (30 m) downstream from First Ave.	6.39	8	91	2	1.0	4	68	28	0.56	13	81	6	0.90	88	290	2.7	9	32
R.E.*	500 Ft. (152 m) upstream from Campbell Ave.	7.60	18	82	1	1.75	34	58	9	1.00	—	—	—	—	67	220	2.4	8	28
R.F.	910 Ft. (277 m) downstream from Dodge Blvd.	11.32	13	81	6	1.32	13	70	16	0.25	17	66	17	0.35	41	135	4.5	14.7	9
R.G.	200 Ft. (61 m) upstream from Swan Rd.	12.89	5	89	7	0.85	29	68	4	1.65	34	60	6	1.70	128	420	1.8	6	70

* Data collected and analyzed by the U.S. Geological Survey, Tucson, 1980.

Table 5. *Particle-size distributions of sediment samples collected from the banks and streambed of Pantano Wash at five cross-section locations, and corresponding channel measurements. (See Plate 1 for cross-section locations.)*

LOCATION			STREAMBED				RIGHT BANK				LEFT BANK									
CROSS SECTION	With Respect to Street	Miles Above Mouth	Gravel (%)	Sand (%)	Silt-Clay (%)	Median Grain Size D_{50} (mm)	Gravel (%)	Sand (%)	Silt-Clay (%)	Median Grain Size D_{50} (mm)	Gravel (%)	Sand (%)	Silt-Clay (%)	Median Grain Size D_{50} (mm)	CHANNEL-FLOOR WIDTH (m)	(feet)	MEAN CHANNEL DEPTH (m)	(feet)	BANKFULL WIDTH-DEPTH RATIO (F)
P.A.	910 Ft. (277 m) upstream from Craycroft Rd.	0.17	16	71	13	0.63	0	59	41	0.09	0	62	38	0.09	40	130	1.6	5.4	26
P.B.	3,260 Ft. (994 m) upstream from Tanque Verde Rd.	2.73	18	75	8	0.64	3	78	19	0.22	12	66	22	0.24	56	184	4.3	14.1	13
P.C.	1,080 Ft. (329 m) upstream from Broadway Blvd.	4.54	9	88	4	0.80	36	63	2	1.7	0	50	50	0.07	24	79	1.9	6.2	13
P.D.	2,610 Ft. (796 m) upstream from 22nd St.	5.80	16	83	1	1.15	45	52	2	2.8	25	62	13	0.80	30	98	2.4	7.9	12
P.E.	5,650 Ft. (1,722 m) downstream from Harrison Rd.	7.22	4	82	14	0.44	0	56	44	0.09	2	84	14	0.31	30	99	2.1	6.8	14

the lowest banks, shallowest slopes, and densest vegetation usually exist on inner convex banks, where velocities of flow are less and deposition of sediment dominates.

The channel banks of the Rillito Creek system generally increase in height with distance from the headwaters. The banks of Tanque Verde Creek are the lowest, ranging from 1.8 to 8.5 feet (0.5 to 2.6 m; Figure 7; Table 3), and are also the most vegetated of the stream channels. In contrast, the banks of Rillito Creek attain heights of approximately 6 to 15 feet (1.8 to 4.6 m) and are the least vegetated (Figure 8; Table 4). Ground-

Figure 7. *Right bank of Tanque Verde Creek at site T.D., approximately 1,900 feet (579 m) upstream from Tanque Verde Road, 1980. See Plate 1 for site location.*

Figure 8. *Right bank of Rillito Creek at the northern end of Cactus Boulevard, 1980. See Plate 1 for site location.*

Figure 9. *Right bank of Pantano Wash at site P.D., approximately 2,600 feet (792 m) upstream from 22nd Street, 1980. See Plate 1 for site location.*

Figure 10. *Left bank of Pantano Wash at site P.C., approximately 1,100 feet (335 m) upstream from Tanque Verde Road, 1980. See Plate 1 for site location.*

water withdrawal from the aquifer underlying the northern portion of the Tucson basin has eliminated most of the riparian vegetation in the lower and middle reaches of Rillito Creek, rendering the channel banks in these areas less resistant, and thus more susceptible to erosion (Thomas Maddock, Jr., University of Arizona, written commun., 1980). Bank heights along Pantano Wash vary between those of Tanque Verde Creek and Rillito Creek, ranging from approximately 6 to 14 feet (1.8 to 4.3 m; Figures 9 and 10; Table 5).

CHANNEL COMPOSITION

Cross-sectional channel shapes within the Rillito Creek system were examined in light of the composition of channel boundaries. In a study of erosion of stream channels in semi-arid regions, Schumm and Hadley (1961) discussed the importance of bank and streambed composition in determining cross-sectional channel geometries. Sandy channels are often shallower and wider than channels that contain large quantities of silt and clay. Channels tend to become narrower and deeper with increasing silt and clay content as the resistance to erosion of the channel boundaries increases.

Sediments that compose the channel banks and streambeds of Pantano Wash, Tanque Verde Creek, and Rillito Creek were collected at the sites previously described and analyzed using the following method presented by Schumm (1961). The first inch of streambed sediment was sampled at 10 to 12 points, depending on channel width, equally spaced across the channel floor. The samples were then combined into a composite sample of the streambed alluvium. The banks of the channels were sampled in a similar manner. Percentages of gravel,

sand, and silt-clay of each composite sample and its median grain size were determined in the laboratory from particle-size analysis

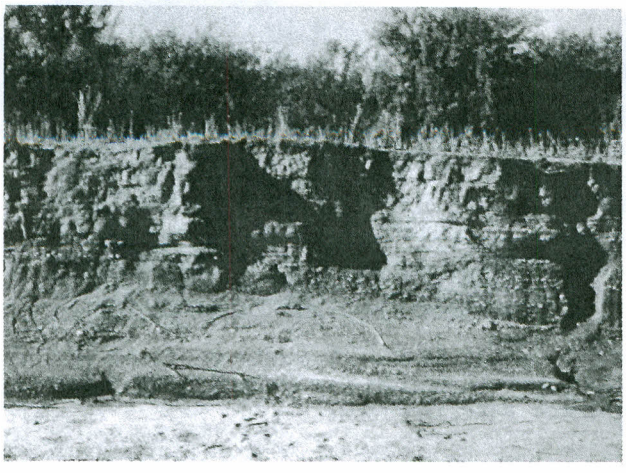


Figure 11. *Stratified, relatively fine-grained bank materials indicative of sediments deposited under low-velocity conditions: (a, top) left bank of Rillito Creek at site R.B., approximately 740 feet (226 m) upstream from Highway Drive, 1980; and (b, bottom) right bank of Tanque Verde Creek at site T.E., approximately 5,440 feet (1,658 m) upstream from Tanque Verde Road, 1980. See Plate 1 for site locations.*

(Tables 3 to 5). The silt-clay content is defined as that fraction of sediment measuring less than 0.074 mm in grain size.

The banks of Tanque Verde Creek, Pantano Wash, and Rillito Creek are sandy in nature, containing between 39 and 86 percent sand at the sample sites (Tables 3 to 5). The remaining portions of the bank samples contain amounts of silt-clay and gravel that vary widely. Sediment sizes within the banks locally tend to cluster about a small range, as in the banks of Rillito Creek, where layers of fine sediment contain almost no coarse particles, and coarse sand layers contain little silt-clay (Matlock, 1965). Silt-clay deposits found in the banks of this stream system are primarily indicative of past low velocities of flow within the channels or on their flood plains during periods of overbank flooding (Tables 3 to 5; Figure 11). Silt-clay contents may have also resulted from infiltration of fine-grained sediment and water into the banks during high stages of streamflow (W. B. Bull, University of Arizona, written commun., 1981). Large percentages of gravel also exist at several sites within the banks of this stream system, often in the form of gravel lenses that probably represent former channel bars (Figure 12).

Figure 12. *Bank materials composed of alternating deposits of coarse- and finer grained sediments, possibly including channel bars: (a, top) right bank of Rillito Creek near First Avenue, 1980; and (b, bottom) right bank of Pantano Wash at site P.D., approximately 2,600 feet (792 m) upstream from 22nd Street, 1980. See Plate 1 for site locations.*

In contrast to the compositions of the channel banks, the streambeds of Tanque Verde Creek, Pantano Wash, and Rillito Creek consist almost exclusively of sand (Tables 3 to 5). At the sites examined, the bed materials of

Figure 13. *The sandy streambeds of the Rillito Creek system: (a, top left) Tanque Verde Creek at Craycroft Road, looking upstream; (b, top right) Pantano Wash at Craycroft Road, looking upstream; and (c, bottom left) Rillito Creek, looking downstream.*

Tanque Verde Creek contain between 73 and 87 percent sand (Table 3), and those of Pantano Wash and Rillito Creek range from 71 to approximately 88 percent, and from 81 to approximately 93 percent, respectively (Tables 4 and 5). The sandy nature of these streambeds is shown in Figure 13.

Variation in silt-clay and gravel content among the three streambeds reflects the geologic materials underlying each subwatershed and the distances of the sample sites from the headwaters of each stream. The bed of Tanque Verde Creek contains the largest amounts of gravel and the least amounts of silt-clay, probably because of the short distances between this stream's sample sites and its headwaters, where granites, diorites, schists, and gneisses are being weathered and eroded. Conversely, the streambed of Pantano Wash generally contains the largest percentages of silt-clay, primarily because of the extensive basin-fill area traversed by this stream and the greater distances between its sample sites and headwaters (Figure 1). The sediments of the Rillito Creek streambed display a comparatively small range in percentages of silt-clay and gravel and appear uniform to a depth of 10 feet (3 m) or more (Matlock, 1965; Table 5). At two bridge construction sites across Rillito Creek, coarse material was found to be continuous to a depth of 30 feet (9 m) and may extend even further. Layering of fine-grained material is not seen in the bed, but a layer 1/16 of an inch (1.6 mm) may be found on the streambed surface following a flow event (Matlock, 1965), in addition to clay lenses resulting from local ponding of runoff.

In summary, the alluvial stream channels of the Rillito Creek system can be categorized as sandy, according to the classification scheme of Schumm and Hadley (1961). This scheme is based on sediment sizes within channel banks and streambeds. The cross-sectional channel geometries of the Rillito Creek system, however, appear to be influenced by the silt-clay contents of the banks as well. Silts and clays are easily eroded, but are capable of maintaining nearly vertical to vertical banks, which exist at many locations throughout this stream system.

Flow Regimes of the Rillito Creek System

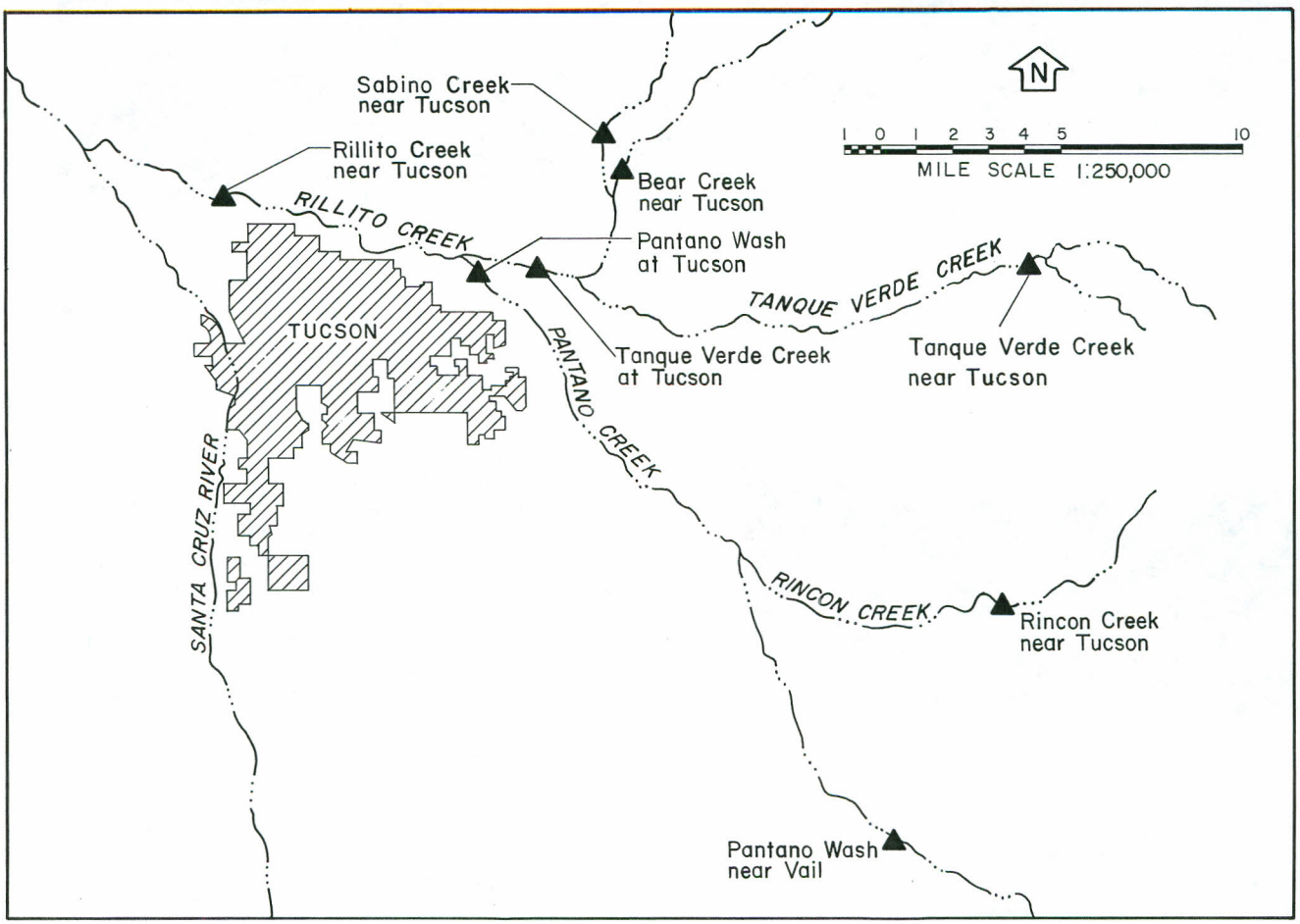


Figure 14. *Location map of cited streamflow gaging stations (after Condes de la Torre, 1970).*

Streamflow in the studied portion of the Rillito Creek system is ephemeral, meaning that flow occurs in direct response to local precipitation (Condes de la Torre, 1970). As in all semiarid regions, such streamflow is extremely variable because of differences in precipitation, temperature, topography, and geology within any given watershed. Annual flow statistics compiled by Condes de la Torre (1970) and Keith (1981) indicate that yearly flow volumes within the Rillito Creek system are so variable that mean annual flow values are not indicative of volumes to be expected each year. The reason for this lies in the distribution of flow events, which at most gaging stations is dominated by low flows with a few years of high flows. A brief examination of the major contributing factors to these flow distributions is warranted for the reader unfamiliar with ephemeral-stream systems in general and the Rillito Creek system in particular. This discussion leads to a summary of flow regimes within the Rillito Creek system.

STREAMFLOW GAGING PROGRAM

The U.S. Geological Survey has monitored streamflow in the Rillito Creek system as part of an extensive streamflow-monitoring program begun in the upper Santa Cruz River basin in the early 1900's (Condes de la Torre, 1970; Figure 14). Continuous-record gages, which daily record streamflow rates, were established at various times along the Rillito Creek system between 1915 and 1975 at the gaging stations shown in Figure 14. The lengths of record at these stations range from

15 to 60 years, and not all records are continuous since their beginnings. Most of these stations were converted in 1975 to partial-record stations, which only record flow peaks with crest-stage gages, and in 1981 to either flood-warning or flood hydrograph stations (H. W. Hjalmarson, U.S. Geological Survey, Tucson, oral commun., 1982).

SEASONAL STREAMFLOW TRENDS

Like many stream systems in southern Arizona that drain mountainous areas, streamflow in the Rillito Creek system reflects summer and winter precipitation seasons, as revealed by annual peak-discharge records and mean monthly flow statistics. Annual peak discharge is the highest discharge recorded in a given year. The annual peak-discharge records for the three gaging stations in the study area -- Tanque Verde Creek at Tucson, Rillito Creek near Tucson, and Pantano Wash at Tucson -- are shown in Figures 15b, 16b, and 17b. These records will be frequently referred to in later discussions of channel change.

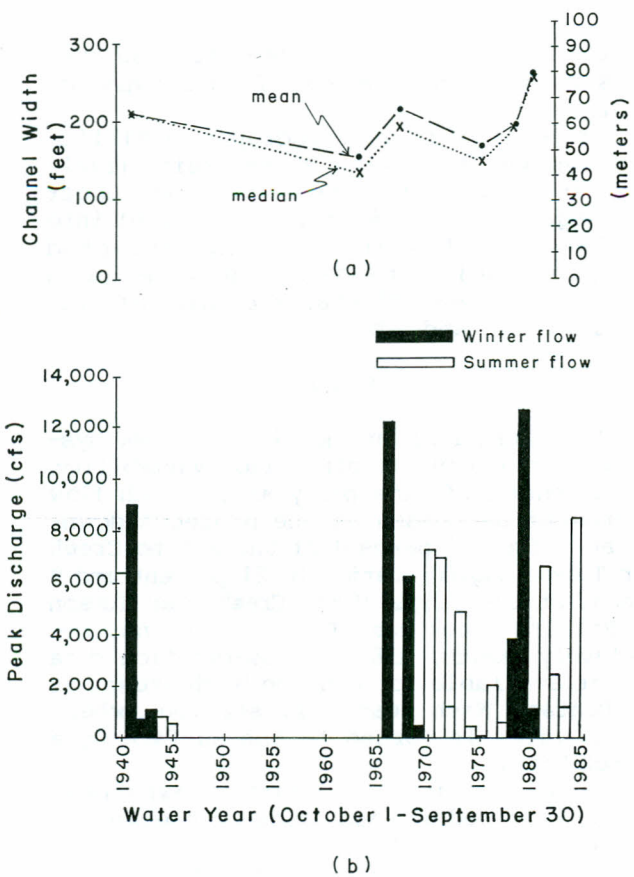


Figure 15. *Increases and decreases in the mean and median active-channel widths of Tanque Verde Creek from 1941 to 1979. Graph (a) is correlated with the annual peak flows recorded at the Tanque Verde Creek at Tucson gage [graph (b); see Figure 14 for location of gage]. Flows were not recorded between 1945 and 1966. The horizontal axes for graphs (a) and (b) are the same.*

Near Tucson, Pantano Wash flows primarily in response to intense, localized, summer thunderstorms (Table 6). About 82 percent of annual peak flows recorded at the Pantano Wash at Tucson station have occurred during the summer precipitation season, as has 73 percent of the mean annual flow above a selected base discharge recorded at the Pantano Wash near Vail station. In contrast, Tanque Verde Creek

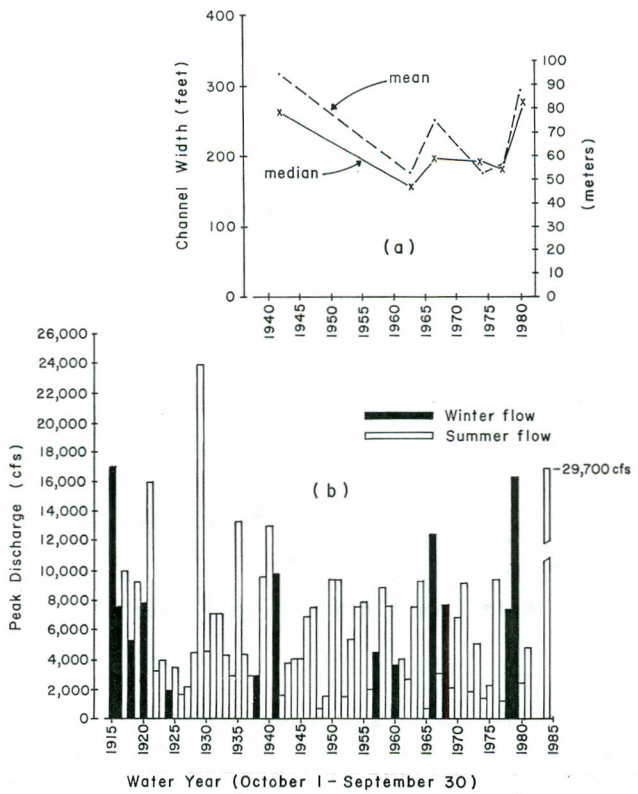


Figure 16. *Increases and decreases in the mean and median active-channel widths of Rillito Creek from 1941 to 1979 [graph (a)], correlated with the annual peak flows recorded at the Rillito Creek near Tucson gage [graph (b); see Figure 14 for location of gage]. The horizontal axes for graphs (a) and (b) are the same.*

has conveyed approximately 73 percent of its mean annual flow during the winter season, with about three times the number of winter annual peak flows as Pantano Wash. The majority of annual peak flows in Tanque Verde Creek, however, have been produced by summer thunderstorms (Condes de la Torre, 1970; Table 6). The more even distribution of flood peaks in Tanque Verde Creek is a result of large flow volumes produced when snowmelt is supplemented by rainfall (Condes de la Torre, 1970). Mean annual flow percentages for the two seasons are even more balanced in Rillito Creek

than in Tanque Verde Creek, although the distribution of annual peak flows is also weighted towards summer.

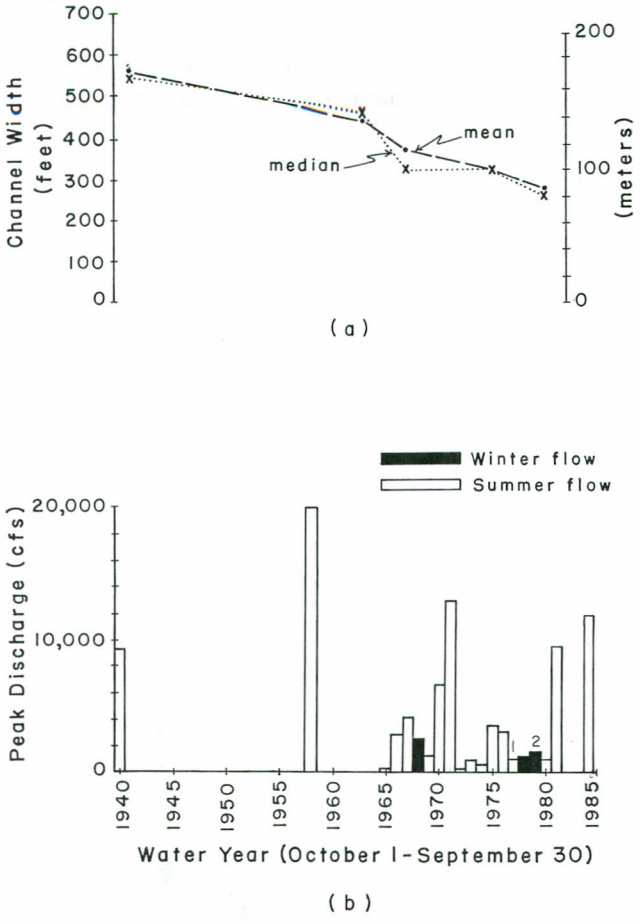


Figure 17. *Increases and decreases in the mean and median active-channel widths of Pantano Wash from 1941 to 1979. Graph (a) is correlated with the annual peak flows recorded at the Pantano Wash at Tucson gage [graph (b); see Figure 14 for location of gage]. Flows were not recorded at this gage between 1940 and 1958, or from 1959 through 1964. The horizontal axes for graphs (a) and (b) are the same.*

(1) Estimated peak discharge equals less than 900 cfs.

(2) Peak discharge recorded at Broadway Boulevard.

The seasonal distribution of streamflow in the Rillito Creek system, therefore, appears to be related to subwatershed topography because the seasonal distribution of precipitation is about the same for both basin and mountain areas (Keith, 1981). Pantano Wash, which drains large basin areas, is dominated by summer flow. Tanque Verde Creek mainly conveys winter flow because it drains primarily mountainous terrain. A more equitable distribution of summer and winter flow characterizes Rillito Creek, whose watershed contains roughly equal areas of both types of terrain.

Table 6. *Seasonal distribution of streamflow in the Rillito Creek watershed.*

Gaging Station	Percent* Mean Annual Flow		Percent* Annual Peak Flows	
	Winter	Summer	Winter	Summer
Rillito Creek near Tucson**	58	42	20	80
Tanque Verde Creek at Tucson**	--	--	44	56
Tanque Verde Creek near Tucson	73	24	44	50
Sabino Creek near Tucson	74	26	38	62
Bear Creek near Tucson	83	17	53	47
Pantano Wash at Tucson**	--	--	18	82
Rincon Creek near Tucson	67	33	62	29
Pantano Wash near Vail	27	73	6	94

* Due to the definitions of the precipitation seasons and rounding of figures, the percentages may not add to exactly 100.

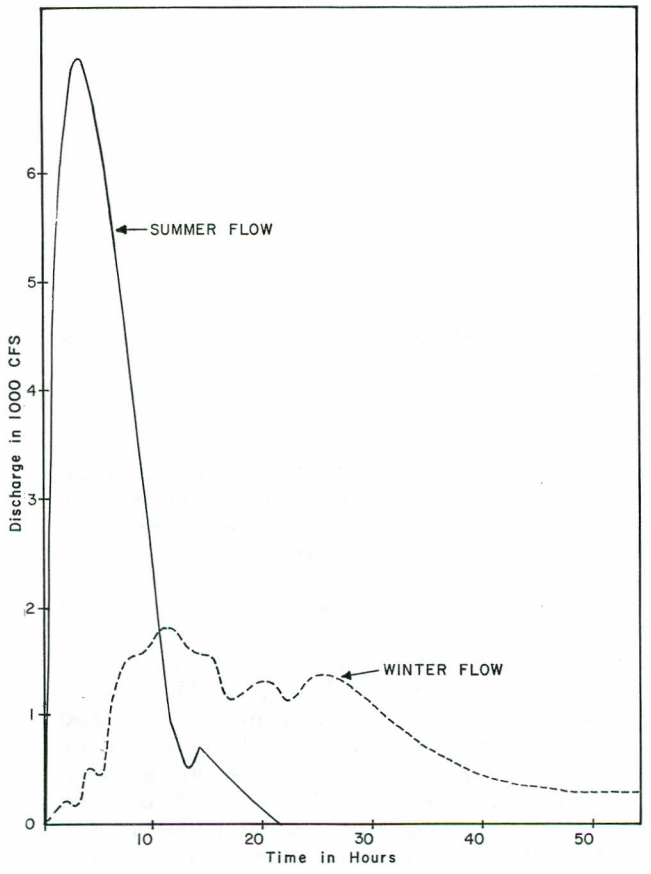
** Percent annual peak flows for these gaging stations are computed through 1979; all other figures are computed through 1975.

From streamflow hydrographs of Rillito Creek and the Santa Cruz River, Keith (1981) noted an episode of increased winter runoff that began in the 1960's and continued into the 1970's. This increase is reflected throughout the Rillito Creek system, as shown in the annual peak-discharge records of Figures 15b, 16b, and 17b.

FLOW DURATION

Flow durations in the Rillito Creek system also contribute to streamflow variability. The percentage of time per year in which flow is present decreases as one proceeds downstream: from 75 percent at the Sabino Creek near Tucson gaging station to 21 percent and 9 percent at the Tanque Verde Creek near Tucson and Rillito Creek near Tucson stations, respectively (Keith, 1981). Flow-duration data are not available for Pantano Wash except at the Pantano Wash near Vail station, where ground water is forced to the surface by a bedrock barrier.

Reductions in flow duration downstream can be explained by less frequent precipitation in the foothill and basin areas than in the mountains and by increasing loss of flow through infiltration to the subsurface with increasing distance from the mountain fronts. Approximately 55.6 percent of the average annual streamflow infiltrates the streambeds of Tanque Verde Creek and Rillito Creek; in Pantano Wash this figure rises to 72.2 percent (Burkham, 1970). From 1936 to 1963, mean annual infiltration totaled 15,300 acre-feet along Rillito Creek and Tanque Verde Creek and about 8,660 acre-feet along Pantano Wash



(Burkham, 1970; Davidson, 1973). Keith (1981) provides further detail on streamflow infiltration and recharge in the Tucson basin.

FLOW REGIMES

Seasonal streamflow trends based on seasonal precipitation characteristics and subwatershed topographies indicate that at least two flow regimes, summer and winter, are present in the Rillito Creek system (Figure 18). Summer flows are characterized by high peak discharges and short durations. Winter flows generally have lower peak discharges, but last longer. Summer flows have also been observed to transport larger quantities of suspended sediment than winter flows (Smith, 1910; Matlock, 1965; Keith, 1981).

Keith (1981) believes there is a third flow regime that consists of extreme flow events. According to Keith, these events usually result from summer tropical storms or extended periods of heavy winter precipitation and are characterized by high peak discharges, prolonged durations, and high sediment loads.

Figure 18. *Typical summer and winter hydrographs of large flow events in the ephemeral-stream channels of southern Arizona (after Matlock, 1965).*

Historical Channel Change in the Rillito Creek System

Historical channel change along the Rillito Creek system was documented through analysis of aerial photographs taken in 1941, 1963, 1967, 1974, 1978, 1979, and 1983. These photographs were chosen for their depiction of (1) channel change produced by major flow events and (2) subsequent natural channel recovery and artificial reconstruction. Natural channel recovery consists of those processes previously discussed in the section on channel narrowing. Artificial channel reconstruction consists of measures such as excavating and filling in a channel by using earth-moving equipment, dumping material over the banks, or constructing bank-protective works.

Dominant channel changes within the Rillito Creek system are presented in this section by time period from pre-1941 to late 1979. Analysis includes the following: (1) visual comparison of variance in channel-bank positions and plan-view patterns; (2) statistical comparison of channel widths; (3) presentation of magnitudes of change in streambed elevations; and (4) discussion of causative flow events determined from annual peak-discharge records and historical observations. Channel change that occurred in October 1983 is treated separately as an update to the earlier analyses.

The annual peak-discharge records from the Tanque Verde Creek at Tucson, Pantano Wash at Tucson, and Rillito Creek near Tucson gaging stations provide summaries of historical streamflow within the study area (Figures 15 to 17). The Tanque Verde Creek at Tucson station is at Sabino Canyon Road (Figure 14; Plate 1). Discharges within Tanque Verde Creek have been recorded at this station from 1941 to 1946 and from 1966 to the present (Figure 15b). The Pantano Wash at Tucson station, located at Tanque Verde Road, recorded discharges in 1940 and 1958 and from 1965 through 1978 (Figure 17b). In 1979 this station was reestablished on the downstream side of the Broadway Boulevard bridge. The annual peak-discharge record for the Rillito Creek near Tucson station extends continuously from 1915 to the present (Figure 16b). Its location has varied, however, between the First Avenue bridge and approximately 1,800 feet (549 m) downstream from Oracle Road. The years upon which these records are based are water years, which extend from October 1 to September 30.

METHODS OF ANALYSIS: 1941-79

From aerial photographs, Tanque Verde Creek was divided into six reaches and Pantano Wash into eight between their confluence near Craycroft Road and the eastern limit of the study area at Houghton Road (Plate 1). Rillito Creek was divided into nine reaches (Plate 1). The reaches of Rillito Creek that were examined are those that have been the least restricted by engineered channelization, which refers to some form of bank-stabilization works such as soil cement or wire-tied riprap. Riprap consists of rocks placed on the bed or banks of a stream channel as protection against erosion (Scott, 1981).

These stream-channel segments were mapped from each photograph with a Zoom Transfer Scope. This instrument allowed each reach to be mapped at a uniform scale, even though the scales of the photographs varied widely. Active-channel widths were measured through time from the maps at 22 equally spaced locations along Tanque Verde Creek, 31 along Pantano Wash, and 35 within selected reaches of Rillito Creek (Plate 1). These measurements are tabulated in the Appendix. Mean and median channel widths were computed from these measurements and are shown in Table 7. Mean channel width, defined here as the arithmetic average of widths for a given year, is influenced by extreme values and is therefore indicative of extreme variations in channel width. Median channel width for a given year represents the width around which the majority of measurements cluster: approximately 50 percent of the measurements are equal to or larger than this value and approximately 50 percent are equal to or smaller. Changes in these statistics from 1941 through 1979 are shown in Figures 15, 16, and 17 in conjunction with the appropriate annual peak-discharge records.

Maps of two reaches of Tanque Verde Creek (T3 and T5), two of Rillito Creek (R7 and R9), and one of Pantano Wash (P3) were chosen to illustrate dominant changes in channel width and plan-view patterns of the Rillito Creek system from pre-1941 to late 1979 (Figures 19 to 23; Plate 1). Reach R7 of Rillito Creek also typifies the engineered channelization that has frequently followed a period of extensive bank erosion (Figure 21). Other maps of this stream system compiled during this study are on file at the Arizona Bureau of Geology and Mineral Technology.

Table 7. *Variations in mean and median channel width from 1941 to 1979 of Tanque Verde Creek, Rillito Creek, and Pantano Wash. Channel width was measured at 22 cross-section locations along Tanque Verde Creek, 35 along Rillito Creek, and 31 along Pantano Wash.*

Year	Mean Channel Width (ft)	Mean Channel Width (m)	Median Channel Width (ft)	Median Channel Width (m)	Time Period	Percent and Direction of Change in Channel Width: mean	Percent and Direction of Change in Channel Width: median
			TANQUE VERDE CREEK				
1941	210	64	210	64	1941-63	-24	-38
1963	160	49	130	40	1963-67	+38	+46
1967	220	67	190	58	1967-74	-23	-21
1974	170	52	150	46	1974-78	+18	+27
1978	200	61	190	58	1978-79	+35	+37
1979	270	82	260	79			
			RILLITO CREEK				
1941	320	98	260	79	1941-63	-44	-38
1963	180	55	160	49	1963-67	+39	+25
1967	250	76	200	61	1967-74	-24	-8
1974	190	58	185	56	1974-78	0	-3
1978	190	58	180	55	1978-79	+50	+50
1979	285	87	270	82			
			PANTANO WASH				
1941	570	173	560	171	1941-63	-21	-16
1963	450	137	470	143	1963-67	-16	-30
1967	380	116	330	101	1967-74	-13	-9
1974	330	101	300	91	1974-79	-15	-10
1979	280	85	270	82			

PRE-1941

Channel positions of the Rillito Creek system before 1941 can be inferred from 1941 aerial photographs that show patterns of remnant riparian vegetation and flow traces left on the landscape. Some comparison can thus be made between pre-1941 and 1941 channel configurations. Because adequate peak-flow records for Tanque Verde Creek and Pantano Wash are not available for this period (Figures 15 and 17), pre-1941 interpretation draws heavily on historical observations. Only the annual peak-discharge record of the Rillito Creek near Tucson station begins before 1941 (Figure 16).

Remnant channel boundaries displayed in the 1941 photographs suggest that the main channels of the Rillito Creek system were once wider than those in existence when the photographs were taken. Tanque Verde Creek probably consisted of a series of braided channels, although a single channel of greater width than at present is also possible (Figures 19a and 20a). Rillito Creek and Pantano Wash both appear to have been extensively braided (Figures 21a, 22a, and 23a). Pre-1941 channel widths were not obtained because of the indefinite nature of channel boundaries shown in the photographs.

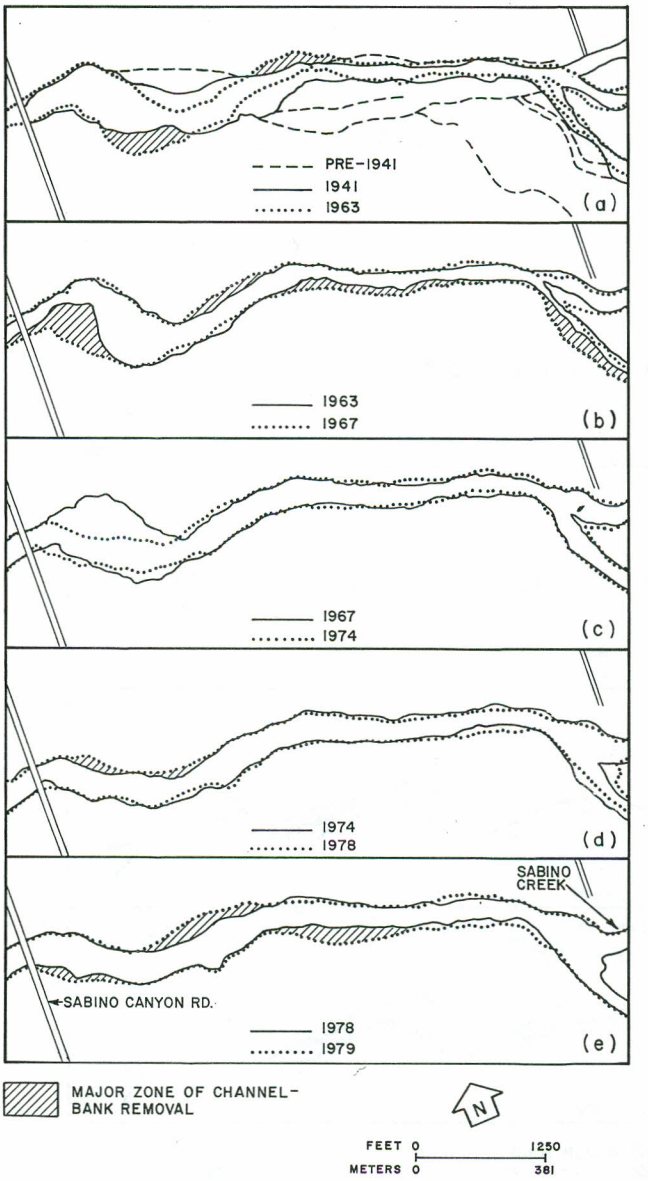


Figure 19. *Changes in channel width and pattern of Tanque Verde Creek from 1941 to 1979 in reach T3, upstream from Sabino Canyon Road. See Plate 1 for location of reach.*

By 1941 Tanque Verde Creek was a partially braided stream, as was Rillito Creek, which varied locally from a single channel to a braided-channel system. Pantano Wash was primarily a wide channel accompanied by numerous lesser braids. Mean channel widths within this stream system ranged from approximately 210 feet (64 m) for Tanque Verde Creek to 570 feet (173 m) for Pantano Wash (Table 7). Median channel widths were similar.

Braiding of the Rillito Creek system before and during 1941 may be related to dam-

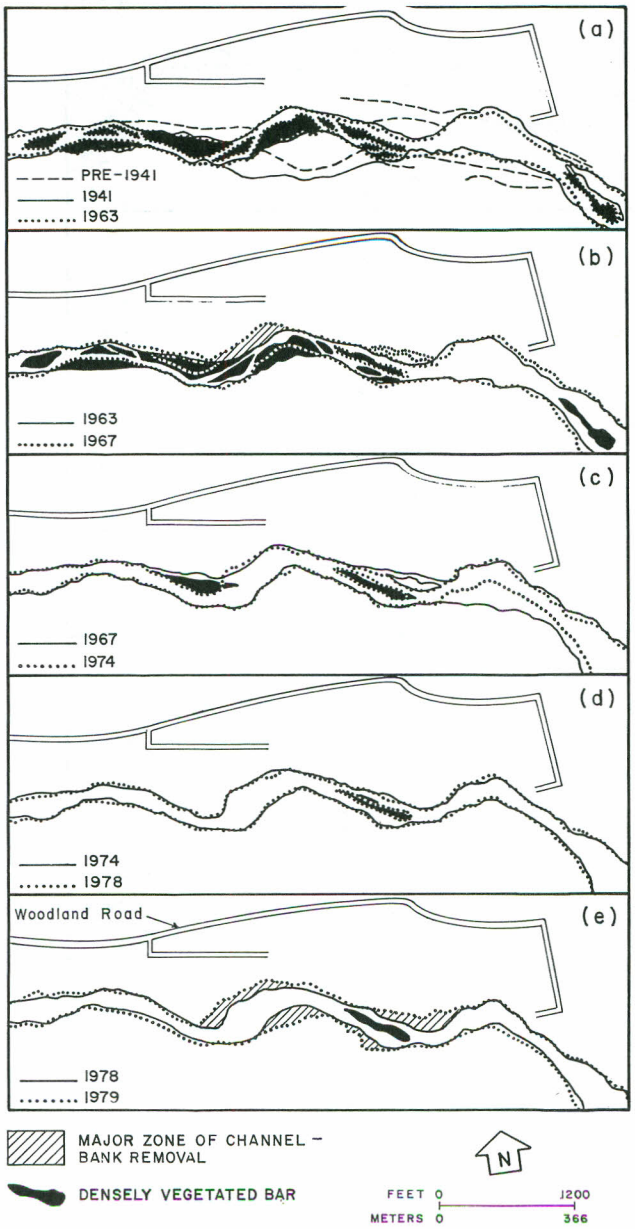


Figure 20. *Changes in channel width and pattern of Tanque Verde Creek from 1941 to 1979 in reach T5, upstream from Tanque Verde Road and parallel to Woodland Road. See Plate 1 for location of reach.*

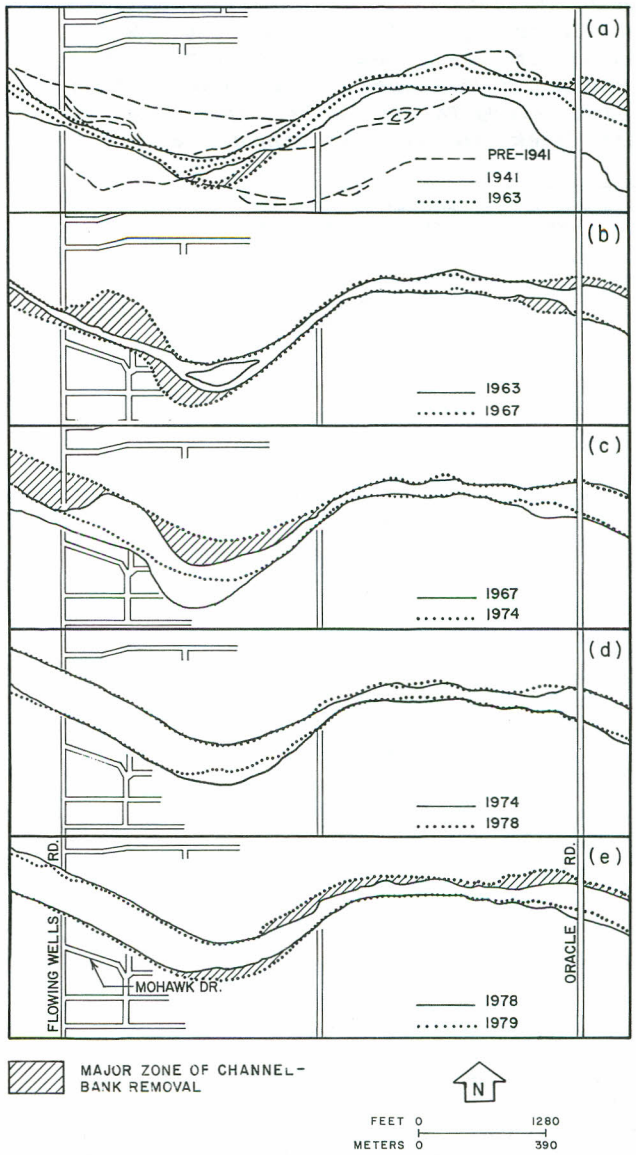


Figure 21. *Changes in channel width and pattern of Rillito Creek from 1941 to 1979 in reach R7, downstream from Oracle Road. See Plate 1 for location of reach.*

aging floods that began in 1880 (Grove, 1962; U.S. Army Corps of Engineers, 1973). In 1887 a flood of possibly the greatest magnitude ever observed in Rillito Creek was reported by The Arizona Daily Star on September 11:

> THE RILLITO
>
> The flood in the Rillito on Friday last was much worse than was thought. Many cattle being taken unaware by the sudden overflow of the stream were swept away and drowned. Trees of good size, bridge timbers and other debris was found scattered along its banks yesterday. The Narrow Gauge Railroad bridge was taken by the turbulent stream and was landed in many pieces on the bottoms. The waters north of the town are reported to have stood two miles wide.

A series of high-magnitude flows that ranged from 10,000 to 24,000 cubic feet per second (cfs) or 283 to 680 cubic meters per second (m^3/s) was recorded from 1915 to 1941 at the Rillito Creek near Tucson gage (Figure 16b). Because Tanque Verde Creek and Pantano

Wash are both tributaries of Rillito Creek, magnitudes of flows within these tributaries before 1941 were probably similar to those recorded downstream in Rillito Creek.

Periods of drought noted in Tucson from 1899 to 1904, 1927 to 1930, and 1937 to 1940 were often followed by one or more wet years (Cooke and Reeves, 1976). The 1929 summer flow of 24,000 cfs (680 m^3/s), the largest recorded through 1979 at the Rillito Creek near Tucson gage, occurred near the end of a drought. The winter of 1940-41, the wettest on record through 1979 in the Tucson area, also marked the end of a dry period (Durrenberger and Wood, 1979). A flow of 9,500 cfs (269 m^3/s) was recorded in Rillito Creek at this time.

The braided patterns of the Rillito Creek system are likely to have been a response to this climatic variability. Erodible banks, large volumes of bed load, and frequent fluctuations in discharge are thought to be necessary for the development of braids (Ritter, 1978). As previously mentioned, detailed studies have shown that braided stream channels are usually wider and shallower and have steeper bed slopes than undivided channels that convey equivalent amounts of flow, thus facilitating the transport of large amounts of sediment (Leopold and Wolman, 1957). The dry periods recorded in Tucson probably lessened the vegetative cover of the Rillito Creek watershed and the riparian vegetation of the stream channels, both of which take years to recover in this semiarid region. Greater runoff and valley-floor erosion during the succeeding wet years probably produced a larger supply of sediment for transport, which, in conjunction with the increased erodibility of the channel banks produced by diminishing riparian vegetation, resulted in the braided channels evident in the 1941 photographs.

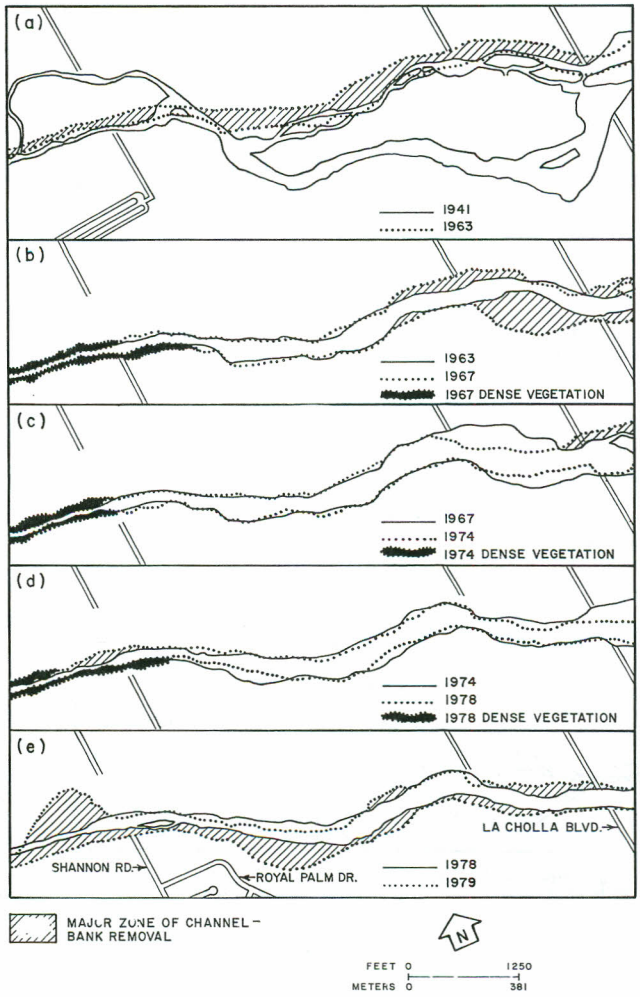


Figure 22. *Changes in channel width and pattern of Rillito Creek from 1941 to 1979 in reach R9, downstream from La Cholla Boulevard. See Plate 1 for location of reach.*

1941-63

From 1941 to 1963, channels of the Rillito Creek system narrowed significantly by evolving towards single-channel patterns. By 1963 deposition of sediment within secondary channels and portions of the main channels, coupled with growth of riparian vegetation, produced marked decreases in mean and median active-channel widths (Table 7). Reaches R9 of Rillito Creek and P3 of Pantano Wash offer particularly striking examples of this process (Figures 22a and 23a; Plate 1). The braided channels of reach R9 were reduced to a single channel, and midchannel bars that existed in reach P3 and other reaches of Pantano Wash in 1941 coalesced with decreasingly active braids to form part of its geologic flood plain. By 1962 the average width of the low-flow channel of Rillito Creek varied from only 100 to 200 feet (30 to 61 m), and its capacity diminished to 9,000 cfs (255 m^3/s; Grove, 1962). The capacity of Pantano Wash was similarly reduced, as illustrated by the decrease of 120 feet (37 m) in its mean active-channel width (Table 7).

Tanque Verde Creek also narrowed, primarily by rearranging its plan-view pattern from that of a partly braided stream-channel system to a single channel containing flow paths separated by densely vegetated bars. Reach T5 illustrates this process (Figure 20a). The southernmost braid of this reach, partly active in 1941, ceased to function by 1963, at which time it was discernible on aerial photographs only by remnants of its lining of riparian vegetation.

Not all reaches of this stream system behaved uniformly during this period, however. Reach T3 of Tanque Verde Creek, only approximately 1.4 miles (2.3 km) downstream from reach T5 (Plate 1), exemplifies channel behavior tending to oppose that of reach T5. Erosion of as much as 220 feet (67 m) along the

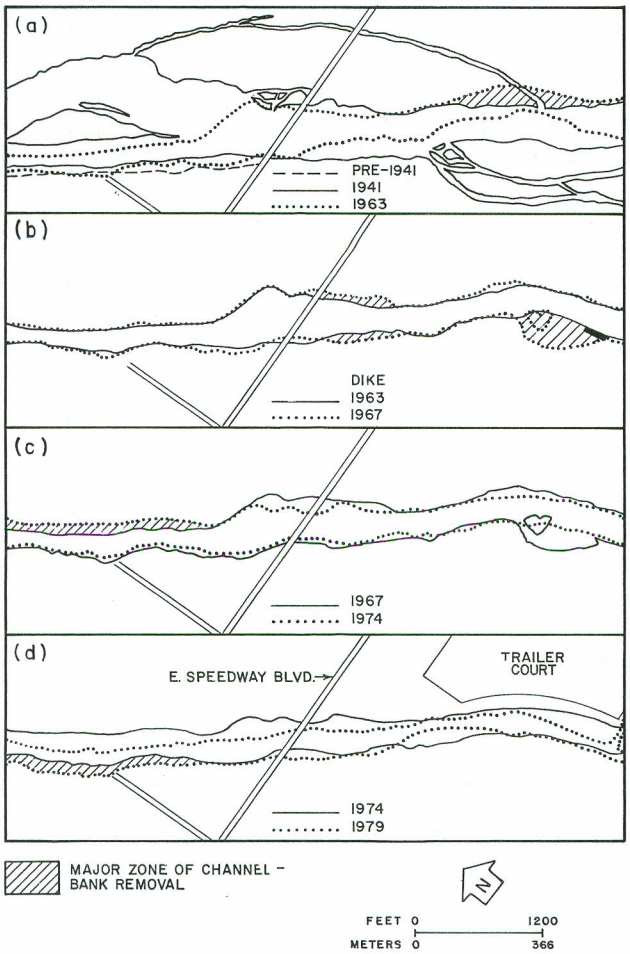


Figure 23. *Changes in channel width and pattern of Pantano Wash from 1941 to 1979 in reach P3, near East Speedway Boulevard. See Plate 1 for location of reach.*

outer channel banks of reach T3, downstream from the mouth of Sabino Creek, increased the amplitude of the channel bends by approximately 200 feet (61 m; Figure 19a). Local channel widening attained a maximum of only 100 feet (28 m), however, because of compensating point-bar deposition and bar maturation.

In summary, channel width decreased at 94 percent of the cross-section locations along Rillito Creek, and at 74 and 75 percent of the locations along Pantano Wash and Tanque Verde Creek, respectively, within a range of approximately 10 feet to as much as 870 feet (3 to 265 m; see Appendix). At the remaining cross-section locations, the stream channels widened or shifted in position through local bank erosion.

The narrowing of the Rillito Creek system between 1941 and 1963 probably resulted from a decline in streamflow. The annual peak-discharge record of the Rillito Creek near Tucson gage displays a series of peak flows of less than 10,000 cfs (283 m^3/s) during this period (Figure 16b). The 1941 braided-channel system of Rillito Creek, created by high peak flows that probably carried large volumes of sediment, was apparently too wide and perhaps too shallow to convey the succeeding lower flows efficiently. Less sediment also may have been supplied to Rillito Creek during this period compared to the pre-1941 period. Drought was recorded only from 1947 to 1950 and was followed by summer flows of less than 10,000 cfs (283 m^3/s). One general response of Rillito Creek to these lower magnitude flows, and perhaps to a lesser influx of sediment, was to reduce its active-channel width.

Despite the lack of discharge data for Tanque Verde Creek and Pantano Wash for this period, it is reasonable to infer that the general narrowing of these stream channels between 1941 and 1963 resulted from a similar decline in streamflow. A flow event did, however, peak at 20,000 cfs (566 m^3/s) at the Pantano Wash at Tucson gage in August 1958 (Figure 17b). Effects of this flow on Pantano Wash are not readily apparent in the aerial photographs, although the flow may have caused the local increases in channel width measured at 19 percent of the cross-section locations where channel widening reached a maximum of about 360 feet (110 m; see Appendix). The flow may have also reduced or temporarily halted the dominant narrowing of the stream channel. Channel-recovery rates may have been high enough to mask impacts of the flow by 1963, the duration of the flow may have been very short, or sediment eroded from the Pantano Wash subwatershed or its streambed may have prevented excessive bank erosion. Unfortunately, longitudinal profiles of the Pantano Wash streambed date only from 1967 (Figure 24), and those of Tanque Verde Creek do not adequately cover this period (Figure 25). Some information, however, may be gleaned from changes over time in the Rillito Creek profiles and cautiously extrapolated to its tributaries.

Longitudinal profiles of the Rillito Creek streambed indicate that degradation of this stream channel did occur in at least one area sometime between 1941 and 1963 (Figure 26). These profiles, acquired from the Pima County Department of Transportation and Flood Control District for the years 1954, 1960, 1967, 1976, and 1979, extend downstream from the First Avenue bridge to about 0.7 miles (1.1 km) beyond La Cholla Boulevard. Profiles for February and March of 1960 extend only from First Avenue to Oracle Road. From 1954 to February 1960, the streambed in this reach fluctuated about the 1954 profile, alternately degrading and aggrading for a distance of 2,600 feet (792 m) downstream from the First Avenue bridge. Maximum aggradation of approximately 4.5 feet (1.4 m) occurred about 1,700 feet (518 m) downstream from First Avenue. From this point to Oracle Road, the streambed

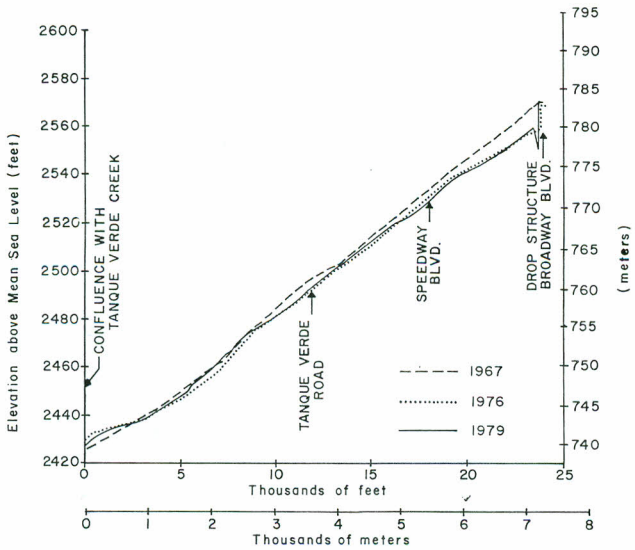


Figure 24. *Longitudinal profiles of the streambed of Pantano Wash from 1967 to 1979 from Broadway Boulevard to the confluence with Tanque Verde Creek at Craycroft Road. Profiles courtesy of the Pima County Department of Transportation and Flood Control District.*

Included in the period from 1954 to 1960 is a portion of the general narrowing of Rillito Creek documented from the aerial photographs taken from 1941 to 1963. At least in this one reach, the stream channel increased its depth as its width decreased. Similar increases in channel depth are likely to have taken place along much of Rillito Creek and also along Pantano Wash and Tanque Verde Creek as their channel widths decreased.

1963-67

Between 1963 and 1967, the behavior of Tanque Verde Creek, Pantano Wash, and Rillito Creek began to diverge. Pantano Wash continued to narrow more than it widened, whereas both Tanque Verde Creek and Rillito Creek widened extensively. Reductions in channel width of approximately 10 to 560 feet (3 to 171 m), which occurred at 58 percent of the cross-section locations along Pantano Wash, produced decreases of 16 percent and 30 percent in its mean and median active-channel widths, respectively (Table 7). These figures represent a decline of 70 feet (21 m) in mean channel width and twice that amount, 140 feet

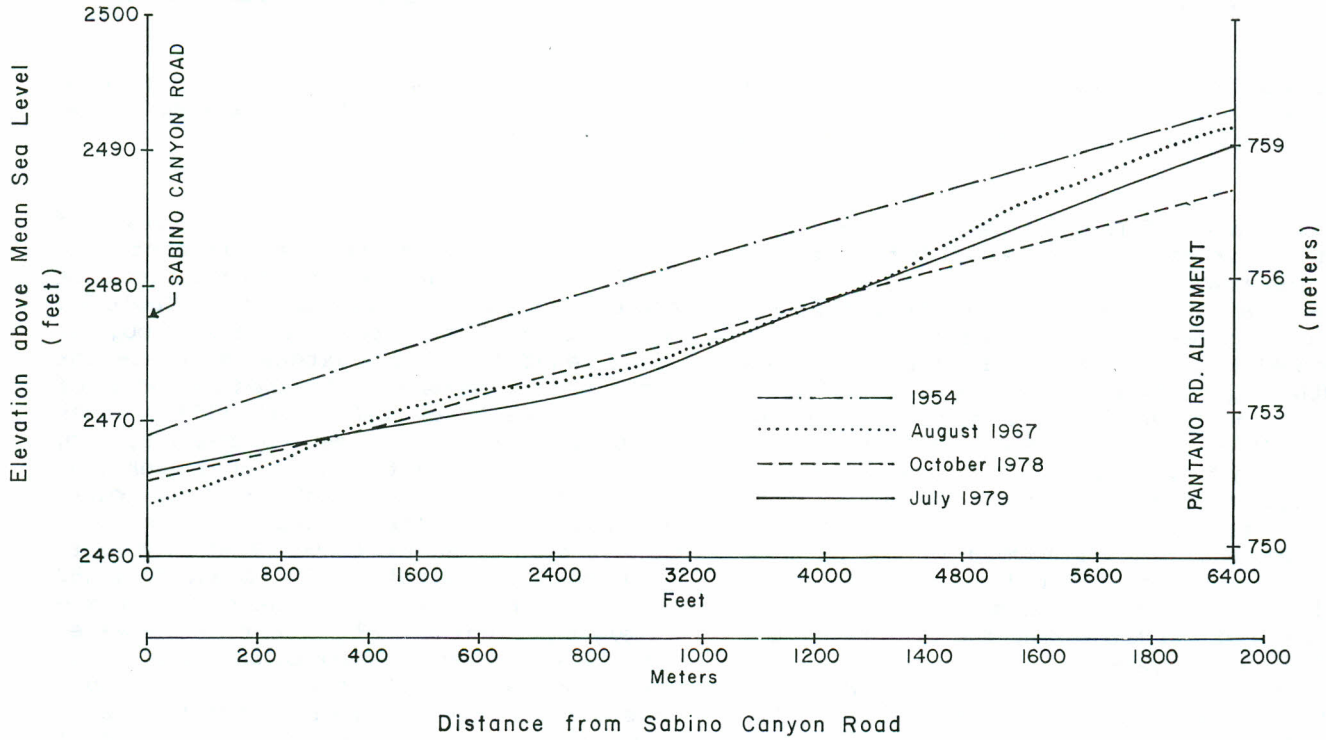


Figure 25. *Longitudinal profiles of the streambed of Tanque Verde Creek from 1954 to July 1979, from the Pantano Road alignment to Sabino Canyon Road. Profiles courtesy of the Pima County Department of Transportation and Flood Control District.*

downcut a maximum of approximately 3 feet (0.9 m) below the 1954 profile. In March 1960, the streambed was artificially lowered to a more uniform profile.

(43 m), in median channel width. This stream channel, however, also widened from about 10 to 370 feet (3 to 113 m) at 35 percent of the cross-section locations (see Appendix).

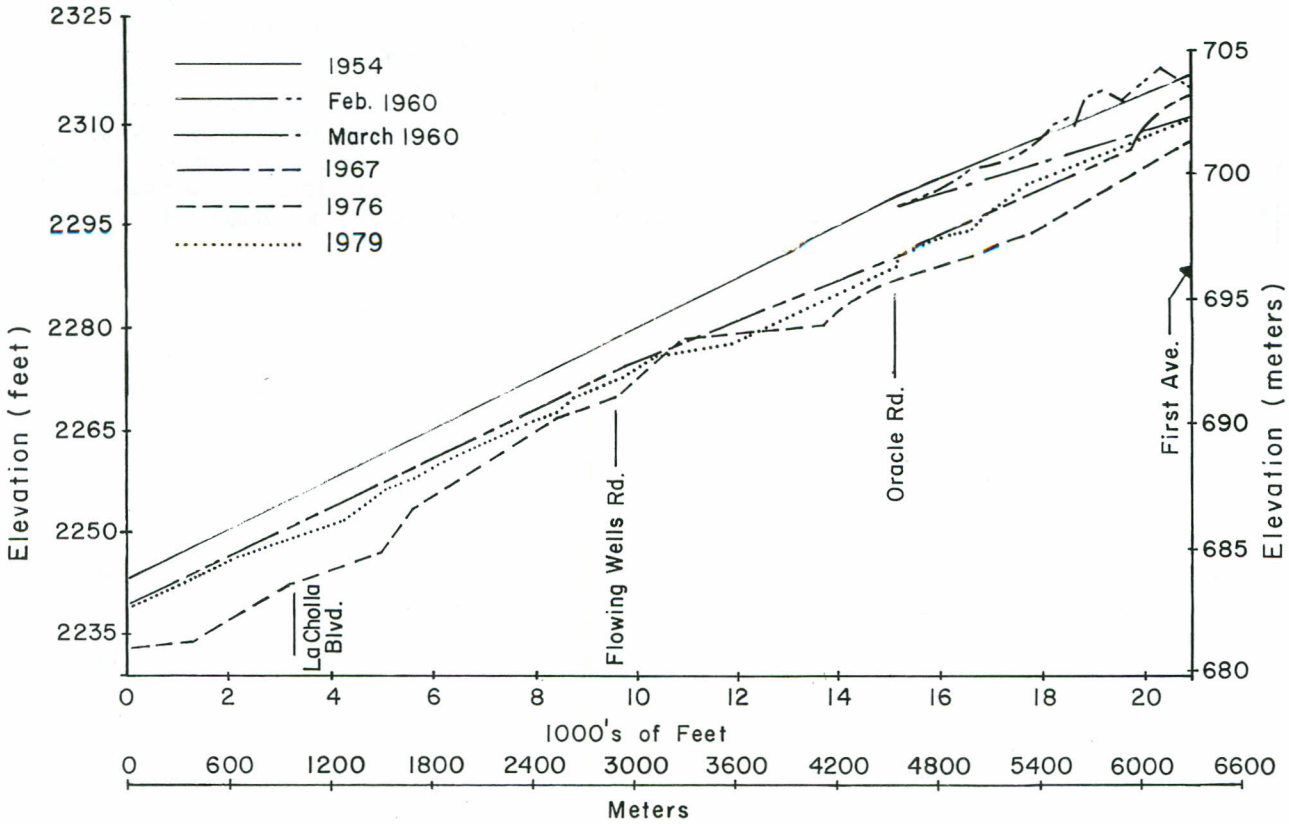


Figure 26. *Longitudinal profiles of the streambed of Rillito Creek from 1954 to 1979, from First Avenue to approximately 0.7 miles (1.1 km) beyond La Cholla Boulevard. Profiles courtesy of the Pima County Department of Transportation and Flood Control District.*

Reach P3 of Pantano Wash portrays this spatial variability in channel behavior. At the upstream end of the reach, the channel widened a maximum of approximately 230 feet (70 m), whereas further downstream it either narrowed slightly or maintained its previous width (Figure 23b). This erosional widening cut into a former channel area that existed in 1941. In an effort to reverse the erosion by deflecting flow away from the bank and inducing deposition of sediment in the eroded area, a dike was placed at the location of initial flow impingement. Placement of one or more dikes in a stream channel at an angle to an eroded bank has been a common human response to bank erosion throughout the history of the Rillito Creek system.

Because flows were not recorded at the Pantano Wash at Tucson gage in 1963 and 1964, one can only speculate about the causes of channel change in the wash between 1963 and 1967. Peak-flow magnitudes of less than 3,000 cfs (85 m^3/s) from 1965 through 1967, however, suggest that meandering low flows caused the secondary widening of Pantano Wash through localized bank erosion and collapse, while primarily inducing general decreases in channel width through sediment deposition and vegetation growth.

In contrast, Tanque Verde Creek and Rillito Creek experienced significant bank erosion between 1963 and 1967 in a reversal of the previous morphological trend (Table 7). Widening of these stream channels throughout their lengths included extensive outer-bank scour and bar erosion. Reaches T3 and T5 of Tanque Verde Creek and R7 of Rillito Creek illustrate these processes (Figures 19b, 20b, and 21b). Concurrent with general bank erosion in reach T3, outer-bank scour and point-bar erosion caused the two channel bends immediately east of Sabino Canyon Road to migrate downstream approximately 270 to 430 feet (82 to 131 m; Figure 19b). Decreases of approximately 6 percent and 18 percent in the wavelengths of the bends resulted, as their amplitudes increased by about 2 percent. In contrast, the active channel of reach T5 also widened, but primarily through erosion of midchannel bars and point bars (Figure 20b). The relatively narrow, braided flow paths that defined the active channel of this reach in 1963 merged into a single, wider active channel with only minor bank erosion. In this reach, Tanque Verde Creek regained a configuration very similar to that of 1941. Tanque Verde Creek thus increased its median channel width by 60 feet (18 m), or 46 percent, and

its mean channel width also by 60 feet (18 m), or 38 percent (Table 7).

In reaches R7 and R9 of Rillito Creek, increases in channel width during this period ranged from approximately 10 feet (3 m) to 390 feet (119 m; Figures 21b and 22b). Roughly similar amounts of bank erosion occurred in both reaches on the opposite banks of adjacent channel bends because of deflection of flow from one bank to the other. In the western half of reach R7, the formation of a midchannel bar and southward migration of the channel between 1941 and 1963 set the stage for the direct impingement of flow against the southern bank and subsequent deflection of flow to the northern bank. A street and several structures adjacent to the southern bank were destroyed by this erosion (Figure 21b). In reaches R1 and R2 near Swan Road (Plate 1), bank protection in the form of riprap behind wire failed, leading to severe channel-bank erosion that straightened the southern bank of Rillito Creek over a distance of approximately 1,250 feet (381 m), while eroding it laterally about 600 feet (183 m; Figure 27). This bank protection had been constructed in 1956-57. Similar widening at 69 percent of the cross-section locations along Rillito Creek produced an increase of 70 feet (21 m), or 39 percent, in its mean channel width (Table 7). The median width of this stream channel also experienced a significant increase of 40 feet (12 m), or 25 percent.

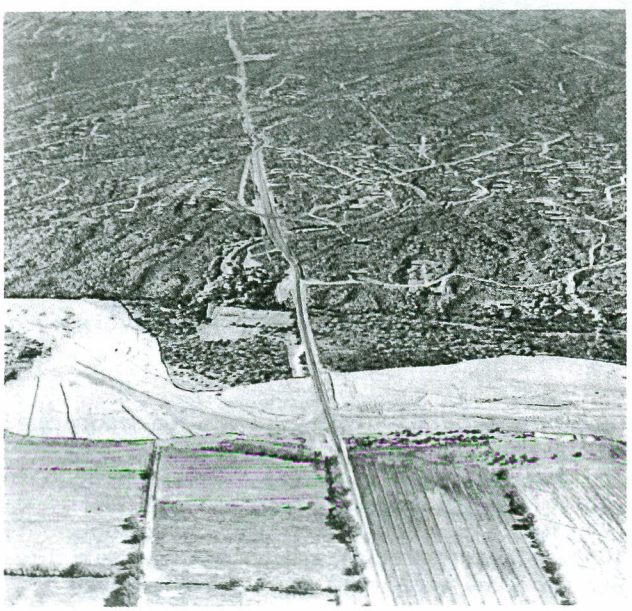


Figure 27. *Extreme bank erosion along Rillito Creek produced by the December 1965 flow event, Swan Road area, looking north. The south bank of Rillito Creek was straightened over a distance of approximately 1,250 feet (381 m) and eroded laterally a maximum of about 600 feet (183 m) from its former position. Photo by L. O. "Pat" Henry, courtesy of Special Collections, University of Arizona Library.*

Riparian vegetation played a role in deterring significant channel-bank erosion at a number of locations along Rillito Creek, and presumably also along Tanque Verde Creek. An example of this phenomenon is the westernmost portion of reach R9, where dense riparian vegetation apparently prevented the banks from being eroded despite the narrow width of the channel (Figure 22).

The general widening of Tanque Verde Creek and Rillito Creek between 1963 and 1967 can be linked directly to a period of flow in late December 1965 (water year 1966). On December 22, streamflow peaked at 12,200 cfs (346 m^3/s) in Tanque Verde Creek and 12,400 cfs (351 m^3/s) in Rillito Creek (Figures 15b and 16b). This flow has been estimated to have 27-year and 16-year recurrence intervals in Tanque Verde Creek and Rillito Creek, respectively (Aldridge, 1970). Recurrence interval of a flow event is defined as the average time interval within which the magnitude of the event will be equaled or exceeded (Chow, 1964). The 1965 peak discharge, therefore, is expected to occur or be exceeded on the average of once every 27 years in Tanque Verde Creek and once every 16 years in Rillito Creek. In comparison, the magnitudes of the 100-year floods projected for Tanque Verde Creek, Rillito Creek, and Pantano Wash have been estimated to range between 31,000 cfs and 35,000 cfs (U.S. Army Corps of Engineers, 1973 and 1975).

Aldridge (1970) has documented the events that led to the 1965 flow. Five major storms originated in the Pacific Ocean and traveled into Arizona and New Mexico in November and December of 1965. The early storms saturated the soils of the Rillito Creek watershed at lower altitudes, deposited snow in the mountains, and also may have saturated the streambeds of Tanque Verde Creek and Rillito Creek. These conditions effectively increased the probability of large flow volumes in late December of that year. Approximately 66 inches of snow (168 cm) were on the ground at Mount Lemmon within the Santa Catalina Mountains before the fourth storm in the series began (The Arizona Daily Star, December 18, 1965). Although this storm was widespread, the largest volume of runoff originated in the Tanque Verde Creek subwatershed, where snowmelt increased runoff (U.S. Geological Survey, Tucson, data files). Rural foothill drainages added little to the runoff, although intense rainfall on urbanized areas caused small flow peaks from urban drainages.

The extensive channel-bank erosion observed in Rillito Creek and Tanque Verde Creek at this time was primarily due to the prolonged duration of flow (B. N. Aldridge, U.S. Geological Survey, Tucson, oral commun.,

1980). Severity of bank erosion tends to be proportional to duration of shear on the banks. Most of the 1965 bank erosion occurred over a period of 2 to 3 days, although flow was recorded from December 10 through 26 in Tanque Verde Creek and through January 3 in Rillito Creek (Aldridge, 1970). The following excerpts from The Arizona Daily Star dramatize the resulting erosion:

> 24 December, 1965
> FLOOD PERIL CONTINUES AS SEWERS WASH OUT; STATE ASSISTANCE SOUGHT
>
> Continuing December rains, mixed with light snow, again battered Tucson yesterday — sending the storm damage estimates soaring to more than $1.25 million as river crossings washed out, trailers were swamped by rising waters and sewage systems were eroded by surging ground water.

> 24 December, 1965
> FLOWING WELLS AREA STUNNED BY WILD RILLITO
>
> The roiled, brown waters of the flooding Rillito Creek tore into two trailer parks in the Flowing Wells area yesterday, demolishing two trailers. A third was about to crumble into the rampaging waters late last night.

> 31 December, 1965
> RUNOFF CRISIS REPEATS ITSELF
>
> Rain and rapidly melting snow in the Catalinas swelled the Rillito River again yesterday, forcing officials of Tucson Sanitary District 1 to authorize emergency efforts to save the crumbling north bank of the river near the Dodge Boulevard crossing.
>
> The authorization, which empowered R and M Construction Co. to work in an around-the-clock effort to bolster the disintegrating bank, was made to prevent the loss of another sewer crossing on the Rillito.
>
> Previously, the manager of the sanitary district said, the Rillito had eaten away at the south bank of the river causing tons of loose earth to tumble into the stream and thus altering its course into the northern bank.

In addition, approximately 60 feet (18 m) of the north approaches to the First Avenue and Campbell Avenue bridges across Rillito Creek (Plate 1) were lost as a result of bank migration (The Arizona Daily Star, December 24, 1965; Figure 28). Damages in the Tucson area totaled $1.25 million, of which approximately $1.13 million were required to repair damaged sewer lines (City of Tucson Planning Department, 1976). Throughout the history of the Rillito Creek system, mobile-home parks

Figure 28. *Destruction of the north approaches to the Campbell Avenue (a, top) and First Avenue (b, bottom) bridges by the December 1965 flow event. Photo by L.O. "Pat" Henry, courtesy of Special Collections, University of Arizona Library.*

have been particularly prone to erosional damage, as occurred in the Flowing Wells area in 1965, because they are often adjacent to actively migrating channels (Figure 29).

Rillito Creek also may have downcut; longitudinal profiles indicate a maximum lowering of the streambed from March 1960 to 1967 by approximately 5.5 feet (1.7 m) between First Avenue and Oracle Road (Figure 26). The extended flow event of December 1965 may have deepened as well as widened this channel, although the degradation cited above cannot be directly linked to this particular flow event.

1967-74

From 1967 to 1974, the channels of Tanque Verde Creek and Rillito Creek narrowed as a result of natural channel recovery and artifi-

Figure 29. *Effect of outer-bank erosion on a mobile-home park adjacent to a channel bend in Rillito Creek, Flowing Wells Road area, December 1965. Photo courtesy of the U.S. Geological Survey.*

cial reconstruction following the December 1965 period of winter flow. As previously discussed, channel recovery refers to channel narrowing due to accumulation of fluvially deposited sediment accompanied by vegetation growth. Artificial reconstruction refers to channel narrowing produced by the placement of fill in the eroded parts of a channel. Installation of bank protection is often included in channel reconstruction. For an area such as the Tucson basin, where urban development is proceeding at a rapid pace, it is often difficult to distinguish on aerial photographs between natural channel recovery and local artificial channel reconstruction, except where a uniform channel width maintained over a distance indicates engineered channelization. Throughout this study, therefore, little attempt has been made to differentiate between the two processes using the photographs. Some speculation has been indulged in, however, regarding the likelihood of one or the other process based on the channel's distance from a highly urbanized area.

Both the mean and median channel widths of Tanque Verde Creek and Rillito Creek sigficantly decreased from 1967 to 1974. Tanque Verde Creek reduced its mean width by approximately 23 percent, from 220 feet (67 m) to 170 feet (52 m), and its median width by 21 percent, from 190 feet (58 m) to 150 feet (46 m; Table 7). The main change in the channel of reach T3 was an approximate 400-foot (122-m) decrease in width upstream from Sabino Canyon Road. This change was mainly due to a local shift of the channel's northern bank by approximately 460 feet (140 m) to the south (Figure 19c). Reach T5 exhibits minimal change, except for a local maximum decrease of about 170 feet (52 m) in active-channel width that resulted from point-bar maturation in the easternmost portion of the reach (Figure 20c).

Rillito Creek similarly reduced its mean channel width by 24 percent, from 250 to 190 feet (76 to 58 m), but its median width decreased by only 8 percent (Table 7). Rillito Creek flows through an area that is being intensely urbanized. In an effort to protect existing land and structures, local authorities and property owners tend to return the banks of this stream channel to their former positions after an erosive flow. The large decrease in mean width of Rillito Creek from 1967 to 1974, compared to that of its median width, suggests that the most severely eroded portions of the channel were artificially reconstructed. For example, the western portion of reach R7 was realigned and channelized through installation of riprap bank protection following the extensive erosion produced by the 1965 winter flow event (Figure 21c). The channelization proved effective until October 1983, when a portion of the riprap was eroded along the southern bank of the channel, upstream from Flowing Wells Road. The unrestricted eastern portion of the reach has widened and narrowed on a local basis since 1974, until the banks of the channel were stabilized with soil cement in 1981. Between 1967 and 1974, Rillito Creek reduced its width in this reach by approximately 160 feet (49 m) immediately downstream from Oracle Road.

Pantano Wash continued to narrow during this period, although the decreases of 50 feet (15 m) in mean width and 30 feet (9 m) in median width are small relative to decreases of previous periods (Table 7). Local reductions in channel width ranged from approximately 10 feet (3 m) to 300 feet (91 m; see Appendix).

Climatic records from weather stations throughout the Tucson basin indicate that above-average precipitation characterized this area from 1966 through 1968 and from 1970 through 1972 (Sellers and Hill, 1974). Resulting peak magnitudes of streamflow were generally moderate, the majority of which measured between 4,930 cfs (140 m^3/s) and 7,430 cfs (210 m^3/s) in Tanque Verde Creek (Figure 15b). Annual peak flows in Rillito Creek ranged from 1,440 cfs (41 m^3/s) in 1974 to 9,290 cfs (263 m^3/s) in 1971 (Figure 16b). Only in 1970 and 1971, the years of the largest peak flows throughout the system during this period, did Pantano Wash experience streamflow greater than approximately 4,000 cfs (113 m^3/s).

In the absence of major flow events, such a relatively wet period encourages growth of riparian vegetation, which in turn increases the hydraulic roughness of a stream channel, decreases flow velocities, and traps sediment. A narrower channel eventually results. This process of channel recovery, observed by Schumm and Lichty (1963) in the Cimarron River in Kansas and by Wolman in a small channel in Oklahoma (Wolman and Gerson, 1978), appears to

have operated in the Rillito Creek system between 1967 and 1974.

Degradation also played a major role in shaping the channels of this stream system during this period. Both Rillito Creek and Pantano Wash downcut significantly between 1967 and 1976. Along the length of Rillito Creek shown in the longitudinal profiles (Figure 26), degradation of the streambed ranged from less than 1 foot (0.3 m) to 11 feet (3 m), except for one location: a 700-foot (213-m) reach upstream from Flowing Wells Road, where the streambed aggraded a maximum of 0.5 foot (0.2 m). The longitudinal profiles of Pantano Wash from Broadway Boulevard to Craycroft Road indicate that degradation of this stream channel reached a maximum of 12 feet (4 m) near the Broadway Boulevard bridge, which was built in 1965 (Figure 24). To arrest downcutting, and thus stabilize the bridge and save utility lines that serve the eastern side of Tucson, Mountain Bell and Pima County collaborated in grouting the streambed at this location in 1975-76. The streambed was further stabilized at this site in 1979, which will be discussed in the section covering the next time period.

The general degradation of Rillito Creek and Pantano Wash was produced, at least in part, by the peak flow of 1971 (B. N. Aldridge, U.S. Geological Survey, Tucson, oral commun., 1981), and possibly also by that of 1970. On August 19, 1971, flow in Pantano Wash reached 12,800 cfs (362 m^3/s). Further downstream in Rillito Creek, this same flow measured 9,290 cfs (262 m^3/s). Sediment that had accumulated in these stream channels from preceding smaller flows was essentially swept out by this flow (B. N. Aldridge, U.S. Geological Survey, Tucson, oral commun., 1981). Both Pantano Wash and Rillito Creek apparently adjusted to the flow by lowering their streambeds rather than widening their channels. The relatively small reductions, however, in the mean and median widths of Pantano Wash -- 13 and 9 percent, respectively, between 1967 and 1974 -- suggest that the narrowing trend of this channel, noted since 1941, may have been temporarily offset by this particular flow. It is likely that similar channel adjustments occurred during other peak flows of this period, as during the 6,280-cfs (179-m^3/s) flow in Pantano Wash on July 20, 1970 and the 7,000-cfs (198-m^3/s) flow in Rillito Creek on September 9 of the same year.

In contrast, profiles of Tanque Verde Creek from Pantano Road to Sabino Canyon Road do not exhibit as clear a trend in streambed behavior (Figure 25), even though the streamflow record for Tanque Verde Creek parallels those of Rillito Creek and Pantano Wash for this period, particularly in 1970 and 1971 (Figures 15b, 16b, and 17b). Streambed data for 1967 and 1978 indicate only that Tanque Verde Creek spatially alternated between aggradation and degradation.

1974-78

This section covers the behavior of Tanque Verde Creek and Rillito Creek from November 1974 to September 1978. The year 1978 was excluded from the analysis of Pantano Wash when it became evident from the aerial photographs that this stream channel had changed very little between 1978 and 1979. This section, therefore, discusses the behavior of Pantano Wash from November 1974 through 1979.

From 1974 to 1978, outer channel-bank erosion widened much of Tanque Verde Creek without significantly altering its plan-view pattern. Increases in width up to about 180 feet (55 m) were noted at 59 percent of the cross-section locations along this stream channel (Table 7). In reach T3, the channel exhibited local widening of approximately 110 to 130 feet (34 to 40 m) upstream from the Sabino Canyon Road bridge and a shift of about 70 feet (21 m) to the south, downstream from the confluence of Sabino Creek and Tanque Verde Creek (Figure 19d). The channel of reach T5 did not change significantly (Figure 20d).

Rillito Creek primarily narrowed during this period, even though the channel widened locally. Local channel reconstruction and channelization, begun after the 1965 winter flow event, probably continued into 1978 in conjunction with natural channel recovery (Figures 21d and 22d). Rillito Creek also may have downcut because this period includes a portion of the 1967-76 time period, during which the longitudinal profiles displayed degradation (Figure 26).

Annual peak flows in Tanque Verde Creek from 1974 through 1978 ranged from 10 to 3,880 cfs (0.3 to 110 m^3/s; Figure 15b), and those in Rillito Creek varied from 1,440 to 7,500 cfs (41 to 212 m^3/s; Figure 16b). The localized outer-bank scour observed in both stream channels may have been caused by a 3-day winter flow event that peaked on March 2, 1978 at 3,880 cfs (110 m^3/s) in Tanque Verde Creek and 7,500 cfs (212 m^3/s) in Rillito Creek. This flow occurred during a period of severe flooding in Arizona that extended from October 1977 to February 1980 (B. N. Aldridge, U.S. Geological Survey, Tucson, written commun., 1980).

From 1974 to 1979, Pantano Wash again mainly narrowed, as its mean channel width decreased by about 15 percent, or 50 feet (15 m), and its median width dropped by 10 percent, or 30 feet (9 m; Table 7). Bank erosion widened the channel by 10 to 270 feet (3 to 82 m), however, at about 40 percent of the cross-section locations along its length (see Appendix). Reach P3 displays a maximum decrease in width of approximately 230 feet (70 m), accompanied by a westward shift of the channel beginning roughly in the middle of the reach (Figure 23d).

Low flows of less than 3,200 cfs (91 m^3/s) were recorded in Pantano Wash during this period (Figure 17b), to which the stream channel primarily responded by decreasing its width rather than significantly altering its depth. Between 1976 and 1979, when profile data were obtained, Pàntano Wash locally aggraded as much as 4.5 feet (1.4 m) and degraded as much as 2.5 feet (0.8 m), although at several locations the elevation of the streambed in 1979 nearly equaled that of 1976 (Figure 24). Degradation both upstream and downstream from the Broadway Boulevard bridge continued to endanger the bridge as well as the major utility lines serving the eastern side of Tucson, despite the grouting of the streambed at the bridge site in 1976. The grouting mainly functioned as a local obstruction to flow and was being undermined when the City of Tucson and the U.S. Army Corps of Engineers replaced it in 1979 with a $750,000 concrete drop structure (Figure 30). The present assessment of the structure is that it is vulnerable to being undermined, primarily on its downstream side, by a large flow event or a sustained lesser one (M. E. Zeller, Simons, Li & Associates, oral commun., 1982).

Figure 30. *Concrete drop structure constructed in 1979 in the Pantano Wash channel at the Broadway Boulevard bridge.*

1978-79

Between September 1978 and December 1979, both Tanque Verde Creek and Rillito Creek attained their greatest single-channel widths. Tanque Verde Creek widened up to 190 feet (58 m) at 73 percent of its cross-section locations, resulting in 35 and 37 percent increases in its mean and median channel widths, respectively (Table 7). Both banks of Tanque Verde Creek were eroded, although outer-bend erosion produced the maximum increases in channel width, such as in reaches T3 and T5, where extensive downstream migration of channel bends was accompanied by general channel widening (Figures 19e and 20e). Channel sinuosities increased, such as in the western half of reach T3 adjacent to Sabino Canyon Road, where the wavelength of the channel bends decreased by about 350 feet (107 m; Figure 19e).

Bank erosion along Rillito Creek was even more dramatic than the erosion observed in Tanque Verde Creek during this period (Figures 31 and 32). Increases in channel width ranged from approximately 10 feet to as much as 580 feet (3 to 177 m) at 91 percent of its cross-section locations (see Appendix). The mean width of this stream channel increased by 50 percent, from 190 to 285 feet (58 to 87 m), and its median width also increased by 50 percent, from approximately 180 to 270 feet (55 to 82 m; Table 7).

General channel widening as well as extensive outer-bank erosion are shown in reach

Figure 31. *Erosion of the right bank of Rillito Creek on the downstream side of the Oracle Road bridge during the flow event of December 1978. Photo taken on December 19, 1978 by the U.S. Geological Survey.*

Figure 32. *Emergency rebuilding of the right bank of Rillito Creek at a Tucson Electric Power substation during the flow event of December 1978. Photo taken on December 19, 1978 by the U.S. Geological Survey.*

R9 (Figure 22). A potential hazard exists near Royal Palm Drive, where outer-bank scour brought the southern bank of Rillito Creek to within 230 feet (70 m) of the road. The stream also eroded to the north into an area where active braiding was evident in the 1941 photographs (Figures 22a and 22e). Channel widening was less severe in reach R7, although an increase in channel width of approximately 100 feet (30 m) did occur on the downstream side of Oracle Road. Partial channelization of this reach was effective against further bank erosion near Mohawk Street (Figure 21e).

B. N. Aldridge and T. A. Hale (U.S. Geological Survey, Tucson, written commun., 1980) have documented the series of climatic events that led to the widening of Tanque Verde Creek and Rillito Creek between November 1978 and December 1979. Moist tropical air from the eastern Pacific produced warm, heavy rains in this region from November 23 to 26 and from December 17 to 30, 1978. In conjunction with record low temperatures, the November precipitation reduced soil-infiltration rates by saturating and freezing the ground, particularly at higher elevations. Approximately 5.62 inches (14.3 cm) of precipitation were recorded in November at the Palisades Ranger Station at the headwaters of Sabino Creek. A light snowpack also existed prior to the December rains. Because of the orographic uplift of air, the heaviest precipitation during the December 17-20 period occurred in the mountains, where warm rains melted much of the snow. Snowmelt, plus the antecedent moisture conditions set by the November precipitation, significantly increased the amount of runoff that originated on the north slopes of the Rincon Mountains and south slopes of the Santa Catalina Mountains. On December 18, 1978, tributaries draining these mountains attained their highest peak discharges in many years. Runoff in Sabino Creek, in particular, reached its highest stage since 1933. A peak flow of 12,700 cfs (360 m^3/s), which has a recurrence interval of approximately 22 to 24 years, was recorded in Tanque Verde Creek on this date (Figure 15b). In Rillito Creek this same flow measured 16,400 cfs (464 m^3/s), which corresponds to about a 20-year flow (B. N. Aldridge, U.S. Geological Survey, Tucson, oral commun., 1981; Figure 16b).

The peak flow of March 1978 helped set the stage for the widening of Tanque Verde Creek and Rillito Creek. Two such winter flow events within a 9-month period had never been recorded before in either Rillito Creek or Tanque Verde Creek. The March flow reduced the amount of easily entrained sediment within the stream channels, which increased the tendency of the December flow to erode the banks (Thomas Maddock, Jr., University of Arizona, written commun., 1980). Undercutting of the banks of Rillito Creek caused large blocks to collapse into the channel, where they were disaggregated and swept downstream (Figure 3).

One result of these conditions was a shift in alignment of the Rillito Creek approach to the Southern Pacific Railroad bridge east of Interstate 10 (Figure 33; Plate 1). The bridge was constructed in 1925 perpendicular to flow direction in Rillito Creek. The channel maintained essentially the same alignment until the peak flow of December 18, 1978, when a large bend in the channel directly upstream from the bridge shifted to the west, removed approximately 50 acres of land, and damaged the northern abutment of the bridge (Laursen, 1979). As a result, the channel and bridge are no longer aligned. The river currently tends to flow northward adjacent to the railroad embankment before turning approximately 90 degrees to the west beneath the bridge, which has since been reinforced. Stands of tires have been placed in the channel in an effort to trap sediment and redirect streamflow, and the banks have been riprapped to prevent further bank erosion. The approaches to several other bridges across Rillito Creek were also damaged extensively by this flow event (Federal Emergency Management Agency, 1981).

Between 1976 and 1979, Rillito Creek also experienced aggradation, the majority of which the primary author attributes to the December 1978 flow event. Aggradation occurred along all but 1,800 feet (549 m) of the length of streambed shown in the longitudinal profiles (Figure 26). Maximum aggradation of 7.5 feet (2.3 m) occurred approximately 2,400 feet (732 m) downstream from La Cholla Boulevard. As Rillito Creek widened, therefore, its depth decreased. In the absence of a substantial influx of sediment from the Tanque Verde Creek subwatershed, where the flow originated, Rillito Creek probably widened and became shallower to reduce its sediment transport capacity (after Maddock, 1969).

SUMMARY: Pre-1941 to 1979

Channel change within the Rillito Creek system since 1941 has been characterized by prolonged periods of channel narrowing interrupted by abrupt episodes of bank erosion. Table 7 summarizes the variability of channel width within this stream system from 1941 to 1979, and Figures 15, 16, and 17 illustrate the correlation between changes in channel width and magnitudes of streamflow.

The present cross-sectional channel shapes of the Rillito Creek system have evolved from the late 1800's and early 1900's, when arroyo-cutting prevalent throughout the southwestern United States initiated channel entrenchment. Before 1941, one or more wet years following extended periods of drought produced high-magnitude flows that may have carried large quantities of sediment within this system. The stream channels apparently

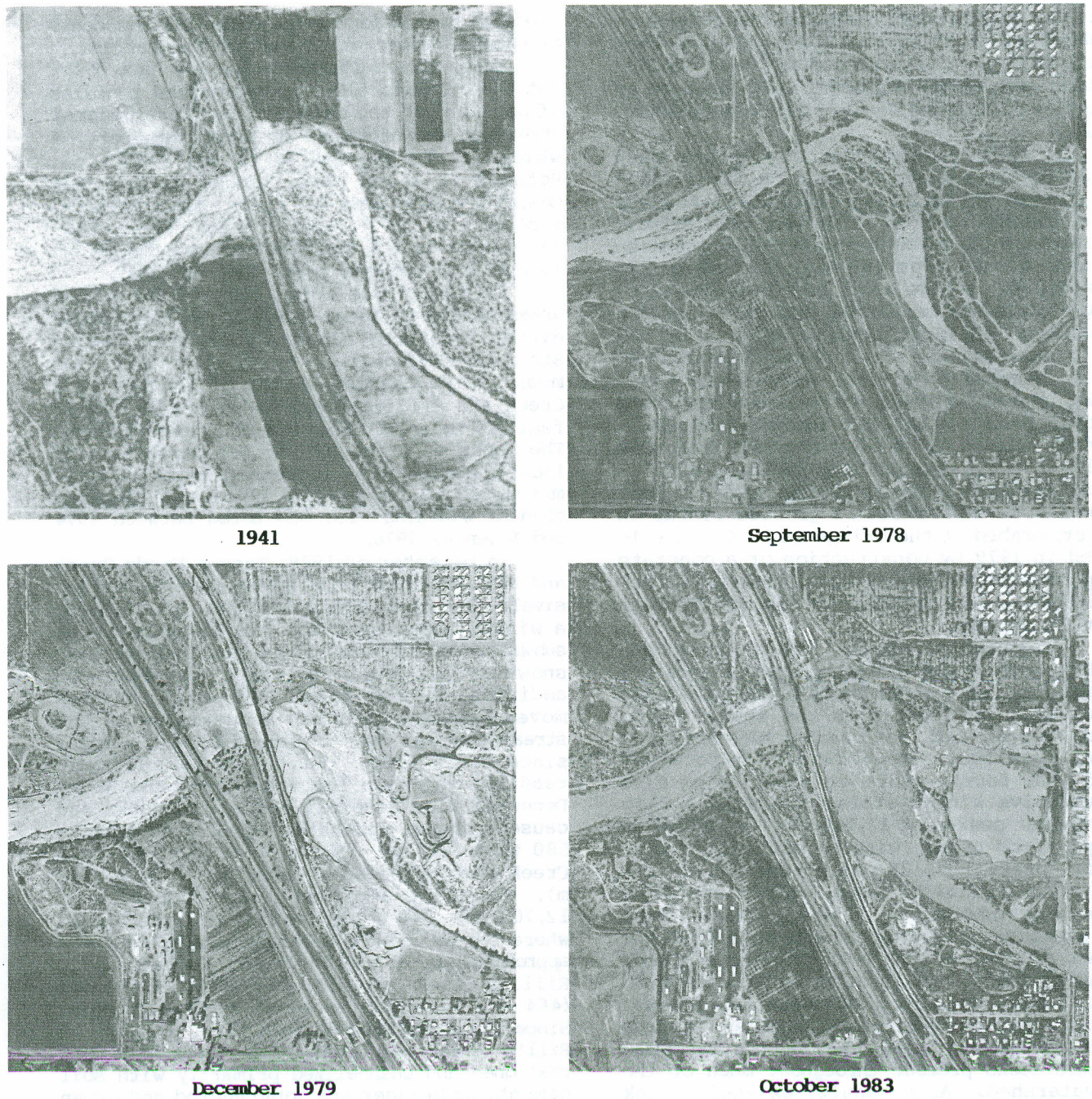


Figure 33. *Widening and realignment of Rillito Creek at its approach to the bridges of the Southern Pacific Railroad and Interstate 10. Changes resulted from the prolonged winter flow event of December 1978. Note that from 1941 until this flow the channel had maintained the same alignment (after Laursen, 1979).*

responded to this influx of runoff and sediment by braiding. In general, the greatest channel widths found in this study were measured from the 1941 aerial photographs, which recorded braided patterns or evidence of former braiding throughout the system.

In the 25-year period from 1941 through 1965, Rillito Creek was dominated by flows of less than 10,000 cfs (283 m^3/s) that occurred in the summer and early fall. These flows were of short duration and probably transported large sediment loads (Thomas Maddock, Jr., University of Arizona, written commun., 1980). Between 1941 and 1963 Rillito Creek narrowed significantly by developing single-channel patterns. Similar behavior by Tanque Verde Creek and Pantano Wash has led to the hypothesis that these channels experienced flows similar to those in Rillito Creek during this time. The general channel narrowing through-

out the system that produced decreases in channel width of up to 870 feet (265 m) suggests that the channels did not have the hydraulic competence necessary to distribute or transport incoming sediment (after Burkham, 1972).

In 1965 the behavior of Pantano Wash began to diverge from that of Rillito Creek and Tanque Verde Creek. From 1963 to late 1979, Pantano Wash steadily narrowed, effecting about a 38-percent reduction in its mean channel width, from 450 feet (137 m) to 280 feet (85 m). Severe local bank erosion, probably produced by meandering low flows and the relatively high peak flows of 1958, 1970, and 1971, accompanied this general narrowing trend. Channel depth also increased dramatically, particularly at the Broadway Boulevard bridge, where a total drop in streambed elevation of 12 feet (3.7 m) was recorded from 1967 to 1976. This degradation has been attributed, at least in part, to the 1970 and 1971 peak flows. Placement of grouted riprap on the streambed at the bridge in 1976 was followed in 1979 by construction of a concrete drop structure, which has effectively restricted vertical movement of the bed upstream from the bridge.

In contrast, Tanque Verde Creek and Rillito Creek widened and narrowed in cyclical fashion, primarily because of prolonged winter flows that originated in the Tanque Verde Creek subwatershed, followed by more frequent, lower magnitude summer flows. In December 1965, the fourth storm in a series of five consecutive winter storms produced a flow event that peaked at 12,200 cfs (346 m^3/s) in Tanque Verde Creek, with an estimated recurrence interval of 22 years, and 12,400 cfs (351 m^3/s) in Rillito Creek, with an estimated recurrence interval of 16 years. Runoff from the storm was augmented by snowmelt from the higher elevations within the mountainous portions of the Tanque Verde Creek subwatershed. It is likely that little sediment was provided to the resulting streamflow, however, because of the relatively impervious igneous and metamorphic rocks present throughout much of the subwatershed. As a result, extensive bank erosion occurred along both stream channels. The largest increases in channel width were produced by erosion of the outer concave banks of channel bends, which migrated downstream.

These stream channels also may have downcut during this flow. Longitudinal profiles of portions of the channels indicate general streambed degradation, at least some part of which may be attributed to the 1965 flow. Between 1954 and 1967, Tanque Verde Creek downcut locally from 1 foot to approximately 7 feet (0.3 to 2.1 m), and Rillito Creek similarly lowered its streambed by as much as 5.5 feet (1.7 m) between March 1960 and 1967.

Following this event, many of the eroded areas of Tanque Verde Creek and Rillito Creek either recovered naturally or were reconstructed artificially. By November 1974, the mean active-channel widths of Tanque Verde Creek and Rillito Creek had decreased by 50 feet (15 m) and 60 feet (18 m), respectively. The banks were eroded locally, however, and local channel widths increased from approximately 10 to 180 feet (3 to 55 m). General channel widening also was noted between 1974 and November 1978.

In December of 1978, Tanque Verde Creek and Rillito Creek once again widened extensively throughout their lengths. As in 1965, a winter storm over the Tanque Verde Creek subwatershed produced streamflow that included snowmelt but probably little sediment. In addition, flow in March 1978 previously removed sediment that had accumulated in the stream channels over a period of time, perhaps since early 1966. With little sediment readily available for transport, the 3-day December flow severely eroded the banks and caused channel widths to increase as much as 580 feet (177 m). The streambed of Rillito Creek also aggraded as much as 7.5 feet (2.3 m). This flow attained a peak discharge of 12,700 cfs (360 m^3/s) in Tanque Verde Creek, where its recurrence interval ranged between approximately 22 and 24 years. Downstream in Rillito Creek, the flow peaked at 16,400 cfs (464 m^3/s), which is about a 20-year flow. Since the occurrence of this flow, portions of Rillito Creek and Tanque Verde Creek have been realigned and channelized primarily with soil cement, as bridges are constructed and urban development continues near the channels.

The October 1983 Flow Event

Between September 28 and October 2, 1983, much of southeastern Arizona was subjected to pronounced rainfall from a surge of tropical moisture moving northeastward from the coast of Baja California. The persistence of this storm for several days produced total rainfall of 6.7 inches (170 mm) to 10.5 inches (267 mm) in the Tucson basin. Persistent heavy rains were especially pronounced during the morning hours of October 1 and 2. Some overbank flooding from this storm occurred at two locations along Rillito Creek and along the upper reaches of Tanque Verde Creek. Runoff was primarily contained within the channels of the Rillito Creek system, however, which responded with spectacular channel changes and pronounced channel-bank erosion. The October 1983 event, therefore, cannot be classified as a flood as defined in this paper, but as a major flow event along most of the Rillito Creek system.

The general effects of the October 1983 event are documented for the entire Tucson basin by Baker (1984), Peirce and Kresan (1984), and Saarinen and others (1984). The description that follows will emphasize the detailed effects in the Rillito Creek system.

NATURE OF THE RAINSTORM

The flow event of October 1983 was produced by a complex of tropical air-mass interactions. Figure 34 shows a standard National Weather Service "500-millibar analysis" of conditions prevailing at the time of the storm. Note that the contours indicate an immense trough elongated northwestward from a low-pressure cell off the California coast. Not shown, just off the southwest corner of the map, was tropical storm Octave. Winds from the southwest were blowing from the vicinity of Octave inland across Arizona.

Precipitation in Tucson began with light rain at 5:00 p.m. on Wednesday, September 28 (Figure 35). Heavier rains followed from noon on September 29 until early September 30. A pattern of embedded waves developed around the low-pressure trough noted above (Figure 34). As these waves rotated around the trough from the southwest to the northeast, they funneled moisture from tropical storm Octave across southern Arizona in the form of northeastward-streaming cloud systems. Heavy rains began in the early morning of Saturday, October 1 (Figure 35), and the wavelike rainfall pattern remained strong through Sunday, October 2.

It is important to realize that many aspects of this rainstorm were not unusual in southern Arizona. The short-duration precipitation intensities reached 0.5 inch/hour, but this rate is much lower than those of many summer thunderstorms. Even the long-term intensities, for 12 and 24 hours, were no rarer than the 10- and 25-year return-period events; i.e., such rainfalls have a 10-percent

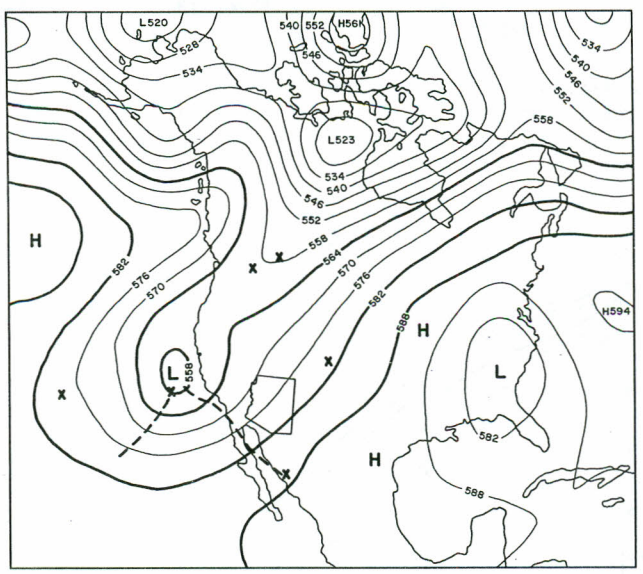


Figure 34. *Map showing height contours (in decimeters) on the 500-millibar atmospheric pressure surface for Friday evening, September 30, 1983. Areas of high (H) and low (L) pressure are indicated. Embedded short waves around a "cutoff low" are shown by dashed lines. From Saarinen and others (1984).*

and 4-percent chance, respectively, of occurring in any given year (Figure 36). Tucson can reasonably expect to have similar rainfall intensities in the near future.

The 1983 rainstorm did involve a remarkably large area of southern Arizona (Figure 37). Much of the precipitation was orographic. As the persistent northeastward flow of wet, tropical air encountered southwestern-facing mountain slopes, it was lifted. Maximum rainfall was recorded on those slopes and on the mountain summits, such as Mount Lemmon in the Santa Catalina Mountains and in the White Mountains of central Arizona.

Runoff from the 1983 rainstorm was enhanced by several factors. August and Septem-

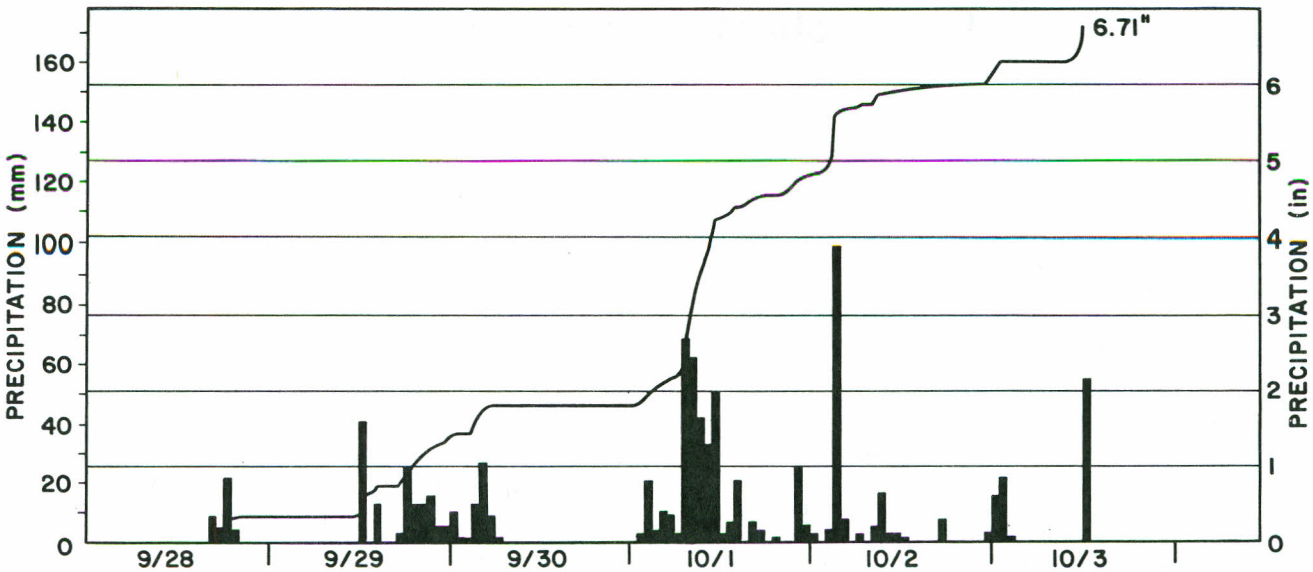


Figure 35. Rainfall recorded at the Tucson National Weather Service office from September 28 through October 3, 1983. The bars indicate hourly totals, and the solid line indicates the cumulative total. Total rainfall was 170.4 mm (6.71 inches). From Saarinen and others (1984).

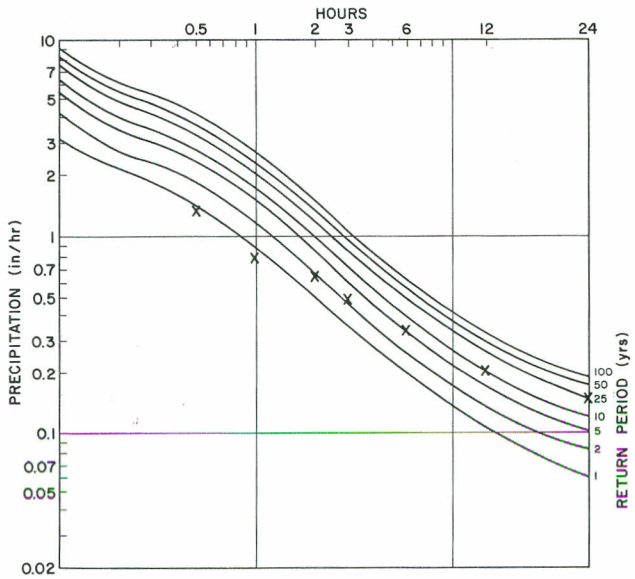


Figure 36. Plot showing the return periods expected for various combinations of rainfall intensity (inches/hour) versus duration (hours). The plotted data show values recorded in the October 1983 storm. From Saarinen and others (1984).

ber had been unusually wet months before the storm. Moreover, the persistent pattern of embedded waves prolonged the storm period and lead to a tremendous areal extent of storm activity. Nevertheless, prolonged surges of tropical air from the eastern Pacific Ocean are occasional events in northwestern Mexico and the southwestern United States, especially in late summer and early fall. These surges affect different regions in different years, depending on the meteorological conditions prevailing at the time.

As with storm conditions thought capable of producing maximum precipitation in southern Arizona (Hansen and Schwartz, 1981), the 1983 event involved significant antecedent moisture accumulation, the development of a midlatitude cold trough to move tropical air in a southwest-to-northeast direction, and the development of high sea-surface temperatures off the west coast of Baja California. Unlike the idealized "super storm," however, the 1983 event did not involve slow movement of a tropical cyclone through the Gulf of California and into southern Arizona. Tropical storm Octave contributed only to the regional moisture-flow pattern and never directly participated in the event.

The climatological evidence is clear on this point: southern Arizona could experience much more severe rainstorm conditions than those it weathered in 1983.

HYDROLOGY

Peak discharges for the Rillito Creek system have been provisionally estimated for several localities (H. W. Hjalmarson, U.S. Geological Survey, oral commun., 1983). These estimates are considered provisional because of the extensive bank erosion that changed many channel cross sections. Nevertheless, postflow hydraulic calculations at several bridge sites are considered accurate and serve as the basis for conclusions concerning flow frequency.

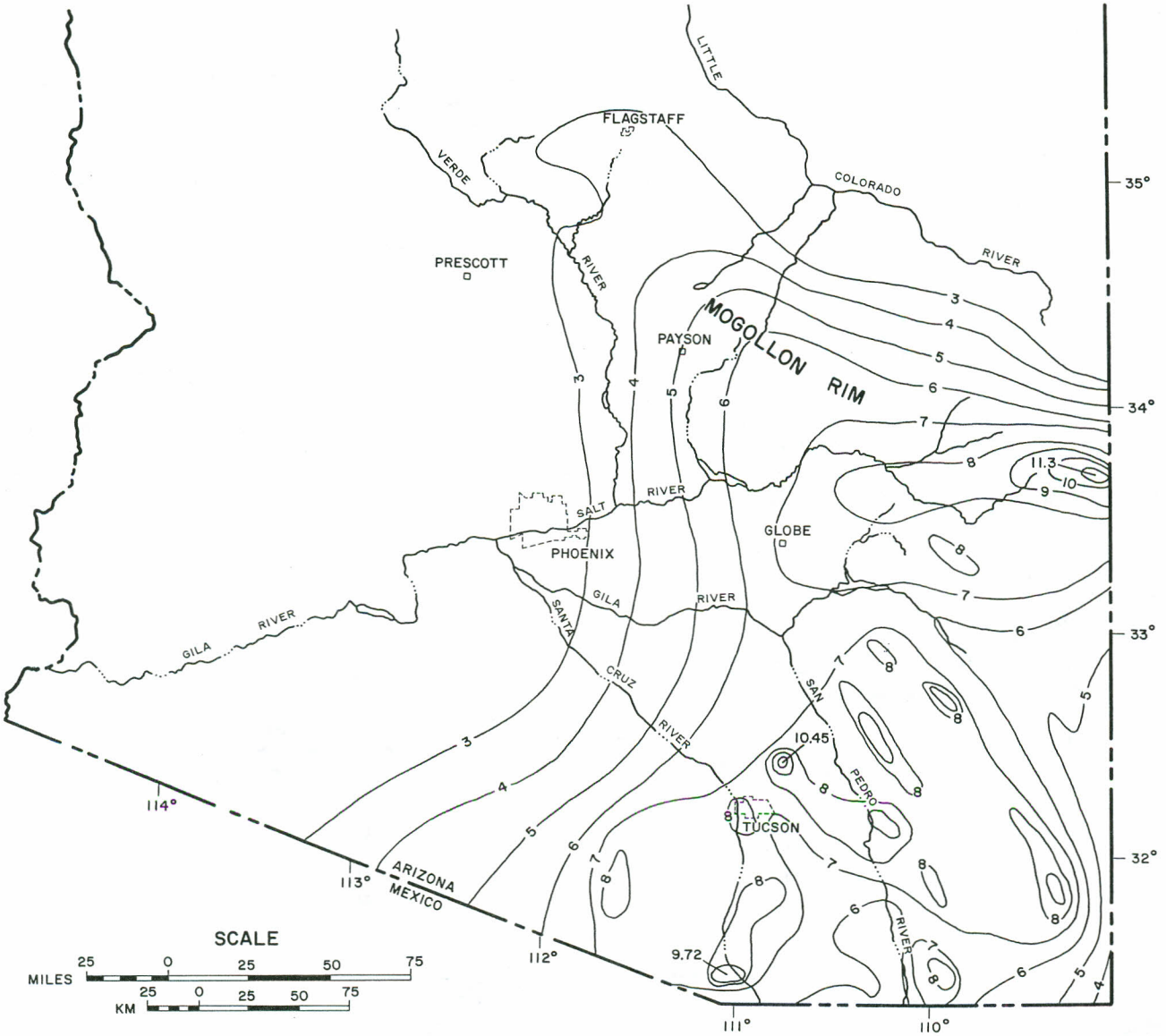


Figure 37. *Isoheyetal map of rainfall in southeastern Arizona for the period September 27 to October 3, 1983. From Saarinen and others (1984).*

The peak flow on Rillito Creek at the Flowing Wells bridge is estimated to have reached 29,700 cfs (840 m^3/s) on October 1, 1983 (Figures 16 and 38). This value is close to the 100-year-flood discharge determined in the Federal Emergency Management Agency (FEMA) Flood Insurance Study for Pima County (Federal Emergency Management Agency, 1982). In contrast, Pantano Wash at Broadway Boulevard

Figure 38. *View upstream (east) from the Campbell Avenue bridge on October 1, 1983, showing erosion of the northern (left) bank by meander flow. Note the dark thread of high-velocity water following the meander thalweg from the next bend upstream. Also note the utility lines in the stream channel. Photo by Peter L. Kresan.* ©

achieved a peak flow of 11,000 cfs (310 m^3/s). This flow rate lies between the FEMA-determined 10-year discharge of 9,000 cfs (250 m^3/s) and the 25-year discharge of 14,000 cfs (400 m^3/s). The record flow of Pantano Wash at Broadway Boulevard was 20,000 cfs (570 m^3/s) in 1958. Flow in Tanque Verde Creek peaked at 8,300 cfs (235 m^3/s) in October 1983, which is approximately a 10-year event.

EROSION

The erosional effects of the 1983 flow event were assessed by systematic observations made along the Rillito Creek system. Because noncontinuous bank protection was found to be a major factor in localizing bank erosion, a separate section is devoted to that issue.

The large drop structure at Broadway Boulevard separates Pantano Wash into an incised reach downstream, to the north of Broadway, and a less incised reach upstream, to the south of Broadway (Figures 39 and 40). Channel-bank erosion from the 1983 event was generally minimal upstream from the drop structure; however, a prominent meander bend at the Rincon Country mobile-home development produced significant damage through lateral channel migration (Figures 41 and 42). Bank erosion also occurred at a sand pit north of Golf Links Road.

Downstream from the Broadway drop structure, Pantano Wash responded to the 1983 event by an alternating pattern of bank erosion (Figure 39). Local areas of bank protection consisting of riprap and wire-fence revetments concentrated erosion at unprotected banks. At the downstream end of revetments around Tanque Verde Road bridge, a major zone of bank recession caused the loss of residential property.

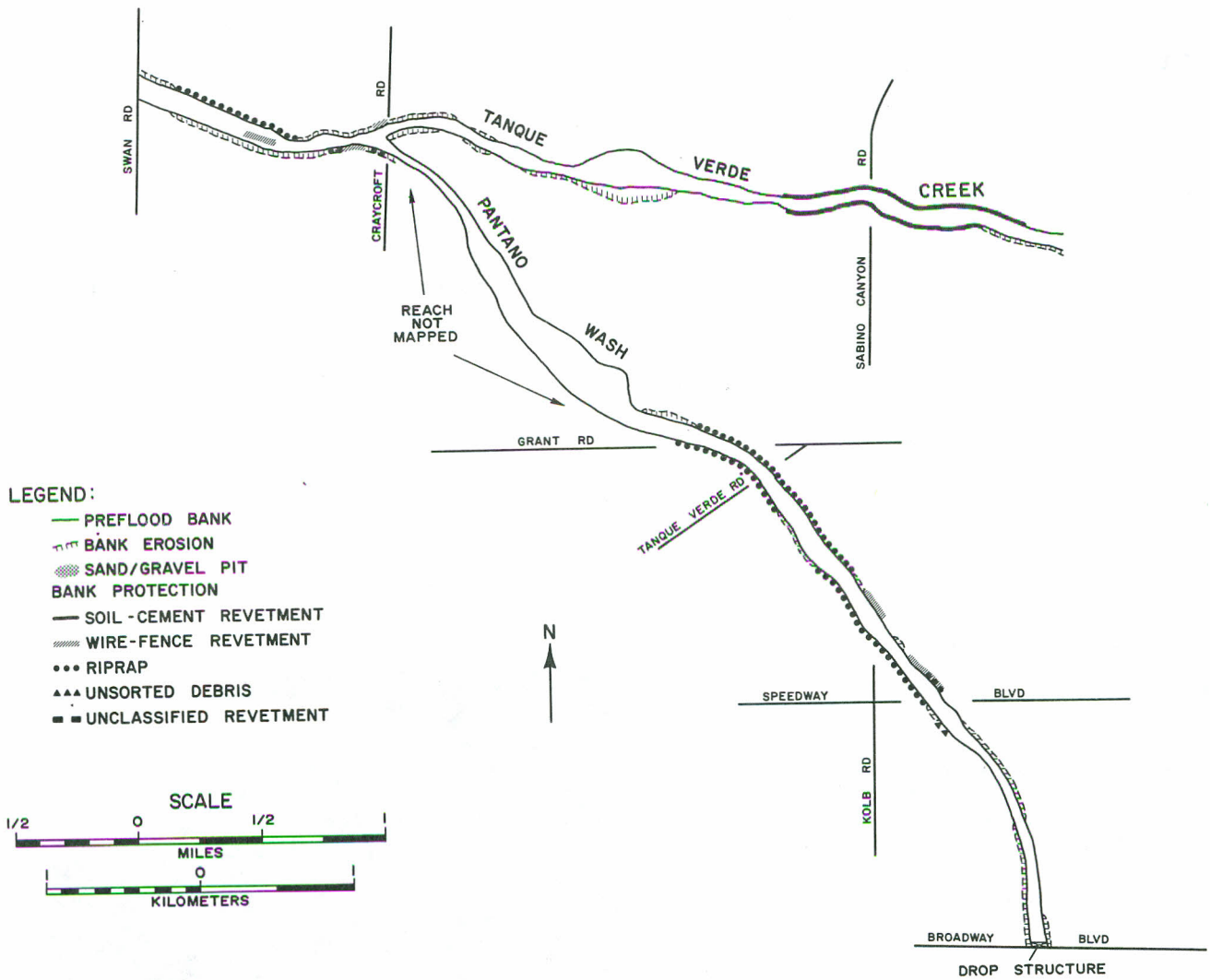


Figure 39. *Map of Tanque Verde Creek downstream from Sabino Canyon Road, Pantano Wash downstream from Broadway Boulevard, and Rillito Creek between Swan and Craycroft Roads. Note the classification of bank protection and the pattern of observed bank erosion. Mapped immediately after the flow event of October 1983.*

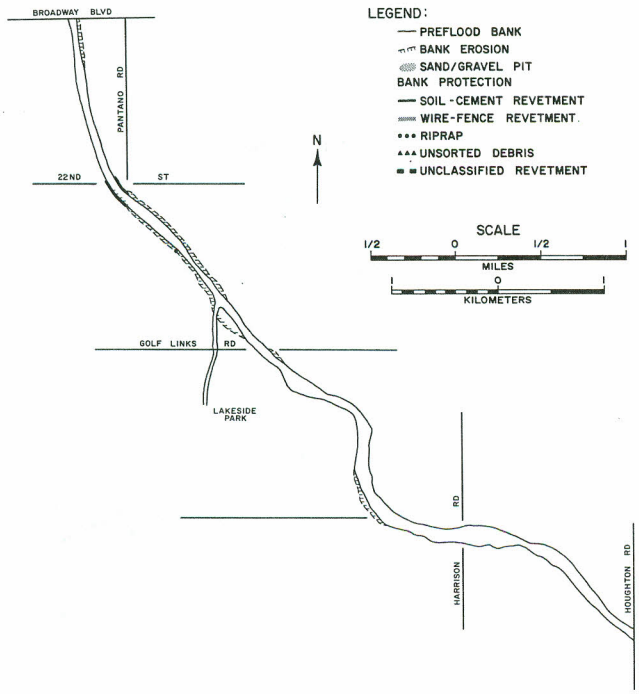


Figure 40. *Map of the 1983 flow effects on Pantano Wash upstream from Broadway Boulevard.*

Figure 41. *Aerial view of the eastern Tucson basin on October 9, 1983, showing Pantano Wash in the foreground and the Santa Catalina Mountains on the skyline. Flow damage to the Rincon Country mobile-home development (bottom center) is shown in Figure 42. Photo by Peter L. Kresan.* ©

The upper reaches of Tanque Verde Creek, as well as upper Pantano Wash, showed much less erosion in 1983 than did entrenched reaches of Rillito Creek and the Santa Cruz River. Banks were sufficiently low that overbank flooding occurred at the Forty-Niners Country Club Estates adjacent to Tanque Verde Creek. As in the past, major bank erosion occurred at the confluence of Sabino Creek and Tanque Verde Creek because of (1) the angle of the stream juncture, which directed flows at an unprotected bank, and (2) changes in the influx of sediment and transport characteristics as the two flows mixed. The second factor probably also explains the increased erosion that occurred immediately downstream from the confluence of Tanque Verde Creek and Pantano Wash.

Rillito Creek from Craycroft Road to the Santa Cruz River is an entrenched system. It responded to the 1983 event by pronounced channel-bank erosion following a pattern of meander bends, as allowed by localized bank protection (Figure 43). From Swan Road to Dodge Boulevard this erosion occurred in a reach that had little bank protection. A major channel bend at Prince Road resulted in migration of a meander cutbank that undermined several homes and townhouses. The bridges at Campbell Avenue and First Avenue suffered

Figure 42. *Pantano Wash at the Rincon mobile-home development (top right) on October 9, 1983. Escalante Road (top) runs east-west. The prominent bend of Pantano Wash (top center) undermined several mobile homes, which can be seen in the channel (bottom center). Several automobiles were also incorporated into the northward flow of Pantano Wash. A ground view of the channel at this location is shown in Figure 48. Photo by Peter L. Kresan.* ©

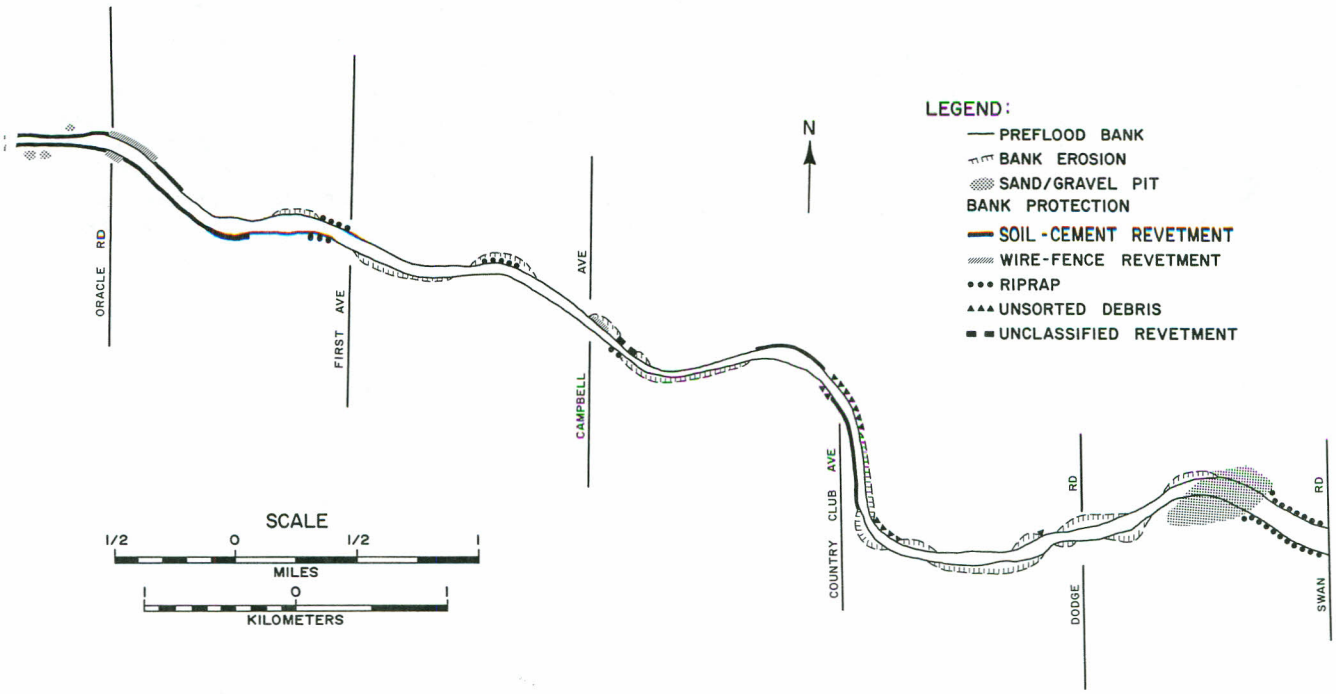


Figure 43. *Map showing the distribution of October 1983 erosion effects along Rillito Creek between Swan Road and Oracle Road.*

erosion of their northern abutments by meander migration. Many of these effects repeated the results of the 1965 and 1978 flow events. Downstream from Oracle Road, Rillito Creek showed a pattern of meander migration constrained by existing bank protection (Figure 44).

DAMAGE

Building damage caused by the October 1983 flow event was predominantly the result of undermining of foundations by channel-bank recession. An office complex immediately southeast of the First Avenue bridge was undermined by the migration of a meander bend upstream from that bridge (Figure 45). Collapse of the structure progressed as flows eroded unprotected banks (Figure 46). Pima Park Townhomes were undermined despite protection by a soil-cement revetment (Figure 47). Although the damage can be traced to improper extension (keying) of that revetment into adjacent land, the experience shows that even the best type of bank protection will not necessarily control the hazard completely. Mobile homes and vehicles can be added to the streamflow either through undermining of the banks beneath them (Figure 48) or by floating in overbank flows. In a major flow event, this debris can pose a hazard by blocking narrow channel reaches such as bridge underpasses.

Bridge failures along Rillito Creek occurred at Swan Road, Dodge Boulevard, Campbell Avenue, and First Avenue. In each case, failure occurred because one abutment was eroded by the migration of a meander bend (Figure 49). Careful study of the 1983 erosion maps (Figures 39, 40, 43, and 44) reveals a systematic pattern of erosion at meander bends, much of it directed or otherwise facilitated by existing localized bank protection. Eroded bridge abutments left breaches in the roadways that closed many highways during and after the flow.

Power lines along Rillito Creek were also severely damaged. Power-line poles near channel banks were toppled when bank recession undermined their support pads. Other poles and towers had deep footings in bed or bank materials that were exhumed by channel-bed scour, causing some towers to topple and others to be severely imperiled by subsequent flows.

One hundred meters west of the Dodge Boulevard bridge, a Tucson Electric Power station was threatened by 50 to 80 feet (15 to 25 m) of bank recession along Rillito Creek (Figure 50) in a repeat occurrence of the 1978 bank erosion shown in Figure 32. Fortunately, as shown in Figure 50, bank erosion ceased before structures at the power station were undermined.

FACTORS IN CHANNEL STABILITY

Surveys of channel-bank erosion following the October 1983 flow event (Figures 39, 40, 43, and 44) show that unprotected banks along

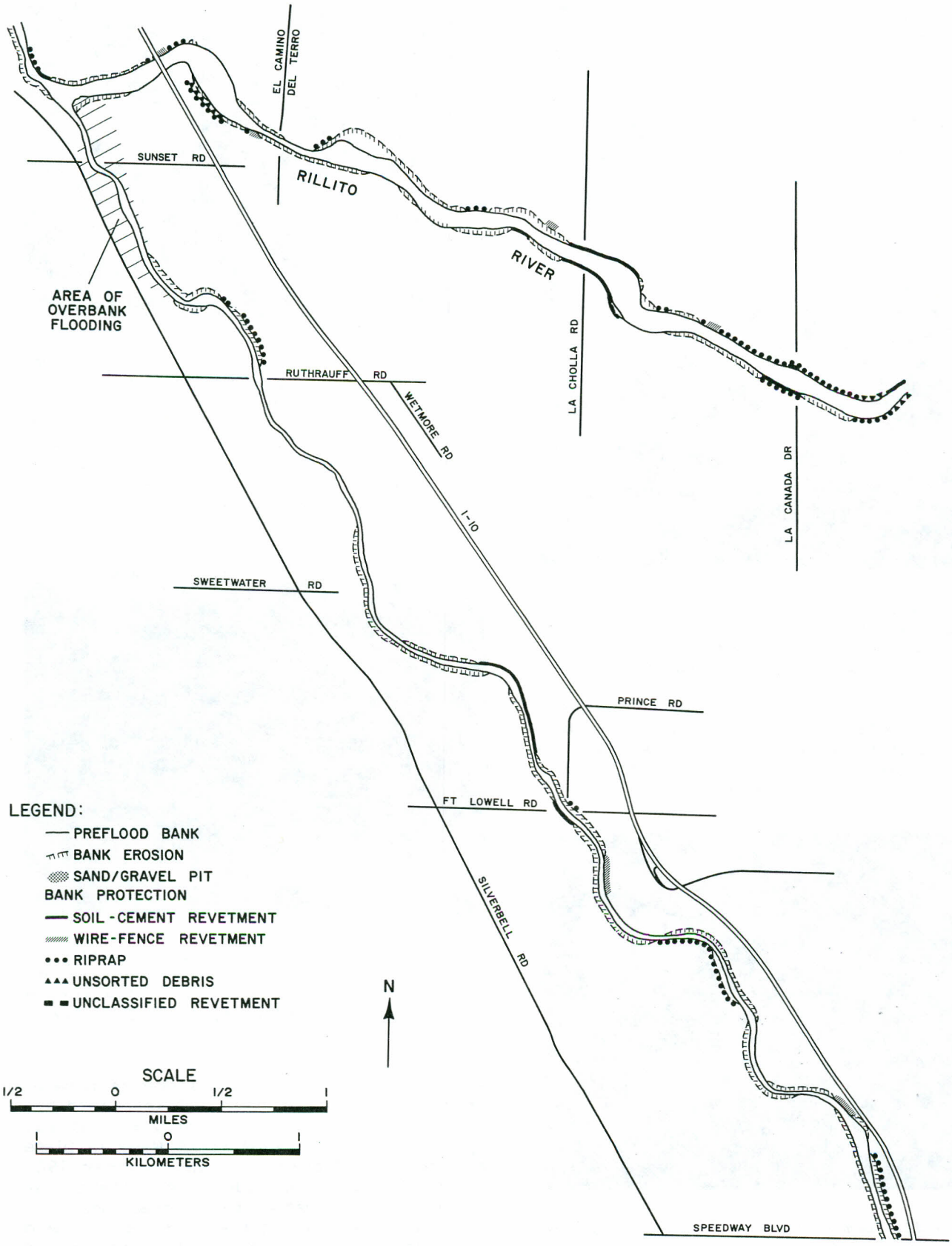


Figure 44. *Map showing the distribution of October 1983 erosion effects along Rillito Creek near its junction with the Santa Cruz River.*

Figure 45. *Rillito Creek at the First Avenue bridge on October 9, 1983, showing meander migration on the southern (left) bank, which undermined the office building complex (top left). The return flow to the opposite bank (top right) damaged the northern (right) abutment of the bridge. Temporary repair had been effected at the time of this photograph. Figure 46 shows damage to the office buildings. Photo by Peter L. Kresan. ©*

Figure 46. *Damage to an office-building complex caused by the undermining of the bank of Rillito Creek at First Avenue. An aerial view of this site is provided in Figure 45. Photo by Tad Nichols.*

Figure 47. *View downstream (northwest) along Rillito Creek from the terminus of Prince Road (bottom left) on October 8, 1983. Compare this picture with the aerial view that includes the same reach (Figure 52). The house (left foreground) toppled into the active meander cut slope. Damage to Pima Park Townhomes is also visible (right background). Photo by Thomas F. Saarinen.*

Figure 48. *Flow debris in Pantano Wash from the Rincon Country mobile-home development, late October 1983. The view is downstream (north). See also Figure 42. Photo by Peter L. Kresan. ©*

the Rillito Creek system suffered phenomenal erosion during this event. This hazard had been recognized for many years, and several types of bank-protective works were in place at the time (Table 8). The October 1983 event, therefore, provided an excellent test of the effectiveness of this protection.

The experience of the 1983 event showed that bank erosion was the most severe hazard encountered on the incised sections of stream channels throughout the Tucson basin. To assess bank protection as a factor in reducing

Table 8. *Types of stream-bank protection observed in watercourses of the Tucson basin (from Saarinen and others, 1984).*

Type of Protection	Description
Soil-cement revetment	Embankment facing composed of 8 to 15 percent portland cement mixed with natural bank material. Soil is removed, mixed with cement, and laid on the prepared bank surface in thin layers. The revetment extends to below the level of channel scour and is keyed into the banks at the upstream and downstream termini.
Wire-fence revetment	Wire enclosures held by vertical steel members (often rails) and filled with boulders. A variety of this revetment consists of wire baskets of rock called gabions.
Riprap	A blanket of boulders that exceed the competence of the largest flood flows. The material is used as facing for the bank.
Unsorted debris	Any material dumped directly on stream banks to prevent erosion. Commonly used materials are automobile bodies, concrete blocks, demolition waste, crushed rock, poured concrete, and rubbish.

this hazard, two questions must be asked: (1) What was the engineering performance of different bank-protection designs, i.e., which designs effectively prevented bank erosion? (2) What was the overall effect of bank protection on the fluvial system? Both questions must be addressed because local bank protection may meet the needs of some individuals by protecting their property, but comprehensive bank protection may be required for the entire stream system.

Since 1974 the design of bank-protective works in Pima County has required the approval of the Pima County Department of Transportation and Flood Control District. Nonstandard protective works, including rail, wire, and rock revetments and cable-tied automobile bodies, probably predate 1974 in most cases.

Revetments of riprap and unsorted debris suffered extensive damage during the 1983

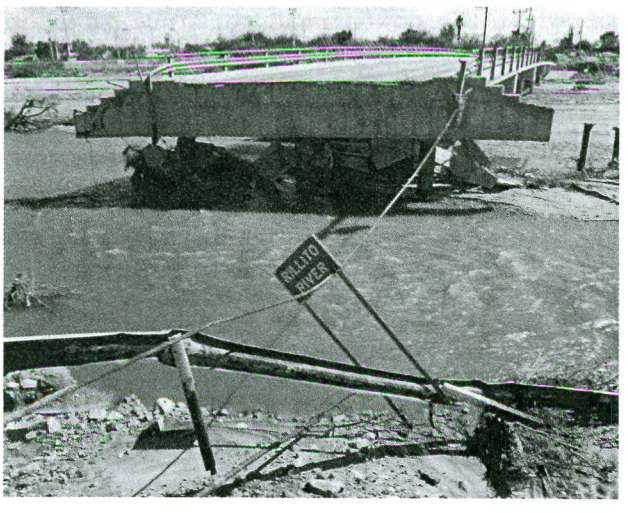


Figure 49. *Rillito Creek at Dodge Boulevard on October 5, 1983, showing the erosion of the northern bridge abutment. Photo by Peter L. Kresan.* ©

Figure 50. *The Dodge Boulevard bridge over Rillito Creek on October 9, 1983. Damage to the northern (left) abutment was caused by meander migration. Note the prominent cutbank on the northern (left) side and the corresponding point bar on the southern (right) side of the stream. The meander bend immediately downstream (bottom right) threatened an electric utility station. The anomalously wide section of channel (top center) was the site of a former sand-and-gravel operation. Photo by Peter L. Kresan.* ©

event. Streambed scour occurred at the junction between the riprap and the unprotected beds. Rocks fell into the scour holes and were either transported downstream or buried in scour holes that developed downstream from individual riprap clasts. Nearly all bank areas protected by riprap showed at least some undercutting and bank recession.

Unlike the unconfined riprap, wire-fence revetments were generally not destroyed by scour; rather, progressive erosion at the upstream or downstream end of the revetment occurred behind the protected bank. In extreme cases, the revetment became isolated in midchannel as the bank receded away from it (Figure 51).

Soil-cement revetments were mostly undamaged, although prominent bank erosion occurred immediately downstream from the protection. Where local failure did occur, the major cause

Figure 51. *Erosion of bank protected by wire-fence revetment along Rillito Creek at Craycroft Road, October 19, 1983. Photo by Thomas F. Saarinen.*

Figure 52. *Rillito Creek near Prince Road (bottom left) on October 8, 1983. Damage to Pima Park Townhomes (center) occurred when the prominent meander bend (bottom center) migrated west (left) into the vacant property immediately upstream from the townhouses. This allowed erosion to occur behind the soil-cement bank protection lining the stream at the property. The prominent point bar (bottom center) developed as the meander migrated westward. Photo by Victor R. Baker.*

Figure 53. *Soil-cement revetment works lining both banks of Tanque Verde Creek immediately east of the Sabino Canyon Road bridge (top left), October 8, 1983. Photo by Victor R. Baker.*

was inadequate keying of the soil cement to the upstream or downstream terminus of the protection. At Prince Road and Rillito Creek, a prominent meander bend caused the flow to scour behind the upstream end of a soil-cement revetment, resulting in major damage to a complex of townhouses (Figure 52).

An example of a properly keyed revetment is the protection for the southeastern abutment of the Sabino Canyon Road bridge over Tanque Verde Creek (Figure 53). The pronounced channel widening upstream from the revetment terminates abruptly at this key.

Major bank erosion occurred immediately downstream from reaches that had been extensively protected with soil cement on both banks. The postflow surveys (Figures 39, 40, 43, and 44) showed that severe erosion occurred at the downstream terminus of every soil-cement protection along deeply incised reaches of the Santa Cruz River and Rillito Creek (Baker, 1984). Because localized protective works clearly concentrate areas of bank erosion as well as protect banks, these erosive consequences should be considered in the overall management of the river system.

The necessity of protecting bridges from loss during flow events unavoidably generates a need for localized bank protection. As observed in the 1983 event, the loss of a bridge most often occurs by bank recession at one abutment (Figures 45, 49, and 50). This recession is generally associated with meander migration during flow. To protect bridge abutments, a reach both upstream and downstream from the bridge must be lined with bank protection. The natural tendency of the stream to widen its channel and incorporate added sediment load is thus impeded in the bridge reach. The stream will therefore attempt to scour the streambed at the bridge

section, leading to failure by undermining the bridge piers. If degradation-control structures are placed on the bed to prevent scour, the bridge reach is transformed into a rigid-walled flume. High-velocity, sediment-impoverished flow passing through the protected bridge reach will be erosive in the reach immediately downstream. As in other examples, given several flow events, partial bank protection will beget the need for more bank protection.

Additional Factors Related to Channel Change

CHANNEL-BANK COMPOSITION

Past bank erosion of Tanque Verde Creek and Rillito Creek appears to be related to local bank composition, defined here in terms of silt-clay content. Higher erosional velocities are usually required to move silt and clay than sand because the former particles are bound together by strong cohesive forces and produce a smooth bank (Morisawa, 1968). Banks that contain large percentages of silt and clay thus tend to be less erodible than those with a high sand content.

Although channel banks within the Rillito Creek system were sampled in 1980, sampling of the natural banks, rather than banks that have been artificially covered with fill material, may allow extrapolation of bank composition into the past. Since 1941 no appreciable bank erosion has occurred at the sample sites along Tanque Verde Creek where both banks contain greater than approximately 17 percent silt-clay (Table 3). Banks of low silt-clay and high sand content, however, have undergone substantial erosion. For example, from 1974 to 1978 the left bank of site T.D., which is in a fairly straight reach and contains only about 16 percent silt-clay, was eroded approximately 50 feet (16 m; Plate 1). The right bank at this site occupies a position similar to that of the left bank, but contains 45 percent silt-clay and has not been eroded since 1963.

Extensive erosion of the right bank of site T.E. from 1978 to 1979 has also been documented (Figure 20e; Plate 1). The silt-clay content of the bank at this site is only about 5 percent (Table 3). In contrast, minimal erosion has occurred at the left bank, which contains about 44 percent silt-clay. The position of this bank on an inner bend of the channel probably protected it even further.

Magnitudes and locations of past bank erosion along Rillito Creek also appear to have been influenced by bank composition. From 1963 to 1967 excessive widening occurred at sites R.C., R.E., and R.G., where the width of the channel increased by 190 feet (58 m), 140 feet (43 m), and 230 feet (70 m), respectively (Plate 1). The banks at these three sites contain the lowest percentages of silt-clay of the seven sample sites along Rillito Creek (Table 4). At the remaining four sites, the channel exhibited the following behavior during the same period: site R.A. narrowed by 20 feet (6 m) and sites R.B., R.D., and R.F. widened by less than 20 feet (6 m). Both banks at these four sites generally contain greater than 16 percent silt-clay. This bank composition appears to have prevented only the excessive local bank erosion noted elsewhere along this stream channel and not the general channel widening that occurred during the 1963-67 and 1978-79 periods. In summary, bank erosion along the Rillito Creek system appears to be related to bank composition, although such factors as density of riparian vegetation and bank position with respect to plan-view pattern are also important.

Tanque Verde Creek and Rillito Creek have also demonstrated a tendency to widen until their banks intersect former bank positions. After a widening event, new channel banks are formed by the natural processes of bar formation and maturation or by the placement of fill over the banks of the eroded channel. In general, the materials of the more recent banks are believed to be less consolidated than those of the former banks, which were probably carved from older sediments. When subject to extensive erosion, banks of the narrower, more recent channel have often migrated to positions held by former banks, where materials are presumably more consolidated. Both Tanque Verde Creek and Rillito Creek have behaved in this manner since 1941.

EFFECTS OF SAND-AND-GRAVEL OPERATIONS ON CHANNEL MORPHOLOGY

The removal of large volumes of sand and gravel from the bed of an active stream channel is believed to have a significant effect on channel morphology. How sand-and-gravel operations influence channel change is not well understood and is a topic that is outside the scope of this study; however, an attempt will be made here to illustrate several possible effects of such operations on the Rillito Creek system.

Sand-and-gravel operations supply high-quality aggregate from mainly unconsolidated stream-channel deposits dominated by sand and gravel (Bull and Scott, 1974; Moore and others, 1974). Shallow pits form the primary method of excavation in the Tucson area. According to a map of construction materials in the Tucson area (Moore and others, 1974), in 1974 there were 7 sand-and-gravel operations along Rillito Creek and 11 within the channel of Pantano Wash or its geologic flood plain.

Thirteen operators are currently active along Pantano Wash, 9 of which involve inchannel mining (Terry Hendricks, Pima County Department of Transportation and Flood Control District, oral comm., 1986). None are currently operative along Rillito Creek and Tanque Verde Creek.

A common stream-channel response to this removal of material is a general lowering of the streambed upstream from a pit due to headcutting (Bull and Scott, 1974). Bank sloughing may also be initiated with the headcutting, as channel deepening renders the banks more susceptible to erosion (Bull and Scott, 1974; Simons, Li & Associates, 1981). Bank erosion also arises downstream from an operation when a sand-and-gravel pit traps enough sediment to impoverish downstream flow significantly. This effect may have occurred downstream from a large abandoned sand-and-gravel pit in Rillito Creek midway between Swan Road and Dodge Boulevard. The pronounced meander-bend erosion downstream from this point, including the erosion of the northern abutment of the Dodge Boulevard bridge, may be related to this pit (Figure 50). Bank erosion near a pit may also be created by temporary structures designed to direct flow around the operation.

Channel Degradation

Bull and Scott (1974) have studied variations in streambed elevation that may be related to sand-and-gravel mining. A study was conducted in 1973 at the Campbell Avenue bridge, which crosses Rillito Creek (see Plate 1 for bridge location). Between February 16 and May 22, 1973, the streambed dropped an average of 0.5 foot (0.15 m) in between six of the bridge piers. At that time, gravel was being mined 300 to 800 feet (90 to 240 m) downstream from the bridge.

Sand-and-gravel extraction from Pantano Wash downstream from the Broadway Boulevard bridge may have played a role in the 12 feet (3.7 m) of downcutting that required grouting of the streambed in 1976 and construction of the concrete drop structure in 1979. The 1967 and 1974 aerial photographs indicate that sand and gravel were being mined in those years at three locations within the channel downstream from Broadway Boulevard. One operation was only about 0.8 mile (1.3 km) north of the bridge.

Long-term general degradation of Tanque Verde Creek near its confluence with Sabino Creek has been directly linked to the extraction of material in this area. Exposure and subsequent rupture of a sewer line that crossed Tanque Verde Creek along the Pantano Road alignment were held by the Honorable Robert J. Hooker to have been caused by this sand-and-gravel extraction (Minutes of Entry, the Superior Court of the State of Arizona, Consolidated No. 182298 and 185856, June 2, 1981).

Bank Erosion

Local channel-bank erosion has often been linked to the extraction of sand and gravel when the former has occurred near a sand-and-gravel operation. The following account from the January 11, 1979 issue of The Arizona Daily Star illustrates this tendency and also the general confusion that frequently surrounds this issue:

> The recent heavy runoff in the Tanque Verde area has widened banks and shortened tempers among residents who lost property to the waters.
>
> Some residents along the north bank of the Tanque Verde Wash blame a sand and gravel operation on the other side for altering the channel by causing the flow of water to hit their property more forcefully and carry away the bank.
>
> ...Mike Zeller of the County Flood Control District said...the heavy erosion was caused by the biggest runoff since December 1965, and that much of the bank walls had become unstable in that time.

The sand-and-gravel operation mentioned in this account became involved in litigation. The permit previously obtained from the Pima County Department of Transportation and Flood Control District to extract sand and gravel from the active channel of Tanque Verde Creek was eventually revoked by the Superior Court of the State of Arizona primarily because of the diversion and impedance of flow in Tanque Verde Creek (Minutes of Entry, The Superior Court of the State of Arizona, Consolidated No. 182298 and 185856, June 1, 1981). The Findings of Fact listed by Judge Hooker in the reference cited above includes the following statement: "Some of the short term adverse effects of plaintiffs' sand and gravel operations within the Tanque Verde and Sabino River system are back scour, lateral hole migration and a phenomenon known as sediment trap, which increases the downstream erosive effects of the river." Also noted in the Findings of Fact was a change in position of the north bank of Tanque Verde Creek relative to a major trunk-line sewer carrying about 2 1/4 million gallons of sewage a day. Before December 1978, this sewer line was about 100 feet (30 m) from the bank. By 1980-81, only about 10 to 15 feet (3 to 5 m) of land lay between the sewer line and Tanque Verde Creek.

In summary, although impacts of sand-and-gravel mining on channel morphology are not well understood, evidence suggests that sand-and-gravel mining operations can affect chan-

nel geometry through streambed degradation and lateral bank erosion. A better understanding of stream-channel responses to such operations can only be gained through further research.

Flood-Plain Management

FEDERAL FLOOD-PLAIN MANAGEMENT LEGISLATION

In response to past and potential loss of life and property associated with flooding, the Federal government has attempted to regulate urbanization of flood plains. Approximately 50 percent of the communities of the United States experience significant flooding in the form of overbank flow onto flood plains (White and Haas, 1975). Congress has responded to this hazard by passing a series of acts and amendments that have increasingly standardized procedures for the urbanization of flood plains across the country.

Federal flood-plain legislation has evolved through a number of phases that have addressed engineering solutions to flooding, encouraged States to devise adequate flood-plain land-use programs, and threatened to withhold Federal property loans and disaster relief for property in flood plains unless land-use controls are enacted. From 1936 to 1968, the Federal government spent an estimated $9 billion on flood-protection works. Annual flood losses continued to rise during this period, however, as flood-plain development increased. As a result, Congress passed the National Flood Insurance Act of 1968, Title XIII, of the Housing and Urban Development Act of 1968 (Public Law 90-448). The goals of the act were twofold: (1) to create a national flood-insurance fund and (2) to tie a flood-insurance program to a unified national flood-plain management program (U.S. Code Congressional and Administrative News, 1968). At that time, the definition of a flood plain was refined for administrative purposes to include the area subject to a 1 percent chance of flood inundation in any given year. This event has come to be called a "100-year flood." Despite the legislation, urbanization of flood plains continued at a rate of 1.5 to 2.5 percent per year (White and Haas, 1975). To implement the 1968 act effectively, in 1973 Congress passed the Flood Disaster Protection Act (Public Law 93-234), which was the last piece of major legislation dealing with flood-plain management to date. This act requires local communities to participate in a flood-insurance program and to adopt adequate flood-plain management ordinances as conditions for Federal monies for projects in flood plains.

The key issue decided by the 1973 legislation was the standard to be used in the delineation of flood plains. Congress felt that the standard should be defined in terms of probability so as to achieve national uniformity in determining flood risk and thereby eliminate regional discrimination. The decision was made to continue defining the regulatory flood plain as the area inundated by the 100-year flood because this definition was already accepted and could be nationally applied. The 100-year flood was considered a moderate standard in light of such statistics as the 45 flood disasters in the United States in 1972, 50 percent of which were equal to or greater than the 100-year flood. This standard, however, was also thought to be high enough to focus community attention on what could happen, not just on what had happened in the past (U.S. Code Congressional and Administrative News, 1973).

Because of this legislation, a community must enact a flood-plain management ordinance and submit hydraulic studies of major watercourses for Federal approval before it can qualify for Federal flood insurance, Federal loans for flood-plain property, and Federal disaster relief following a flood. The hydraulic studies result in delineation of flooding zones, within which the adopted flood-plain management ordinance restricts development based on flood risk. The resulting maps are known as Flood Insurance Rate Maps (FIRM). Once a community has entered into the National Flood Insurance Program (NFIP), citizens whose property is within a mapped flood plain must purchase Federal flood insurance at rates based on the potential severity of flooding to qualify for the Federal monies described above.

FLOOD-PLAIN MANAGEMENT IN THE TUCSON AREA

With the current population boom in the southwestern United States, Federal and local agencies have increasingly focused attention on the issue of flood-plain management within this region. Throughout the Southwest, flood-plain management ordinances have been written by communities wanting to participate in the NFIP. In 1974 and 1982, Pima County and the City of Tucson, respectively, adopted flood-plain management ordinances designed to fit their communities' needs within the context of Federal regulations (Ordinances 1974-86 and 5526, respectively). These ordinances have since been revised and are outlined below. The City of Tucson entered the Emergency Program of the NFIP in 1976 and the Regular Program in mid-1982 upon completion of the

city's Flood Insurance Rate Maps and adoption of a flood-plain management ordinance acceptable to the Federal Emergency Management Agency (FEMA). Pima County entered the Emergency Program in 1974 and the Regular Program in 1983. The Emergency Program enables a community to be eligible for some flood insurance if it adopts preliminary land-use regulatory measures for flood plains, pending publication of its Flood Insurance Rate Maps. As of the publication date of these maps, additional flood insurance is available to the community as part of the Regular Program.

In accordance with Federal regulations, flood plains in Pima County and the City of Tucson are generally defined as the areas subject to inundation by the 100-year flood. Each flood plain is divided into two zones, as federally mandated: (1) the regulatory floodway, which includes the channel and adjacent areas that must be reserved for conveyance of floodwaters without increasing flood heights by more than 1 foot (0.3 m); and (2) the floodway fringe, which is defined as the land outside the floodway also subject to 100-year flooding (Figure 54). Federal regulations do not permit placement of permanent structures within a floodway. Urban development is allowed in the floodway fringe, however, if the basements or finished floors of structures are elevated to at least the level of the 100-year flood.

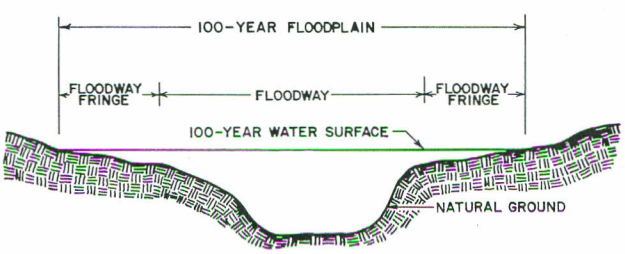


Figure 54. *Diagrammatic sketch illustrating the zones into which the 100-year flood plain of a stream channel is divided.*

Within the framework of Federal regulations, local governing agencies are free to manage their communities' flood plains as they see fit. In the Tucson area, for example, such open-space uses as loading and parking areas, golf courses, other recreational fields, agriculture, and sand-and-gravel operations are generally permitted in the floodways (Pima County, 1974 and 1985; City of Tucson, Mayor and Council Memorandum, 1980). Structures, including commercial and residential buildings, are currently allowed in floodway fringe areas if their basements or first floors are placed a minimum of 1 foot (0.3 m) above the level of the 100-year flood. Development in the floodway fringe is generally not permitted if the elevation of the 100-year flood is increased by more than 0.1 foot (0.03 m). Exceptions to restrictions stated in these ordinances are possible through appeal procedures.

For further details concerning the ordinances, the reader should contact the Pima County Department of Transportation and Flood Control District and the City Engineer's Office of the City of Tucson. These ordinances cover many more flood-related topics than are discussed within this study. Provisions in the ordinances that specifically relate to channel-bank erosion are discussed in the following section.

APPLICABILITY OF FEDERAL REGULATIONS TO SEMIARID REGIONS

Federal flood-plain management regulations have not been entirely successful in semiarid regions. Temporal and spatial variations in the cross-sectional shapes and positions of alluvial ephemeral-stream channels produce uncertainties in delineating 100-year flood plains. To predict the level of the 100-year flood through a given channel and thus determine the areal extent of 100-year flooding, hydraulic analyses generally assume that current channel boundaries will not change significantly before a 100-year flood (Burkham, 1972). This assumption is frequently invalid in semiarid regions.

The observations reported in this study illustrate the geomorphic and hydrologic complexity of stream systems in the semiarid Southwest. The Rillito Creek system has undergone recent channel change that has included lateral shifts in channel positions, evolution of plan-view patterns, locally severe bank erosion, and general channel widening, channel narrowing, and streambed aggradation and degradation. Such changes in channel morphology have been caused by (1) prolonged winter flows with recurrence intervals less than or equal to about 27 years, (2) sequences of lesser summer flows, and (3) major flow events produced by tropical storms. Studies of the Gila River in southern Arizona by Burkham (1972; 1976) suggest that the dynamic behavior of the Rillito Creek system is matched in other areas of southern Arizona. Burkham found that channel change from 1914 through 1970 in a 55-mile (88-km) reach of the Gila River in Safford Valley, Arizona caused significant differences in the magnitude, timing, and conveyance of flood waves through this reach.

Successive delineations of the 100-year flood plains of the Rillito Creek system since 1967 suggest that changes in the passage of flows through these channels have been produced by variations in channel morphology. In 1973 and 1975, the U.S. Army Corps of Engi-

neers published flood studies for Rillito Creek, Tanque Verde Creek, and Pantano Wash that included maps of their 100-year flood plains. These maps were based on channel topography that had been derived photogrammetrically from aerial photographs taken in 1967 (Robert Reynolds, U.S. Army Corps of Engineers, Tucson Urban Study, oral commun., 1981). In 1976 the U.S. Geological Survey determined photogrammetrically that both Rillito Creek and Pantano Wash had downcut approximately 4 feet (1.2 m) since the publication of the studies (B. N. Aldridge, U.S. Geological Survey, Tucson, oral commun., 1981). As a result of these changes in streambed elevation, water-surface elevations for the 100-year floods in Rillito Creek and Pantano Wash were recomputed and their 100-year flood plains redefined. Throughout most of an 8-mile (12.8-km) reach of Pantano Wash between Stella Road and the confluence with Tanque Verde Creek, the level of the 100-year flood had been lowered by the downcutting of the channel (Federal Emergency Management Agency, 1981). A similar lowering of the 100-year flood in Rillito Creek was also noted.

The most recently defined 100-year flood plains of Rillito Creek and Pantano Wash have little chance of remaining valid, as currently delineated, for more than about 2 years (Robert Reynolds, U.S. Army Corps of Engineers, Tucson Urban Study, oral commun., 1981). In contrast, the 100-year flood plain of Tanque Verde Creek has not been subject to major revisions because it has changed little since its original delineation. In an interesting twist, artificial channelization of the Rillito Creek system, particularly along Rillito Creek and Pantano Wash, has become so prevalent that flood-plain maps of the system tend to become invalid almost as soon as they are published. Within the Tucson area, channelization of a reach usually involves containment of the entire 100-year flood within that reach.

In addition to significant fluctuations of 100-year flood plains imposed by variable channel topography, the hazard posed by frequent channel-bank erosion is not treated adequately in the Federal flood-plain management regulations. The Flood Disaster Protection Act of 1973 expanded the meaning of the term "flood," as defined in the National Flood Insurance Act of 1968, to include abnormal erosion caused by unusually high levels of water, as during a flash flood (U.S. Code Congressional and Administrative News, 1977). In the Rillito Creek system and other alluvial ephemeral-stream systems of the Southwest, however, locally severe bank erosion as well as general channel widening have frequently been produced by flows of moderate magnitude that cannot be classified as unusual and unforeseeable events. Potential sites of significant bank erosion along a stream channel, such as areas adjacent to the outer banks of channel bends that have not been artificially stabilized, are not always within the 100-year flood plain. Unless a property owner at such a site happens to carry Federal flood insurance, little compensation is available for property lost to bank erosion during a flow of less than unusual magnitude.

Pima County and the City of Tucson have tried to lessen potential flow-related erosional damage to property in the Tucson basin through their flood-plain management ordinances. In recognition of this situation, minimum setback distances for buildings and other structures from unprotected channel banks are required in the current ordinances. Much of the damage in Pima County caused by channel-bank erosion has been to facilities built before setback distances were established. Since 1974, when the first flood-plain management ordinance was adopted by Pima County, building setback distances along major watercourses have evolved from 100 feet (30 m) for commercial/industrial structures and residential rental structures and 300 feet (91 m) for owner-occupied residences, to 500 feet (152 m) for all structures. The latter distance was adopted after the October 1983 flow event in response to the significant bank erosion and lateral channel migration produced then.

As of this writing, the minimum setback distance of 500 feet (152 m) is required along the Rillito Creek system and other major watercourses in unincorporated Pima County where there are no unusual conditions. Where unusual conditions do exist, including historical meandering of the watercourse, presence of sand-and-gravel operations, poorly defined or unconsolidated channel banks, or local changes in direction, quantity, or velocity of flow, setback distances are to be established on a case-by-case basis by the County Engineer. Setback distances ranging from 50 to 250 feet (15 to 76 m) have also been established along smaller watercourses based on the magnitude of the estimated 100-year peak discharge.

The City of Tucson also adopted the 500-foot (152-m) setback distance from the banks of major watercourses following the October 1983 event. A minimum setback distance of 50 feet (15 m) is currently required along minor watercourses (City of Tucson, 1984). Exceptions to these requirements are to be determined by the City Engineer. The current Tucson flood-plain management ordinance (No. 6068) also states that floodway or floodway-fringe development must not significantly increase channel or bank erosion or cause damage to public facilities because of erosion or flooding.

Pima County and the City of Tucson are also beginning to develop erosion-hazard boundary maps as a means of lessening poten-

tial erosional damage. Along the Santa Cruz River, to which Rillito Creek is tributary (Figure 1), erosion-hazard boundary maps have been compiled based on qualitative and quantitative analyses of channel-bank erosion and lateral channel migration (Simons, Li & Associates, Inc., 1986). These analyses have included investigations of historical channel positions and erosional sites seen on aerial photographs and have considered present channel patterns, sand-and-gravel operations and landfills, and existing and planned bank-stabilization measures. These maps will be used to restrain urban development within zones determined to have a high potential for channel-bank erosion and lateral channel migration. Where erosion-hazard limits exceed mapped floodway and 100-year flood-plain limits, the erosion-hazard limits will form the basis for regulating development adjacent to the stream channels because these limits represent the estimated worst possible flooding and erosional conditions. Such maps have not yet been compiled for the Rillito Creek system.

As aids to urban planning for the flood plains of the Rillito Creek system, the maximum lateral extents of Rillito Creek, Tanque Verde Creek, and Pantano Wash before 1941 and between 1941 and December 1979 are shown in Plate 1, and maps of the October 1983 erosion are provided in Figures 39, 40, 43, and 44. It should be remembered that as urbanization of the Tucson basin progresses, the Rillito Creek system will probably be increasingly restricted through channelization. These stream channels are no longer as free to migrate as they once were and are likely to become even less so as channelization proceeds. It should also be noted, however, that channelization involving bank-protection measures such as riprap and rock-and-rail revetments along the Rillito Creek system have been known to fail, as occurred near Swan Road in 1965 (Figure 27). Such failures allow channel migration to former patterns and positions.

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Appendix

Channel-width measurements of Tanque Verde Creek from aerial photographs, 1941-79. (See Plate 1 for reach and cross-section locations.)

Reach	Cross Section	1941 (feet)	1941 (meters)	1963 (feet)	1963 (meters)	1967 (feet)	1967 (meters)	1974 (feet)	1974 (meters)	1978 (feet)	1978 (meters)	1979 (feet)	1979 (meters)
T.1	1	240	73	130	40	160	49	150	46	140	43	240	73
	2	340	104	300	91	230	70	100	30	280	85	320	98
	3	180	55	140	43	200	61	230	70	230	70	320	98
T.2	4	180	55	200	61	450	137	440	134	450	137	540	165
	5	340	104	120	37	190	58	190	58	200	61	390	119
	6	240	73	140	43	370	113	220	67	300	91	300	91
T.3	7	120	37	170	52	250	76	230	70	230	70	260	79
	8	400	122	490	149	490	149	250	76	270	82	320	98
	9	210	64	210	64	280	85	300	91	280	85	320	98
	10	110	34	100	30	180	55	160	49	190	58	320	98
T.4	11	250	76	90	27	140	43	140	43	120	37	150	46
	12	210	64	100	30	290	88	70	21	80	24	150	46
	13	210	64	120	37	140	43	140	43	190	58	190	58
	14	190	58	210	64	160	49	150	46	190	58	140	43
	15	170	52	150	46	160	49	150	46	150	46	170	52
T.5	16	220	67	70	21	110	34	120	37	130	40	270	82
	17	240	73	100	30	210	64	100	30	160	49	300	91
T.6	18	140	43	230	70	260	79	140	43	130	40	130	40
	19	190	58	90	27	190	58	230	70	270	82	260	79
	20	230	70	180	55	170	52	140	43	180	55	150	46
	21	130	40	90	27	80	24	100	30	90	27	100	30
	22	90	27	50	15	70	21	70	21	70	21	90	27

Channel-width measurements of Rillito Creek from aerial photographs, 1941-79. (See Plate 1 for reach and cross-section locations.)

Reach	Cross Section	1941 (feet)	1941 (meters)	1963 (feet)	1963 (meters)	1967 (feet)	1967 (meters)	1974 (feet)	1974 (meters)	1978 (feet)	1978 (meters)	1979 (feet)	1979 (meters)
R.1	1	170	52	120	37	100	30	90	28	100	32	160	48
	2	80	24	300	91	260	80	150	46	180	56	370	113
R.2	3	250	76	150	46	200	60	180	54	190	58	340	103
	4	230	70	80	24	100	30	60	19	120	36	700	214
	5	130	40	50	15	60	19	60	17	80	26	150	47
	6	140	43	110	34	130	38	110	34	80	23	120	38
R.3	7	80	24	40	12	40	11	40	12	70	20	590	180
	8	300	91	100	30	100	31	120	35	120	35	180	55
	9	220	67	210	64	180	55	190	59	200	62	360	109
	10	260	79	200	61	320	98	340	102	280	86	300	92
	11	490	149	190	58	560	170	230	70	190	59	340	105
R.4	12	630	192	140	43	760	233	--	--	220	66	340	103
	13	310	94	100	30	500	148	--	--	490	150	520	157
	14	710	216	290	88	320	97	120	35	170	52	260	78
	15	260	79	80	24	180	54	350	108	390	118	360	109
R.5	16	170	52	80	24	100	31	90	27	150	47	220	67
	17	260	79	150	46	150	47	130	39	140	43	170	53
	18	620	189	230	70	310	94	300	90	310	94	320	98
R.6	19	380	116	320	98	340	104	200	60	260	78	270	82
R.7	20	760	232	320	98	550	167	270	82	260	80	270	82
	21	380	116	350	107	390	119	320	99	220	68	290	89
	22	280	85	160	49	240	72	280	87	200	60	260	78
R.8	23	310	94	180	55	280	86	230	71	180	55	230	71
	24	590	180	130	40	220	67	210	63	190	57	220	67
	25	260	79	150	46	150	47	130	39	150	47	140	41
	26	170	52	120	37	150	47	130	39	120	35	180	55
R.9	27	370	113	160	49	180	54	190	58	140	43	190	58
	28	80	24	90	27	100	31	100	31	80	23	240	74
	29	180	55	140	43	100	31	120	35	60	19	130	39
	30	240	73	160	49	140	43	190	58	130	39	230	70
	31	230	70	130	40	140	43	140	43	120	35	290	89
	32	460	140	280	85	250	77	270	81	220	66	310	95
R.10	33	440	134	360	110	490	150	480	146	360	111	370	113
R.11	34	480	146	250	76	260	79	260	79	250	75	--	--
	35	350	107	320	98	330	101	230	70	310	93	270	82

Channel-width measurements of Pantano Wash from aerial photographs, 1941-79. (See Plate 1 for reach and cross-section locations.)

Reach	Cross Section	1941 (feet)	1941 (meters)	1963 (feet)	1963 (meters)	1967 (feet)	1967 (meters)	1974 (feet)	1974 (meters)	1979 (feet)	1979 (meters)
P.1	1	280	85	270	82	250	76	250	76	310	94
	2	200	61	180	55	160	49	170	52	180	55
	3	640	195	700	213	610	186	350	107	390	119
	4	720	219	690	210	190	58	250	76	160	49
P.2	5	330	100	340	104	360	110	330	101	290	88
	6	190	58	180	55	180	55	160	49	250	76
	7	390	119	210	64	240	73	230	70	310	94
	8	390	119	310	94	330	100	470	143	280	85
P.3	9	1,070	326	200	61	260	79	310	94	250	76
	10	610	186	490	149	490	149	380	116	230	70
	11	490	149	280	85	280	85	230	70	100	30
	12	590	180	240	73	460	140	270	82	130	40
P.4	13	850	259	380	116	240	73	210	64	190	58
	14	760	232	470	143	360	110	180	55	210	64
	15	560	171	320	98	470	143	470	143	300	91
	16	800	244	500	152	870	265	580	177	210	64
P.5	17	950	88	850	259	290	88	230	70	270	82
P.6	18	430	131	260	79	260	79	300	91	190	58
	19	410	125	320	98	330	100	280	85	270	82
	20	690	210	620	189	450	137	370	113	280	85
	21	520	158	520	158	470	143	300	91	--	--
	22	550	168	340	104	340	104	380	116	180	55
P.7	23	710	216	670	204	640	195	650	198	320	98
	24	840	256	480	146	240	73	300	91	280	85
	25	390	119	430	131	340	104	390	119	390	119
	26	480	146	580	177	330	101	210	64	480	146
	27	410	125	550	168	460	140	290	88	340	104
P.8	28	230	70	590	180	560	171	560	171	550	168
	29	540	165	540	165	560	171	520	158	500	152
	30	840	256	740	226	360	110	320	98	230	70
	31	760	232	610	186	310	94	200	61	220	67