Historical Geomorphology and Hydrology of the Santa Cruz River

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EXTENDED ABSTRACT

This report provides baseline information on the physical characteristics of the Santa Cruz River to be used by the Arizona Stream Navigability Commission in its determination of the potential navigability of the Santa Cruz River at the time of Statehood. The primary goals of this report are: (1) to give a descriptive overview of the geography, geology, climatology, vegetation and hydrology that define the character of the Santa Cruz River; and, (2) to describe how the character of the Santa Cruz River has changed since the time of Statehood with special focus on the streamflow conditions and geomorphic changes such as channel change and movement. This report is based on a review of the available literature and analyses of historical survey maps, aerial photographs, and U.S. Geological Survey streamgage records.

The Santa Cruz River has its source at the southern base of the Canelo Hills in the Mexican Highlands portion of the Basin and Range province. The river flows south through the San Rafael Valley before crossing the international border into Mexico. It describes a loop of about 30 miles before it re-enters the United States six miles east of Nogales, and continues northward past Tucson to its confluence with the Gila River a few miles above the mouth of the Salt River. The "upper" Santa Cruz River (the river south of Marana) and the "lower" Santa Cruz (the river north of Marana) are often discussed separately in this report because of their different geomorphic and hydrologic characteristics. Along the upper Santa Cruz River, the channel is located in an inner valley that was created within broad, dissected pediments and alluvial basin deposits, and flanked by mountains. The well-defined, often entrenched channel in the upper reaches contrasts strongly to the ill-defined system of braided channels that exist north of Rillito Peak at the northern end of the Tucson Mountains near Marana. In this lower part of the basin, the Santa Cruz River flows into the great adobe flats known as the "Santa Cruz Flats," a broad plane of indistinct, noncontinuous channels in Pinal County. Floodwaters spread over a wide area with flow concentrated in numerous small washes. A well-defined channel exists only at Greene's Canal and near the Santa Cruz River's confluence with the Gila.

Both the upper and lower reaches of the Santa Cruz River have been subjected to a complex combination of climatic and geomorphic processes and human activities that have resulted in both subtle and dramatic changes in its geomorphic and hydrologic

character. While arroyo development is the most obvious type of channel change to occur since the 1890s in the upper Santa Cruz River, most of the initial channel incision occurred before the time of Statehood. Since 1912, various reaches of the upper Santa Cruz River have been dominated by such processes and activities as meander migration and cutoff, channel widening, arroyo widening, channelization, and the effects of vegetation growth resulting from the discharge of sewage effluent. The channel locations in different reaches have shifted on the order of a few feet to a few thousand feet, depending on the processes that resulted in the movement, and often change could be detected from one year to the next.

The lower Santa Cruz River, which overall is characterized by aggradation of its streambeds, experienced changes of a completely different magnitude from the upper Santa Cruz. Changes in the location of the channel in the lower basin can be measured in miles, and, due to the nature of the causes of the changes, the timing spans decades. Before the construction of Greene's Canal in 1910, the Santa Cruz River downstream from Marana was a broad, flat alluvial plain with intermittent channels. Now the transition from defined channel to alluvial plain occurs near Chuichu, Arizona. Prior to and during the floods of 1914-1915, flood flows followed routes down the North Branch of the Santa Cruz Wash and McClellan Wash through the Casa Grande area. The influence of Greene's Canal and its subsequent development as an arroyo have caused flood flows since 1915 to take more westerly paths *via* Greene's Canal.

The hydrology of the Santa Cruz River, like its geomorphology, has been affected by natural geomorphic and climatic processes and by human activities. Historically (~1890), the Santa Cruz River had year-round (or perennial) flow from its source to Tubac. Climate change since the turn of the century, combined with the extensive groundwater pumping for irrigation and the flow diversion for municipal use that began near the international border during the 1930 to 1950 drought period, has resulted in no flow in the channel in Sonora, Mexico, and discontinuous flow in the channel near Nogales, Arizona. The 1913 gage record at Nogales (the earliest in that region) indicates that by the time of Statehood, the Santa Cruz River at Nogales was no longer perennial, but instead had continuous flow during the winter and occasional flow during the spring, summer and fall. The winter discharge averaged about 15 cubic feet per second (cfs), except for an increase caused by a rainfall event that ranged from 35 to 174 cfs. A survey of the daily data for the rest of the Nogales record indicates that during wet years there were only a few days of no-

flow conditions, while during dry years there were entire months that passed with no flow recorded in the channel. At present, naturally occurring perennial reaches occur only in the uppermost part of the river in the San Rafael Valley. A separate perennial reach occurs north of Nogales due to the discharge of sewage effluent from the Nogales International Wastewater Treatment Plant that began in 1972.

The Santa Cruz River historically had several springs and marshes (*cienegas*) within its channel from Tubac to Tucson, and a marsh at its confluence with the Gila River at Laveen. Even in the historical record, only the very largest floods were sustained from the headwaters to the confluence with the Gila River. A review of the daily discharge record at Tucson indicates that there was some semblance of baseflow with an average of about 12 cfs during the fall and winter of 1912-1913. Such continuous flow for months at a time was not seen again in the years that followed, although there were periods of several weeks that experienced continuous or nearly continuous flow during very wet winter seasons. The Laveen gage recorded nearly year-round flow from its beginning date, 1940, until June of 1956, when it began to measure zero flow for weeks at a time. During the 1940 to 1956 period, the daily flow averaged about 3 cfs during low-flow conditions and had peaks as high as 5060 cfs during the wet periods. By 1960, the Santa Cruz at Laveen also was experiencing no-flow conditions for months at a time. In contrast to the reaches near Tucson and in the lower Santa Cruz River basin, the reach of the Santa Cruz River near Marana and Cortaro now has perennial flow due to the discharge of sewage effluent from the Ina Road and Roger Road sewage treatment plants.

Not only has the location of perennial flow in the Santa Cruz River changed since the time of Statehood, but the seasonality and magnitude of flows also have shifted as a result of climate change in this region. Although the majority of flow events occur during the summer season, the magnitude and number of flows that occur in the fall and winter was higher before 1930 and after 1960 than during the 1930-1960 period. Also, annual peak discharges increased significantly after 1960. For example, six of the seven largest floods on the Santa Cruz River at Tucson occurred after 1960.

In the lower Santa Cruz River basin, human activities as well as climate change have had notable effects on the magnitude of peak flows. Since 1962, the construction of flood-control channels in the washes of the lower Santa Cruz basin have resulted in the reduction of floodplain storage and infiltration losses, therefore reducing the attenuation (the downstream decrease of the flood peak) of peak discharges. For example, the

attenuation of peak flow was greater during the 1962 floods than during the 1983 floods because water was able to spread out over the broad flow zones in the lower reaches of the Santa Rosa and Santa Cruz washes. In contrast, much of the floodwater during the 1983 floods was efficiently transmitted downstream by the flood-control channels, resulting in higher flood peaks in downstream reaches.

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CHAPTER 1. INTRODUCTION

This report provides baseline information on the physical characteristics of the Santa Cruz River to be used by the Arizona Stream Navigability Commission in its determination of the potential navigability of the Santa Cruz River at the time of Statehood. The primary goal is to give a descriptive overview of the geography, geology, climatology, vegetation and hydrology that define the character of the Santa Cruz River. A secondary goal is to describe how the character of the Santa Cruz River has changed since the time of Statehood, with special focus on the streamflow conditions and geomorphic changes such as channel change and movement. This report is based on a review of the available literature, and analyses of historical survey maps, aerial photographs, and U.S. Geological Survey streamgage records. Unfortunately, there is little data presented in the literature or in the gage records, aerial photographs, and maps of the Santa Cruz River for the year 1912. Therefore, the character of the river at the time of Statehood must be interpolated from descriptions made before and after that year.

The Santa Cruz River has been subjected to a complex combination of processes that have resulted in changes in its character. These changes have taken many forms, including changes in the types and density of vegetation in the river basin, the average flow or magnitude of peak flows, the presence of surface water, and even the location of the river channel itself. Human activities clearly have played a role in changing the geomorphology and hydrology of the Santa Cruz River, but it is difficult to separate the effects of human impact from the effects of climate change and "natural" riverine processes. Where possible we have noted the causes of specific changes, whether they be anthropogenic or naturally induced.

The chapters that describe the hydrology and geomorphology of the Santa Cruz River contain a general overview of the topic and a description of the changes that have occurred since the time of Statehood. The "upper" Santa Cruz River (the river south of Marana) and the "lower" Santa Cruz (the river north of Marana) are often discussed separately in the following chapters because of their different geomorphic and hydrologic characteristics. Also included in this report is a chapter that contains a detailed description of the mapping of ordinary low and high watermarks, followed by a chapter that explains the creation and use of stage-discharge rating curves. The concluding chapter provides a

comparison of the hydrological and geomorphological characteristics at the time of Statehood to those of the present day. Throughout this document, key words are highlighted by bold, italicized print. These words have been defined in the "Glossary" section that follows the summary chapter. Ten ground photographs that illustrate the key differences between the different reaches of the upper and lower Santa Cruz River are provided in Appendix A.

CHAPTER 2. GEOGRAPHY & GEOLOGY

The Santa Cruz River has its source at the southern base of the Canelo Hills in the Mexican Highlands portion of the Basin and Range province (Figure 1). Its waters gather into a shallow, perennial channel that flows south through the San Rafael Valley before crossing the international boundary into Mexico. The river describes a loop of about 30 miles with a 348-square-mile contributing drainage area before re-entering the United States 6 miles east of Nogales. Its channel continues northward past Tucson to the Gila River a few miles above the mouth of the Salt River, a distance of about 225 miles.

Along the upper Santa Cruz River, south of Marana (refer to Figure 2), the channel lies within an inner valley created within broad, dissected pediments and alluvial basin deposits, and flanked by mountains (Cooke and Reeves, 1976; Bryan, 1925b). The well defined, commonly entrenched channel in the upper reaches contrasts strongly to the discontinuous system of channels that exist north of the northern end of the Tucson Mountains near Marana. In this lower part of the basin, the Santa Cruz River flows into the great ***adobe flats***[1] known as the "Santa Cruz Flats," a broad plain of indistinct, noncontinuous channels in Pinal County. On most United States Geological Survey (USGS) maps, the term "Santa Cruz Flats" is restricted to the area south and west of Eloy, extending west to the Sawtooth Mountains, south to the alignment of Greene's Canal, and north to the Casa Grande Mountains. In this region, floodwaters spread over a wide area with flow concentrated in numerous small washes. Distinct channels exist only along the former alignment of Greene's Canal and near the Santa Cruz River's confluence with the Gila River.

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[1] Bold, italicized words are defined in the Glossary following the final section.

Figure 1. Physiographic Features in the Santa Cruz River Basin.

Legend:

TABLE TOP MTS. - Mountain Ranges

- Rivers

- Main Flow Route since ~1915

- Santa Cruz Basin Boundary

△ - Stream Gage (Refer to Table 2 for gage name.)

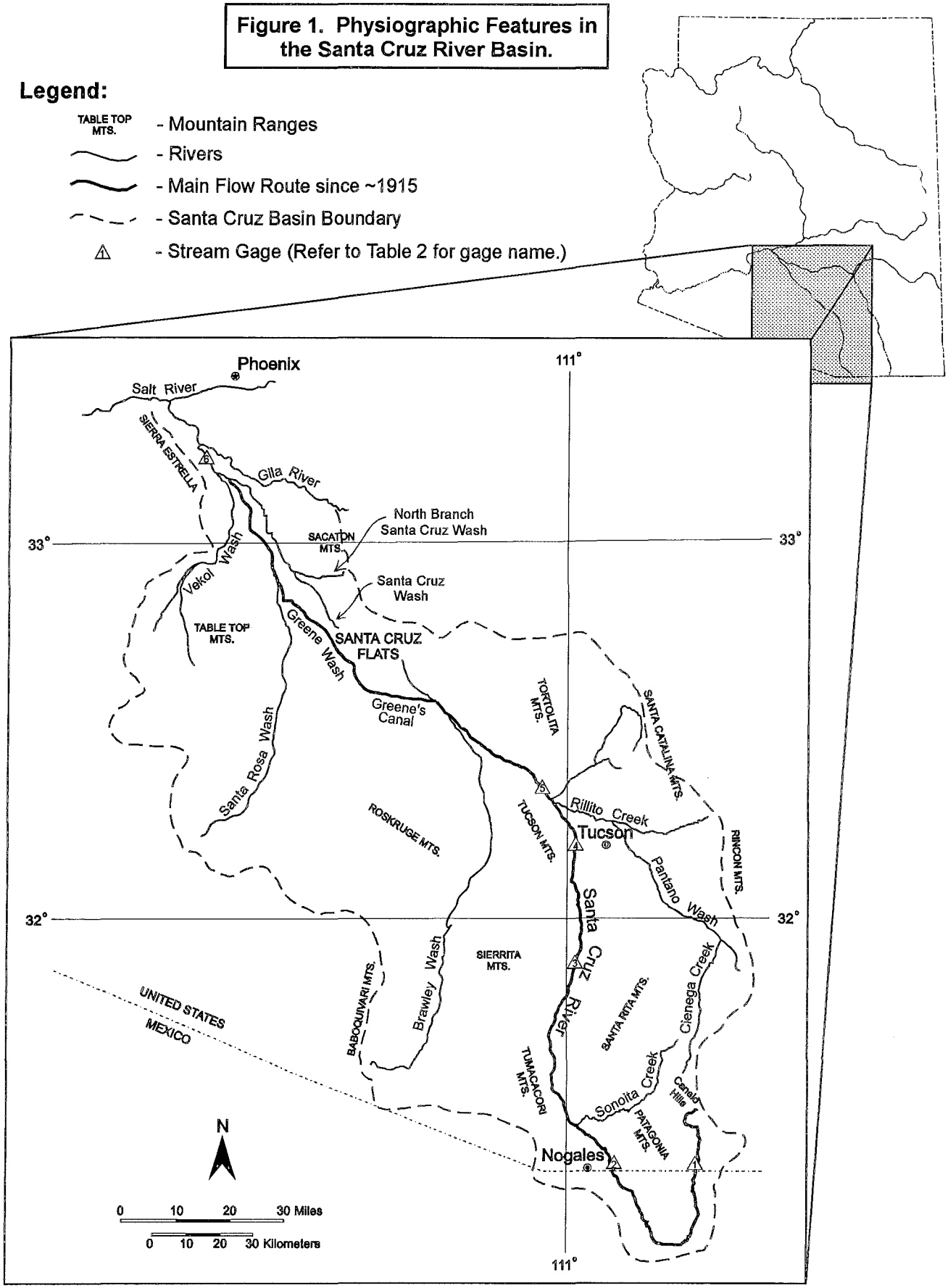
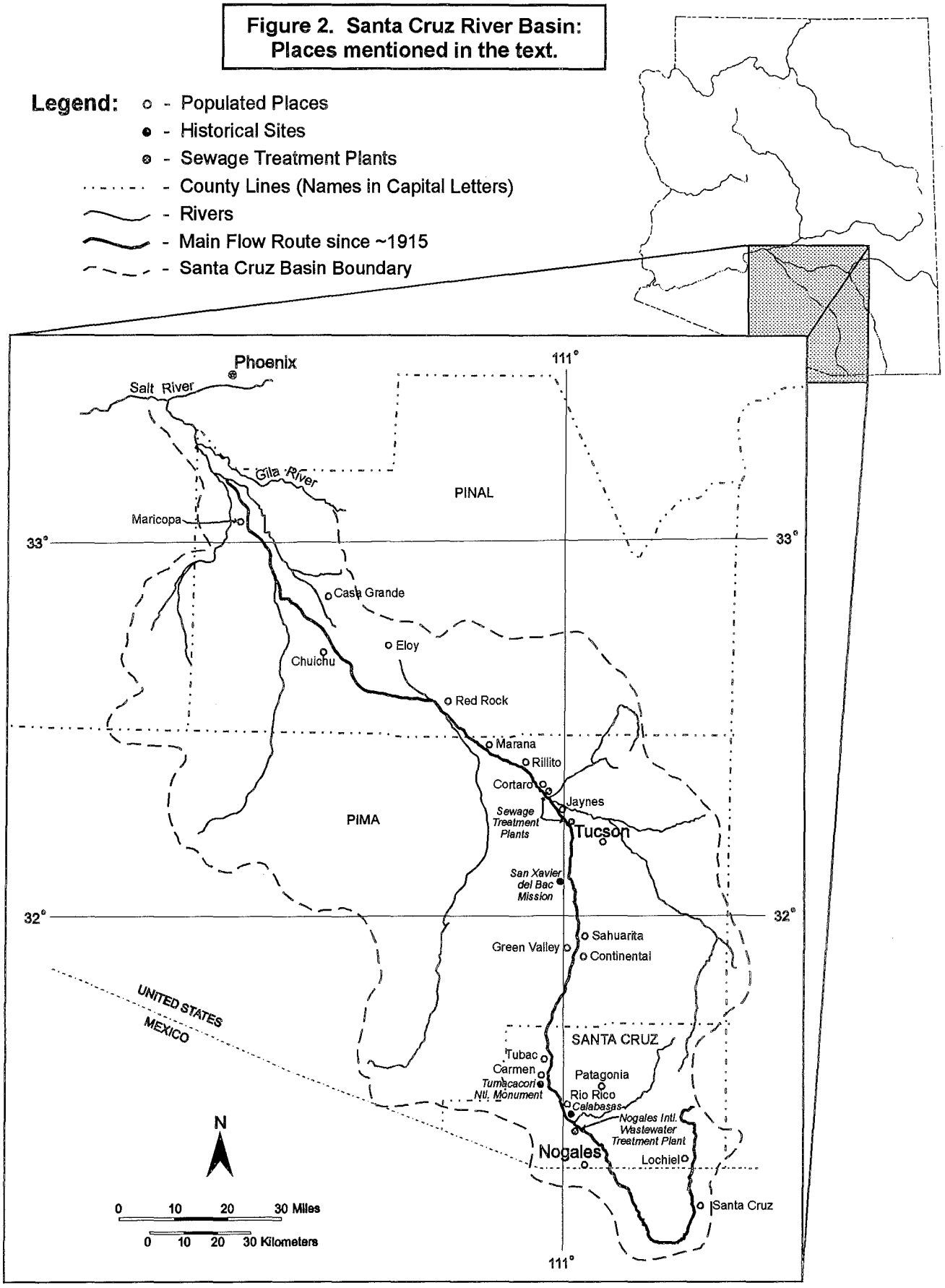


Figure 2. Santa Cruz River Basin: Places mentioned in the text.



CHAPTER 3. CLIMATE

Climate plays both direct and indirect roles in defining the character of the Santa Cruz River. Temperature and precipitation control the amount of evaporation that occurs, which in turns affects the amount of water that flows into and remains in the river channel, the amount of ***infiltration,*** the type and vigor of vegetation along the river banks, and the character of vegetation throughout the basin. The amount and nature of the precipitation plays an even stronger role in defining the character of the river because both the surface and groundwater supplies of the drainage basin have as their primary source the precipitation that occurs in the basin (Schwalen, 1942).

This section provides a brief overview of the seasonal changes in temperature. Seasonal, annual, and decadal changes in the source and nature of precipitation events will be described in more detail because of the role average and unusual precipitation conditions play in defining the hydrology and geomorphology of the Santa Cruz River system.

Temperature

Average January temperatures range from about 40° F in the higher elevations to about 50° F in the lower lying regions, with mean minimum temperatures averaging near or below freezing. Average July temperatures range from 65° in the higher elevations to 85° and 90° in the lower regions, with mean maximums ranging from 80° to 105°, depending on the elevation. The spring and fall months are characterized by large daily temperature changes that average 30° or even 40° (Santa Cruz-San Pedro River Basin Resource Inventory, 1977; Sellers and Hill, 1974).

Precipitation

Annual precipitation in the Santa Cruz River basin tends to increase with altitude and is extremely variable from year to year (Condes de la Torre, 1970). Two distinct seasons of precipitation are evident in the mean monthly precipitation of the Santa Cruz River Basin, with slightly greater precipitation in the summer than in the winter (Sellers and Hill, 1974). This pattern is illustrated by two rain gage records in the basin (Figure 3).

Hirschboeck (1985) and Webb and Betancourt (1992) provided thorough reviews of the sources of the precipitation and identified the circulation anomalies that are associated with variations in monthly and peak streamflow for the Santa Cruz River. The following sections describing seasonal precipitation patterns and variability are based primarily on their work.

Summer

The summer rainy season occurs from the latter part of June through September. During the summer rainy season, the thermally induced high-altitude anticyclonic circulation centered over the southern and southwestern United States entrains moist air from the Gulf of Mexico, the Pacific Ocean and the Gulf of California (Reed, 1933; 1939). The summer rains are often referred to as "monsoon" rains because of the similarity of the southwestern atmospheric circulation pattern to the monsoonal circulation in other parts of the world (Tang and Reiter, 1984). The storm centers of summer thundershowers are the result of convective air currents set up in the lower atmosphere by extremely high temperatures next to the earth's surface, and the effects of local topographic features. Summer precipitation is characterized by widespread and locally scattered thunderstorms. The summer storms tend to result in locally intense rainfall on any given day, yet for short periods during the summer, rainfall may occur in the entire drainage basin (Schwalen, 1942). In the upper Santa Cruz River basin, the precipitation during the summer rainy season is the most dependable and generally is greater than the total for the remaining eight months of the year (Schwalen, 1942; Condes de la Torre, 1970). From north to south in the drainage basin, the ratio of summer rainfall to total annual rainfall increases (Schwalen, 1942).

Winter

The winter rainy season occurs during the period December through March. This second rainy season results primarily from trailing cold fronts associated with large-scale low pressure systems steered into the region by very deep troughs over the western United States in the belt of upper air westerly wind flow. Winter rains in the Santa Cruz River basin are associated with the eastward passage of the cyclonic storm centers originating on the Pacific Ocean. Although individual storms may persist for several days, have wide

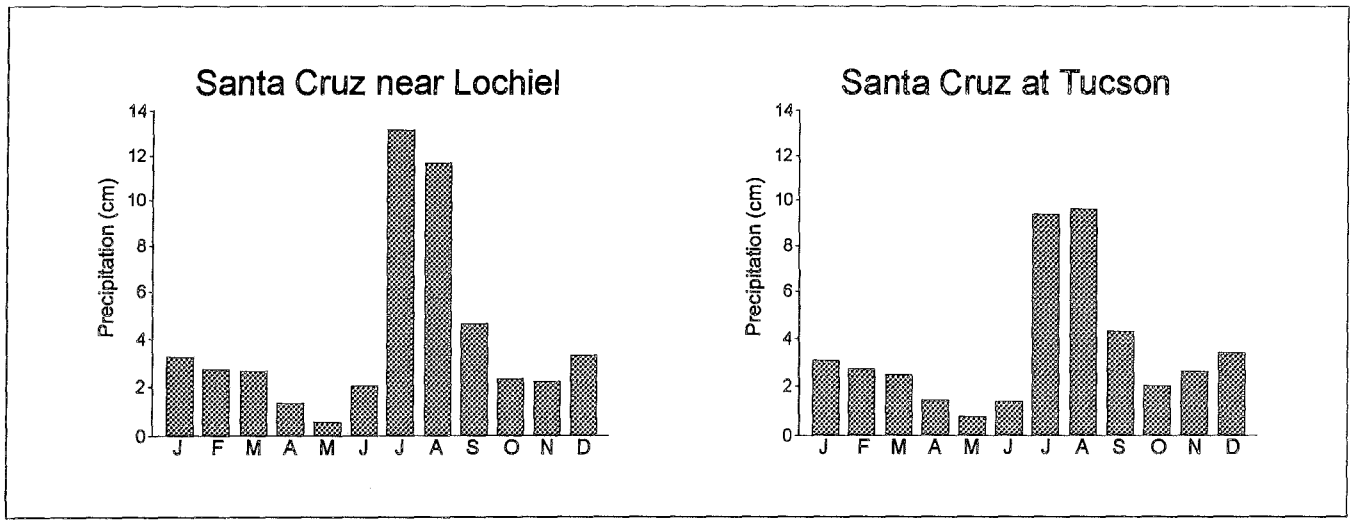


Figure 3. Monthly precipitation at two gages in the Santa Cruz River Basin.
[Source: Hirschboeck, 1985]

spatial extent (i.e. one storm system may cover the entire state of Arizona), move slowly, and have fairly steady intensity, winter rains themselves show a wider variation in their seasonal totals and are more irregular in monthly distribution than the summer rains (Schwalen, 1942; McDonald, 1956). Although the majority of flow events on the Santa Cruz River occur in the summer rainy season, the second largest flood measured at Tucson was caused by a series of winter frontal passages. The fronts were steered along a southerly displaced storm track into the region (House and Hirschboeck, 1995).

Fall and Spring

The spring and fall months in Arizona are usually characterized by clear skies and little precipitation (SC-SP River Basin Resource Inventory, 1977; Sellers and Hill, 1974). While winter frontal storms and summer convectional storms are the most common sources of precipitation in this region, tropical storms and cutoff lows also contribute significant amounts of precipitation (Douglas and Fritts, 1973; Douglas, 1974; Hirschboeck, 1985). Tropical storms tend to influence the precipitation of the region during the months of August through October (Douglas and Fritts, 1973; Hirschboeck, 1985; Smith, 1986). For example, remnants of Tropical Storm Claudia in 1962 caused flooding on the Santa Cruz River at and north of Tucson, Santa Rosa Wash, and Brawley Wash (Lewis, 1963).

Cutoff cyclones tend to develop in the upper atmosphere off the west coast of North America during the fall (September - November) and late spring (May - June) periods, times that are typically dry in the Santa Cruz River basin. Hirschboeck (1985) observed that tropical storms at the surface were often associated with troughs or cutoff lows in the upper atmosphere. Tropical Storm Octave in late September and early October 1983 is an example of such an interaction between a tropical cyclone and a cutoff low pressure system that caused the flood of record on the Santa Cruz River (Roeske *et al*, 1989; Webb and Betancourt, 1992).

Historical Climate Change in the Santa Cruz River Basin

During the past two decades, more and greater flood flows have occurred in the fall and winter seasons and fewer in the summer (Webb and Betancourt, 1992; Hirschboeck, 1985). This increase in magnitude and number of flows in the fall and winter results from a shift in the seasonal distribution of precipitation. Webb and Betancourt (1992) explain the shifts in the seasonal distribution of precipitation in terms of fluctuations in large-scale oceanic and atmospheric processes:

> "Twentieth-century climatic variability stems from decadal trends in atmospheric circulation over the Northern Hemisphere and in the frequency of El Niño-Southern Oscillation (ENSO) phenomena in the equatorial Pacific Ocean. Before 1930 and after 1960, westerly winds on average followed a more meridional path, and ENSO conditions occurred more frequently and with greater variability in the equatorial Pacific. By contrast, the westerlies followed a more zonal flow, and ENSO conditions occurred less frequently with less variability between 1930 and 1960. Meridional circulation and the climatology associated with ENSO conditions enhance Tucson precipitation in the winter, spring, and fall and possibly reduce summer rainfall." (Webb and Betancourt, 1992, p.35-36) ..... "Winter frontal storms are more numerous and intense during certain ENSO years... the probabilities for generation and recurvature of tropical cyclones change during ENSO conditions, but the advection of moisture needed to fuel monsoonal storms is reduced. Hypothetically, ENSO conditions could reduce the number of monsoonal storms but increase the number of frontal systems and tropical cyclones that affect Arizona." (Webb and Betancourt, 1992, p. 12)

Arizona's Statehood occurred during a period characterized by relatively intense winter storm activity. Such intense storm activity, when combined with human activities and other riverine processes, resulted in significant geomorphic changes of the Santa Cruz River channel. These changes and other related hydrologic changes associated with the shift from fall-winter dominated precipitation, to summer dominated and then back to fall-

winter dominated, are described in greater detail in the chapters on hydrology and geomorphology.

CHAPTER 4. VEGETATION

The type and density of vegetation in the Santa Cruz River basin also directly and indirectly affects the character of the Santa Cruz River. For example, the presence of vegetation affects channel form by stabilizing the channel banks against erosion, and affects flow by withdrawing quantities of water that would otherwise contribute to either surface flow or ***subflow*** in the channel. Vegetation indirectly affects the character of the river by how it impedes runoff during precipitation events. Relationships between vegetation, hydrology and geomorphology are discussed in greater detail in the following chapters on hydrology and geomorphology. The purpose of this chapter is to give a brief survey of vegetation types present in the upper and lower Santa Cruz River basin and to provide a description of how that vegetation has changed since the time of Statehood. The Latin names of all plants mentioned in the following text are listed in Table 1.

Vegetation Types

The vegetation cover of the upper Santa Cruz River basin is dominated by semidesert grasslands at elevations between 3000 and 5500 feet, plains grasslands between 4500 and 6000 feet, evergreen woodland between 4000 and 7000 feet, and ponderosa pine and mixed-conifer forests above 7000 feet. Prominent grasses in the semidesert grasslands community are the gammas, threeawns, tobosa, curly mesquite, cotton grass, and bush muhly. The plains grasslands community, in which grasses form a mostly continuous cover, is dominated by such perennial grasses as the gramas, bluestems, plains lovegrass, threeawn, galleta, and plains bristlegrass. Historically, there have been increases in the woody shrubs such as snakeweed and acacia, and in trees such as mesquite and one-seed juniper in the grasslands area. The evergreen woodland community is composed mostly of oaks, the most prevalent being Emory oak, Arizona white oak, and Mexican blue oak. Interspersed among the oaks are alligator juniper, one-seed juniper, and Mexican pinyon. The ponderosa pine and mixed-conifer forests account for only a very small area of the total vegetation cover, occupying the upper parts of the

Santa Rita, Santa Catalina, Huachuca, and Rincon mountains. This vegetation community is dominated by ponderosa pine, Douglas fir, and white fir, with some aspen, and Gambel oak.

Riparian forests line some reaches of the Santa Cruz River and its tributaries. Such forests are composed predominantly of cottonwood and willow with dense thickets of mesquite, and other important riparian trees such as Arizona sycamore, velvet ash, walnut, and saltcedar or tamarisk, an introduced tree that has invaded nearly all of southeastern Arizona's major riparian habitats below 5,000 feet.

The present day vegetation cover of the lower Santa Cruz River basin is dominated by two Sonoran desertscrub communities, the lower Colorado River Valley (LCRV) and the Arizona Upland (AU) communities (Shreve, 1942 and 1951; Bahr, 1991). The LCRV community is composed of creosote bush, bursage, and saltbush, interspersed with species of bunch grasses such as big galetta. The AU community is comprised mostly of foothill paloverde, saguaro, teddy bear cholla, ocotillo, brittlebush, ironwood, catclaw, bursage, and creosote bush, and some annual and perennial grasses.

Changes in Vegetation

Human activities have modified the vegetation of the Santa Cruz River basin. Bahre (1991) described historic human impact on vegetation in southeastern Arizona. He found no evidence that the Sonoran desertscrub communities had invaded extensive areas of former grassland or that grassland distribution had changed during the historic period. However, he and other researchers found that there has been a decline in native grasses (attributed to grazing and a slight trend towards aridity) and an increase in woody ***xerophytes*** such as mesquite. The increase in woody trees and shrubs is generally attributed to a combination of overgrazing and wildfire exclusion. Agricultural clearing, wild hay cutting, clearing for urban and rural development, range management policies, and the introduction of exotics are other factors that have caused changes in the grasslands. Also, there have been changes in the cover, density and number of bursage, brittlebush, foothills paloverde, and other native desertscrub dominants that may be related to plant life cycles and/or short-term cycles linked to climatic and other environmental fluctuations.

Table 1. Vegetation Communities in the Santa Cruz River Basin. [Source: Bahre, 1991]

A. Upper Santa Cruz River Basin:

Semidesert Grasslands Community:
- acacia/catclaw (Acacia greggii)
- burroweed (Haplopappus tenuisectus)
- bush muhly (Muhlenbergia porteri)
- cotton grass (Trichachne californica)
- curly mesquite (Hilaria belangeri)
- gammas (Bouteloua spp.)
- mesquite (Prosopis spp.)
- one-seed juniper (Juniperus monosperma)
- snakeweed (Gutierrezia sarothrae)
- threeawns (Aristida spp.)
- tobosa (Hilaria mutica)

Ponderosa Pine and Mixed-Conifer Forests:
- Douglas fir (Pseudotsuga menziesii)
- Gambel oak (Quercus gambelii)
- ponderosa pine (Pinus ponderosa)
- quaking aspen (Populus tremuloides)
- white fir (Abies concolor)

Plains Grasslands Community:
- bluestems (Andropogon spp.)
- galleta (Hilaria jamesii)
- gramas, perennial grasses (Bouteloua spp.)
- plains bristlegrass (Setaria macrostachya).
- plains lovegrass (Eragrostis intermedia)
- threeawn (Aristida spp.)

Evergreen Woodland Community:
- Arizona white oak (Quercus arizonica)
- Emory oak (Quercus emoryi)
- Mexican blue oak (Quercus oblongifolia)
- alligator juniper (Juniperus deppeana)
- one-seed juniper (Juniperus monosperma)
- Mexican pinyon (Pinus cembroides).

Riparian Forests:
- Arizona sycamore (Platanus wrightii)
- cottonwood (Populus fremontii)
- mesquite (mostly P.velutina and P. glandulosa)
- saltcedar or tamarisk (Tamarix chinensis)
- velvet ash (Fraxinus pennsylvanica)
- walnut (Juglans major)
- willow (Salix spp.)

B. Lower Santa Cruz River Basin:

Lower Colorado River Valley Desertscrub Community:
- big galetta (Hilaria rigida)
- bursage (Ambrosia spp.)
- creosote bush (Larrea tridentata)
- saltbush (Atriplex canescens)

Arizona Upland Desertscrub Community:
- acacia/catclaw (Acacia greggii)
- brittlebush (Encelia farinosa)
- bursage (Ambrosia spp.)
- creosote bush (Larrea tridentata)
- foothill paloverde (Cercidium microphyllum)
- ironwood (Olneya tesota)
- ocotillo (Fouquieria splendens)
- saguaro (Carnegiea gigantea)
- teddy bear cholla (Opuntia bigelovii)
- [some annual and perennial grasses]

In the evergreen woodlands, the density of oaks, brush and shrubby trees has increased and decreased in different areas since 1870. Fire suppression policies in this century and overgrazing have diminished the occurrence of wildfires, allowing brush and shrubby trees to increase and causing a decline in oak regeneration (i.e., due to browsing of oak seedlings and damage to acorns by livestock). Bahre (1991) noted that other changes in the evergreen woodlands are due to clearing of native cover for expanding settlement, invasion of exotics, and an increase in oak in areas that have been protected from fire, grazing and fuelwood cutting.

Since the 1850's and 1860's, the native riparian vegetation has largely disappeared or been replaced by exotics (Bahre, 1991). The development of more efficient water pumps in the 1940's led to a boom in irrigated agriculture in southeastern Arizona. Groundwater irrigation between the 1940's and 1970's led to groundwater overdrafts that had a major impact on riparian ***phreatophytes***, killing extensive areas of mesquite and galeria forests. Rea (1983, as summarized in Bahre, 1991) noted several other causes of riparian deterioration in southern Arizona, i.e., overgrazing of arid and adjacent semiarid uplands, excessive woodcutting in watersheds and mesquite *bosques* (forests), overtrapping of beaver and loss of beaver dams, gullying of stream banks and hillsides by trampling of cattle, and cutting unprotected wagon roads.

Overall, riparian habitats in southeastern Arizona have been significantly altered or decreased by extensive groundwater pumping. However, sewage effluent discharge from two sewage treatment plants located adjacent to the Santa Cruz River have led to the establishment of riparian habitat where formerly there was no perennial flow, or the re-establishment of riparian vegetation in reaches of the river where historically there was perennial flow. Such altered reaches of the of Santa Cruz are discussed in greater detail in the following chapters.

CHAPTER 5. HYDROLOGY

The location and character of surface water in the Santa Cruz River Basin is intrinsically linked to the regional climate, to the level of groundwater, and to the geomorphology of the channel itself. This chapter describes several aspects of the hydrology of the Santa Cruz River basin. It begins with a brief background on the historical and present-day surface water locations. Most of this chapter is devoted to the description

of the average flow conditions (including no-flow conditions) and peak flows as recorded by the six USGS streamgages located throughout the basin. Descriptions of the effects of human activities on river flow and groundwater are interwoven with the discussion of the hydrologic changes throughout this chapter. More detailed information about the changes of the location and character of the surface flow as they relate to geomorphological changes is discussed in the next chapter.

Description of Surface Flow and Groundwater

The upper Santa Cruz River is an ***intermittent*** stream, meaning, most of the river flows for only part of the year or only during wet weather, while some short reaches of its course flow throughout the year (Bryan, 1925b); the lower Santa Cruz River has ***ephemeral*** flow that results directly from precipitation. Even in the historical record, only the very largest floods were sustained from the headwaters to the confluence with the Gila River near Laveen. Historically, the Santa Cruz River was perennial above Tubac. Perennial ***subflow*** maintained several marshes (***cienegas***) near Sentinel Peak in Tucson, where a subsurface dike and an impervious layer formed by the convergence of Pleistocene terraces and the bedrock at the foot of the Tucson Mountains forced the groundwater to surface. ***Cienegas*** existed about 10 miles south of Tucson above the San Xavier Mission (the *Agua de la Misión* and the *Punta de Agua,* see Figure 4) and along both the West Branch and the Santa Cruz River proper about 3 miles south of the Congress Street Crossing in Tucson (Betancourt and Turner, 1988; Halpenny, 1988). Bryan (1922a) observed another *cienega* at the confluence of the Santa Cruz and the Gila Rivers.

In 1949, during the unusually dry period that lasted from 1930 to 1950, the diversion of the Santa Cruz River's flow 19 miles upstream from the Nogales gage began for municipal supply for the city of Nogales, Sonora (USGS Gage Remarks). Because of the increased extraction as Nogales' population has grown and the expansion of irrigated agriculture along the inner valley of the river in Santa Cruz County during the period after the second World War to about 1955, the ***water table*** in the inner valley has been lowered and the ***subflow*** of the river depleted (Halpenny, 1988). The once perennial flow in Sonora, Mexico, is now captured by wells and infiltration galleries for agricultural and

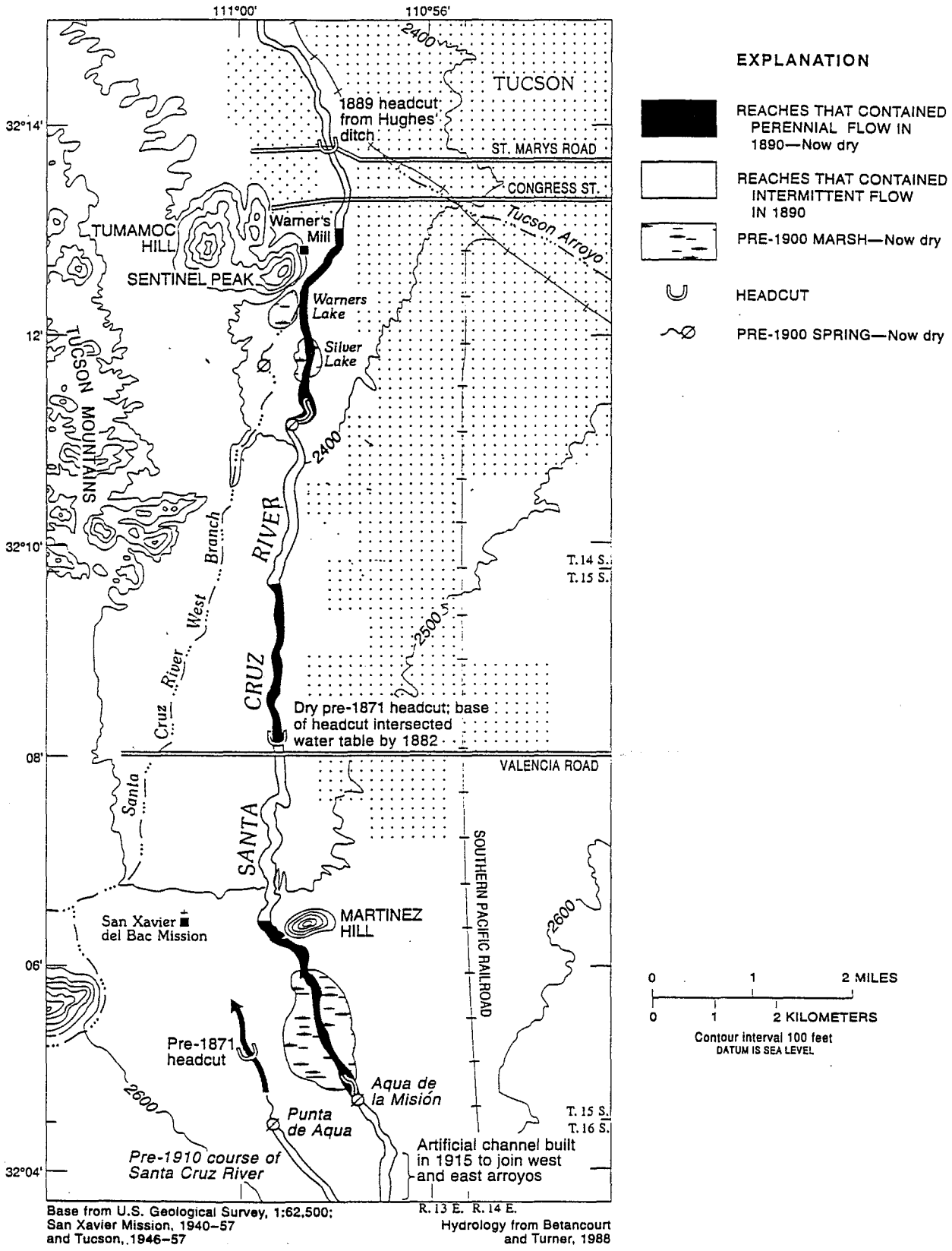


Figure 4. Santa Cruz River in 1988, perennial and intermittent reaches in 1890, and location of headcuts in relation to marshes in the late 19th century. [Source: Parker, 1995. First cited in Betancourt, 1990.]

municipal use. Today, naturally occurring perennial reaches occur only in the uppermost part of the river in the San Rafael Valley (Betancourt and Turner, 1988).

Two reaches of the upper Santa Cruz River have perennial flow and riparian forests resulting from the discharge of secondary-treated municipal effluent. Discharge of sewage effluent from the treatment plants at Ina Road and Roger Road began in 1970 and has resulted in perennial flow in the channel past the Cortaro streamgage. The second reach, south of Nogales, has had perennial baseflow since the Nogales Wastewater Treatment Plant began discharging effluent into the Santa Cruz at the mouth of Potrero Creek in 1972 (Brown *et al*, 1978). The flow is now perennial from the mouth of Potrero Creek to Tubac, as it was during the historical period of 1775-1872, although surface flow becomes underflow near Otero and reemerges upstream from the Rancho Santa Cruz guest ranch, just north of Josephine Canyon. (Applegate, 1981). In winter, the stream frequently flows to just south of Continental Road due to less water consumption by vegetation upstream (Betancourt and Turner, 1990; Halpenny, 1988).

Streamflow Characteristics

The goal of this section is to provide a description of the flow characteristics at the time of Statehood and to determine how the flow characteristics have changed over time. We combine information gathered from previous studies with an analysis of annual peak, daily average and monthly average discharge series. The discharge series records are from gages located near Lochiel, Nogales, Continental, Tucson, Cortaro and Laveen, and are of varying lengths and quality. Table 2 lists the period of record and contributing drainage area for each gage. We begin this section with a description of infiltration processes and the no-flow characteristics of the Santa Cruz River channel, and then focus on the characteristics of the daily, monthly and peak discharge series.

Infiltration and No-Flow Conditions

The streambed of the Santa Cruz River is generally quite permeable, and water is lost to the subsurface as flood flows move downstream (Condes de la Torre, 1970). Figure 5 illustrates the reduction by channel losses of the September 12-14, 1965 flow event. Burkham (1970) analyzed two reaches of the upper Santa Cruz River in his study of streamflow depletion by ***infiltration*** in several streams in the Tucson Basin. He found that

Table 2. Santa Cruz River U.S. Geological Survey Streamflow Gages.

GAGE	PERIOD OF RECORD (Monthly Flow)	DRAINAGE AREA MI^2
1. LOCHIEL:	Jan. 1949 to May 1990	82.2
2. NOGALES:	Jan. 1913 to June 1922, May 1930 to July 1990	533
3. CONTINENTAL:	May 1940 to Dec. 1946, Oct. 1951 to Sep. 1985 Oct. 1989 to July 1989	1,682
4. TUCSON:	Oct. 1905 to Dec. 1907, Jan. 1913 to Sept. 1982	2,222
5. CORTARO:	Oct. 1939 to June 1947, July 1950 to Sept. 1984	3,503
6. LAVEEN:	Jan. 1940 to Sept. 1946, Dec. 1947 to Aug. 1990	8,581

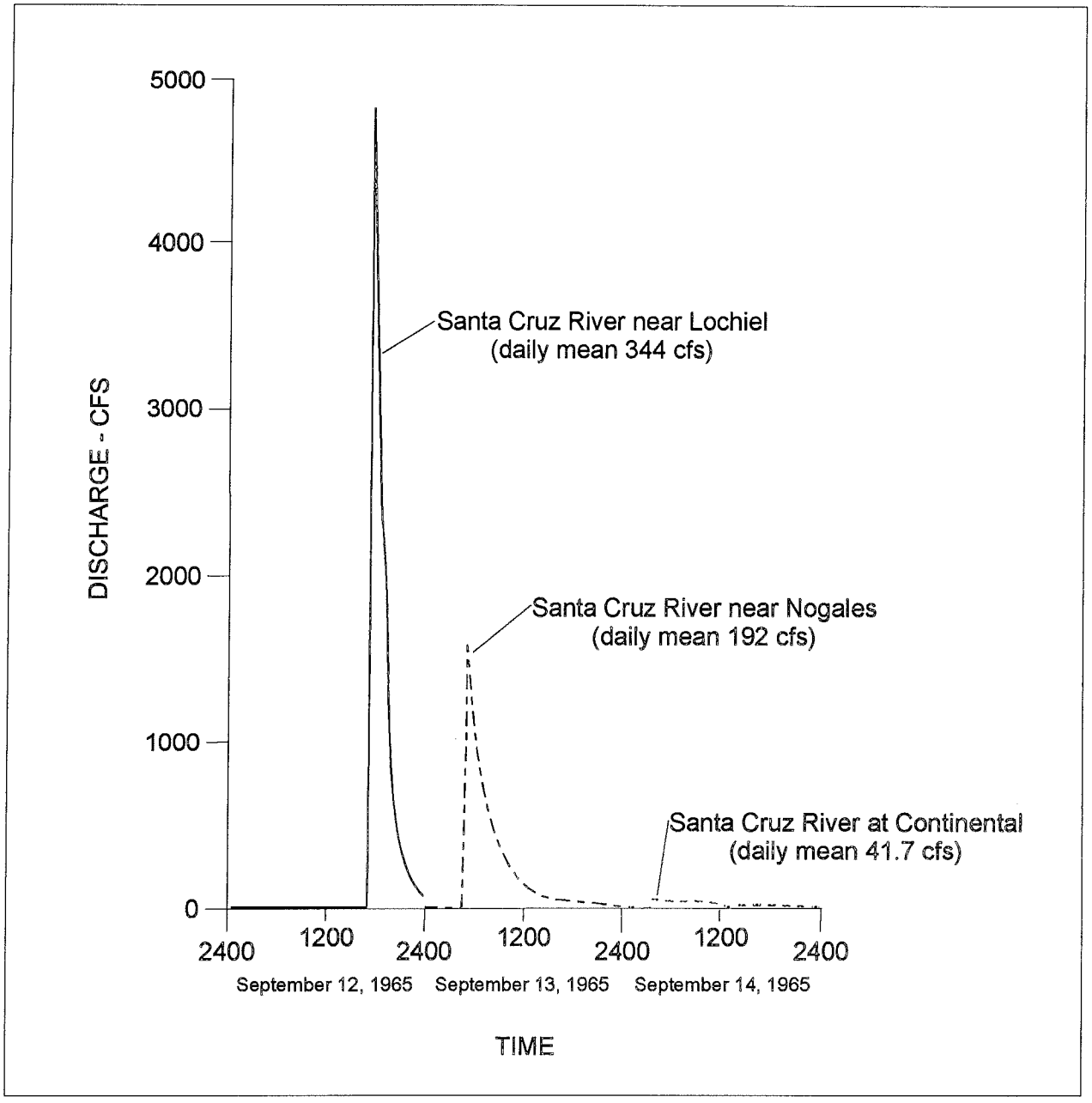


Figure 5. Reduction of the flood peak by channel losses in the Santa Cruz River. [Source: Condes de la Torre, 1970.]

about 40.2% of the average annual inflow was depleted by infiltration along the 28.5 mile reach between the gaging station at Continental and the gaging station at Tucson. About 29.9% of the inflow was depleted along the 12.3 mile reach between the gaging station at Tucson and the station at Cortaro.

Condes de la Torre (1970) discerned several relevant hydrologic characteristics in his analysis of the time distribution of streamflow. He found by studying ***flow-duration curves*** for the period 1936 to 1963 that streamflow occurred in direct response to precipitation and that snowmelt and groundwater discharge did not contribute sufficient amounts of water to sustain flow at any of the gaged reaches in his study. In his analysis of low flows in the Santa Cruz River basin, he calculated the frequency of days having no flow and their return intervals for the period of record for selected gages (Figure 6). For example, in any future year there is a 50 percent chance of 30 or more days of no flow at Nogales and 328 or more days of no flow at Continental.

Daily Average Flow Characteristics

Summer floods are extremely flashy and rarely last longer than a few days in both the upper and lower Santa Cruz River Basin (Figure 7). Schwalen (1942), in his study of the basin south of Rillito, found that flows in the upper part of the basin tend to be more or less continuous during the winter rainy season. Even in the reach near Tucson, flows may continue for four or five days, and during exceptionally wet winters, such as 1914-1915 and 1992-1993, flow may continue over several months. Figure 8 uses the earliest recorded gage data to provide an example of winter daily flow at Tucson and Nogales near the time of Statehood. Figure 9 illustrates the shift from the continuous winter flow to the sporadic flow of the summer season. The gage record indicates that by the time of Statehood, the Santa Cruz River at Nogales was no longer perennial, but instead had continuous flow during the winter and occasional flow during the spring, summer and fall. The winter discharge averaged about 15 cubic feet per second (cfs) except for an increase caused by a rainfall event that ranged from 35 to 174 cfs. The flow throughout the rest of the year ranged from 0 to 80 cfs. The streamflow record at Tucson indicates a similar seasonal flow pattern: an average daily flow of about 12 cfs during the winter, and during the April to September period there were only five days with recorded flow in that reach.

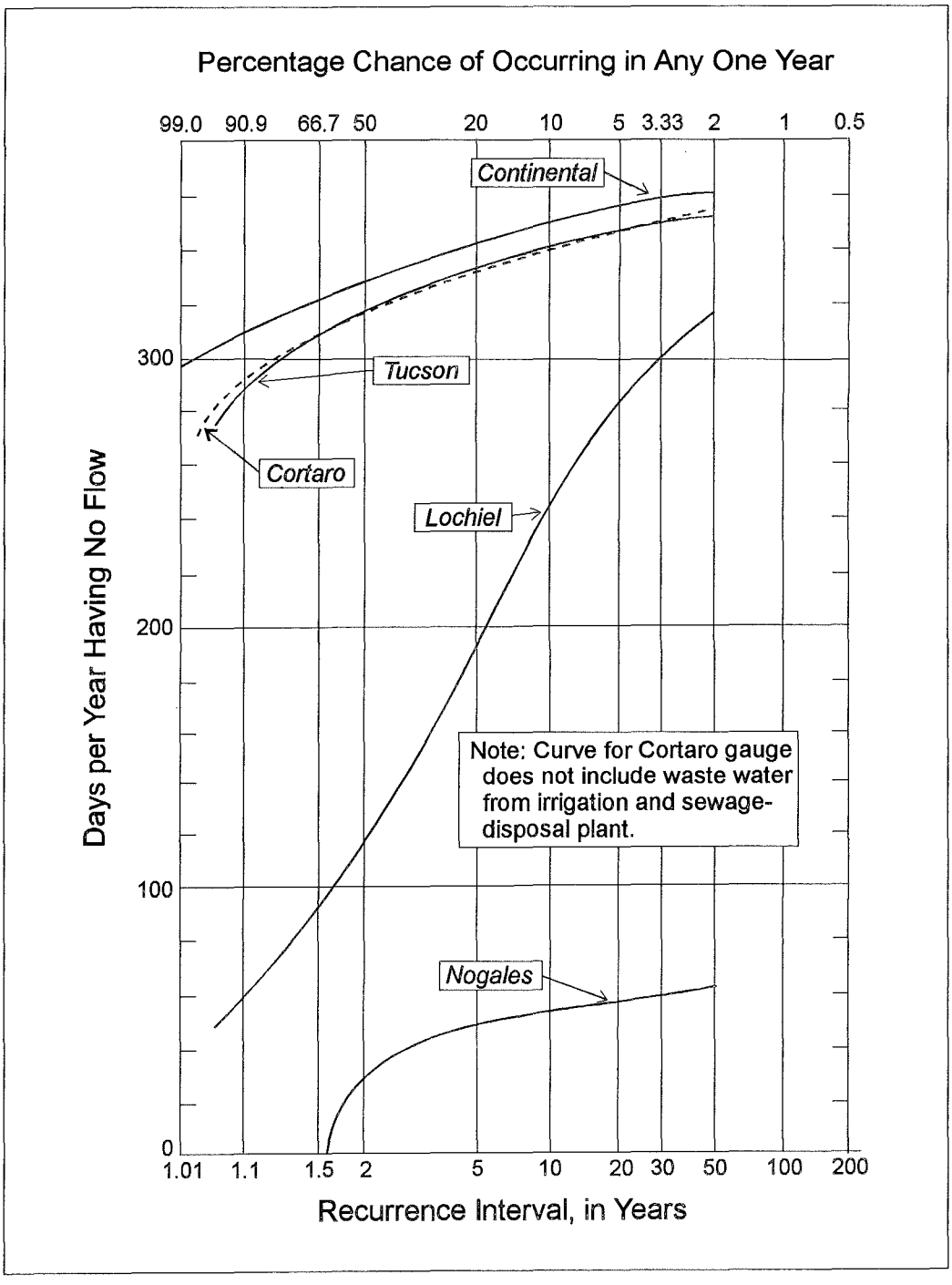


Figure 6. Frequency of days having no flow at selected gaging stations on the Santa Cruz River. [Source: Condes de la Torre, 1970.]

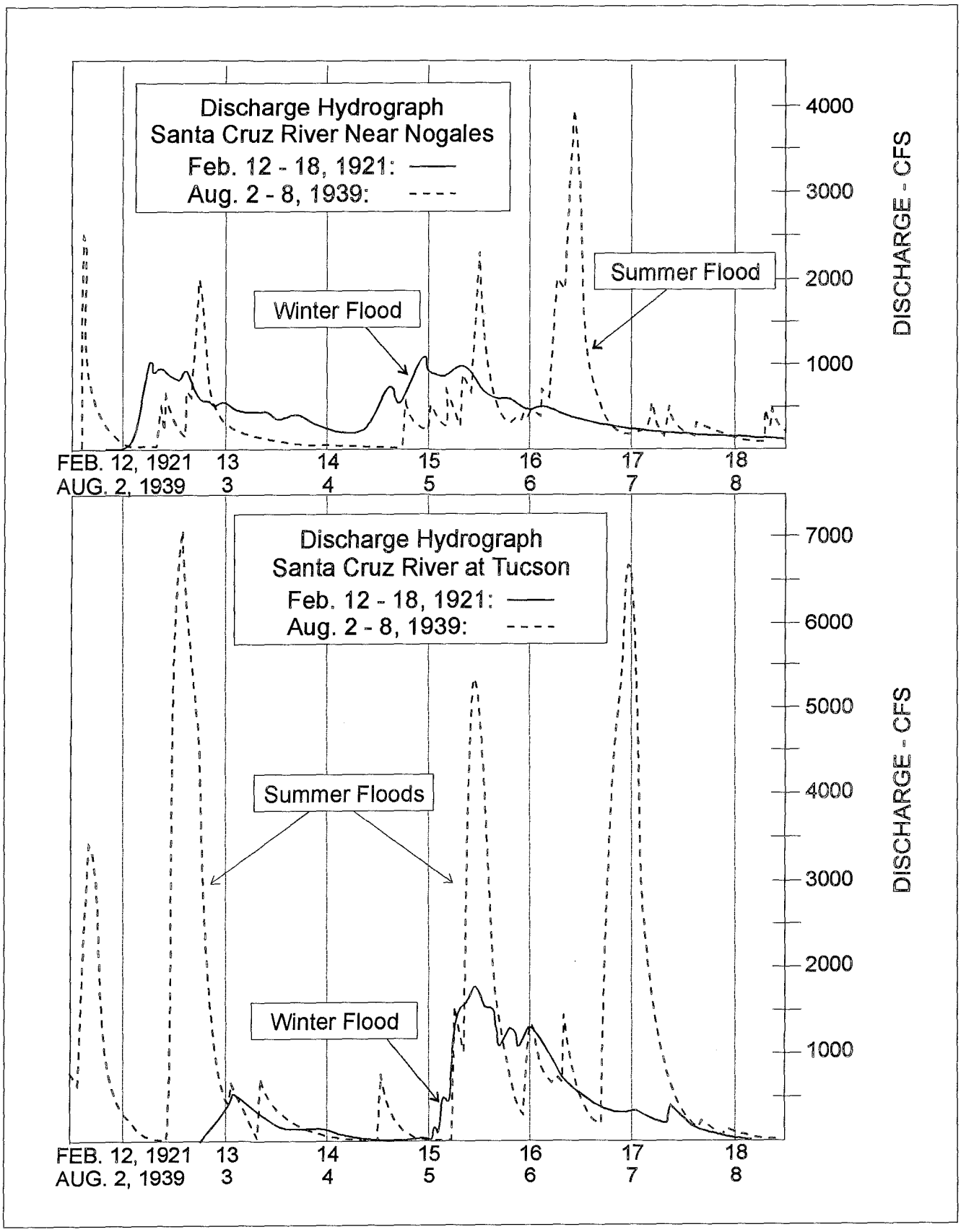
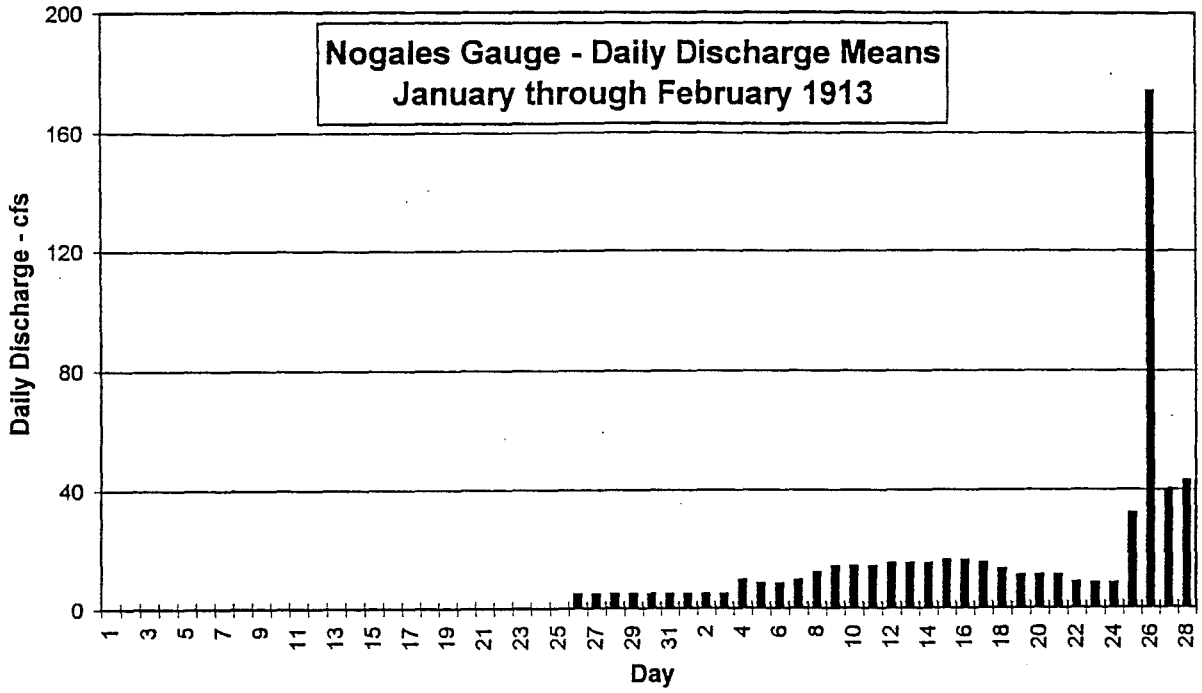


Figure 7. Comparative discharge hydrographs for the Santa Cruz River near Nogales and at Tucson for a summer and winter period of large flow. [Source: Schwalen, 1942.]

Figure 8. Daily discharge data for a winter period at the beginning of the centuy.

Note: the Nogales record began January 26, 1913.



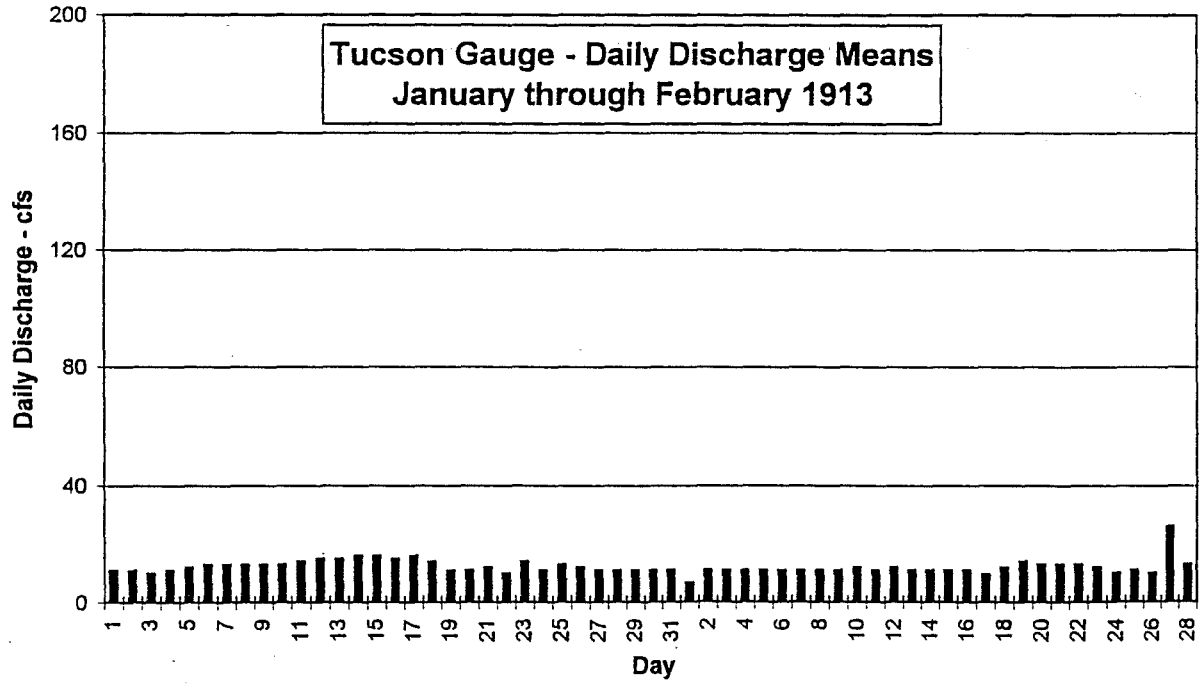


Figure 9a. Daily discharge means at the Nogales gage, March through September, 1913.
Note: days of each month are numbered from left to right, beginning with March 1 and ending with September 30.

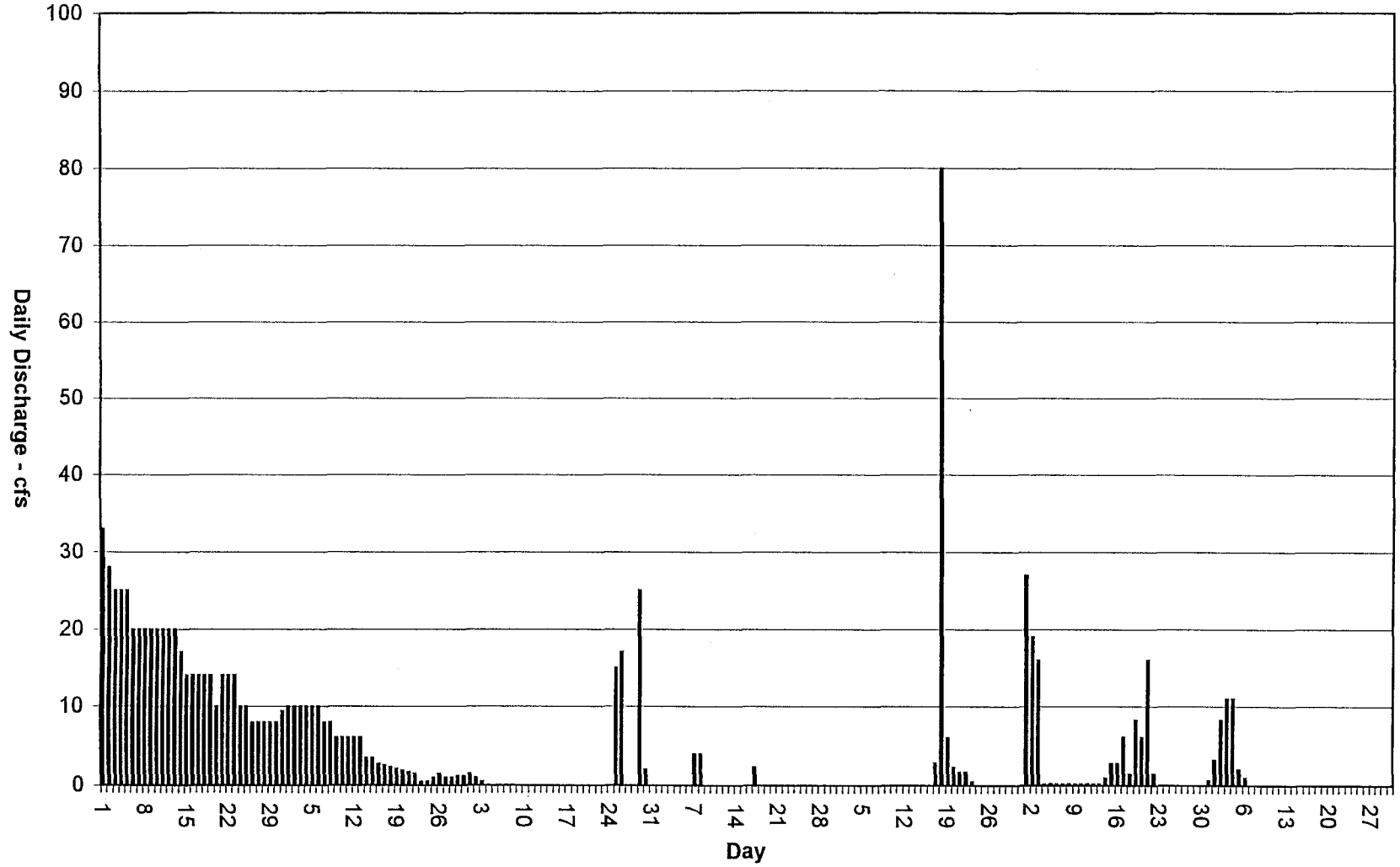
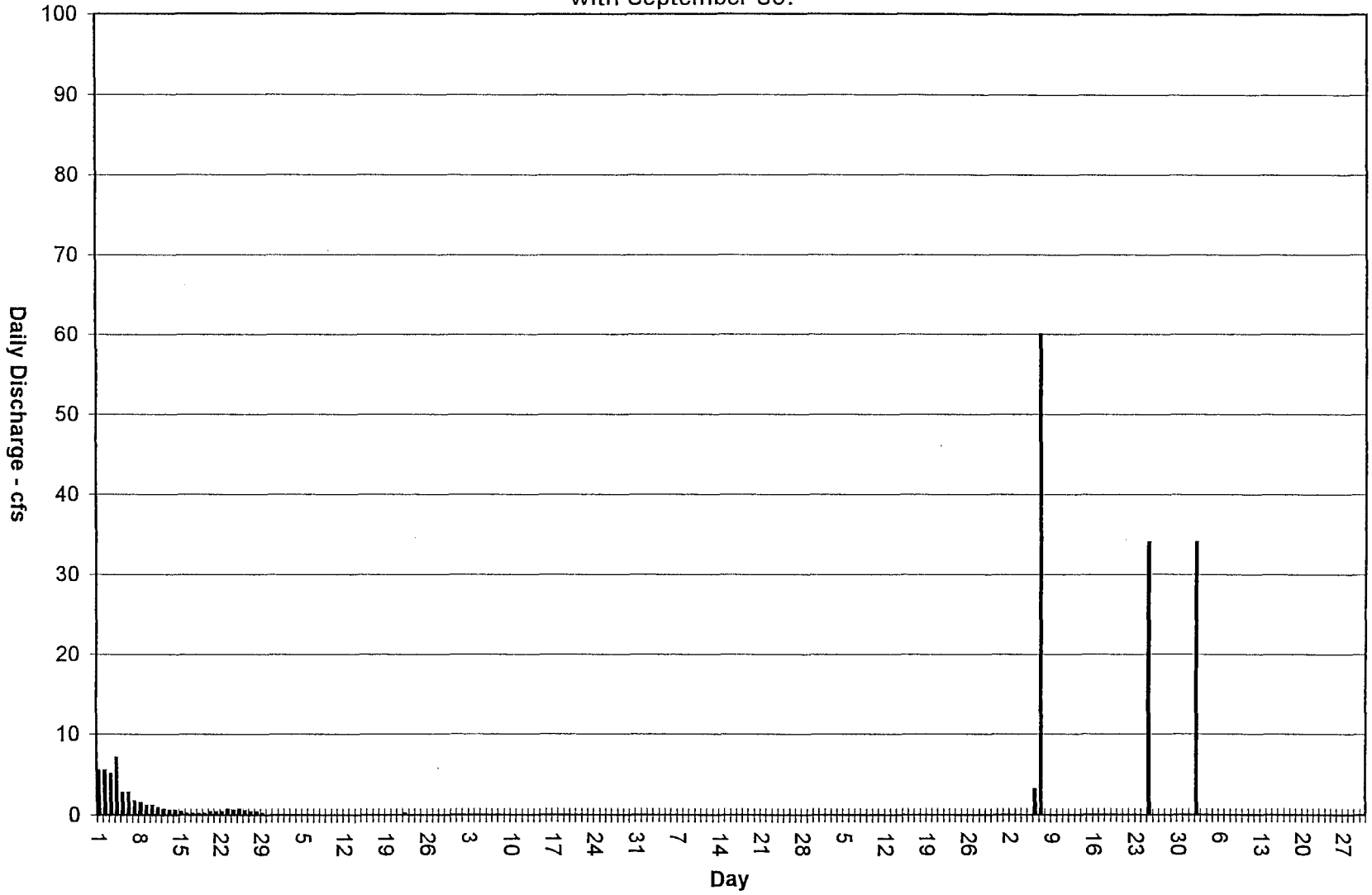


Figure 9b. Daily discharge means at the Tucson gage, March through September, 1913.
Note: days of each month are numbered from left to right, beginning with March 1 and ending with September 30.



The daily stream flow of the Santa Cruz River has changed markedly over time in response to climate changes and human activities. Webb and Betancourt (1992) discerned that daily discharges in summer months that were exceeded less than 2 percent of the time were much higher for 1930-59 than for 1915-29 or for 1960-1986, and that daily discharges in fall months that were exceeded less than 2 percent of the time were much less for 1930-59 than before or after. These temporal changes in daily flow characteristics reflect the changes in climate over the past century that were discussed previously.

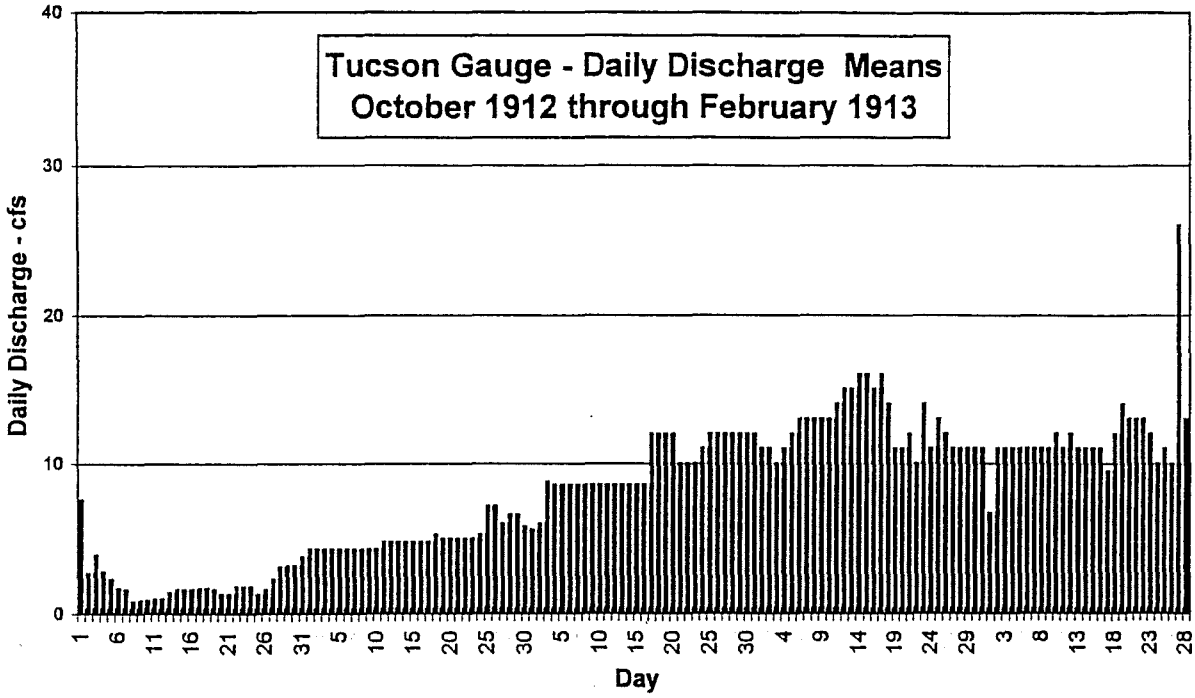
Although much of the change in the hydrologic record can be explained by changes in the climate, some have more direct links to human activities and channel changes. Figure 10 compares the daily flow at Tucson for the period nearest in time to the date of Arizona's Statehood (1912-1913) to the more recent period (1980-1981) measured by the gage before it was deactivated. Although both the 1912-1913 and 1980-1981 records were measured during periods that were dominated by fall and winter flows, the 1980-1981 record does not have the continuous flow that characterizes the 1912-1913 record, and it has much higher daily flow averages. These hydrologic changes resulted from a combination of factors: climate change, the lowering of the water table induced by groundwater pumping, and channel changes such as arroyo development and channelization that are discussed in the next section.

The Laveen gage, which was established in 1940 near the confluence of the Santa Cruz and Gila Rivers, apparently also had continuous baseflow until about 1956. During the 1940 to 1956 period, the daily flow averaged about 3 cfs during low flow conditions and had peaks as high as 5060 cfs during wet periods. In 1960, the Santa Cruz at Laveen began to experience no-flow conditions for months at a time. In the following years, the Laveen reach continued to experience months at a time with no flow. Again, this change probably was a result of the combination of climate change, channel incision at that reach, and the dramatic increase in groundwater pumping that occurred in that region during the middle part of the century.

Monthly Average Flow Characteristics

The monthly flow averages illustrated in Figure 11 reflect the seasonality of the precipitation. The peaks occur during the summer and winter seasons. The high frequency of no-flow conditions result in very low monthly averages for April, May and

Figure 10. Comparison of daily discharge data for the fall-winter period of 1912-13 and 1980-81.



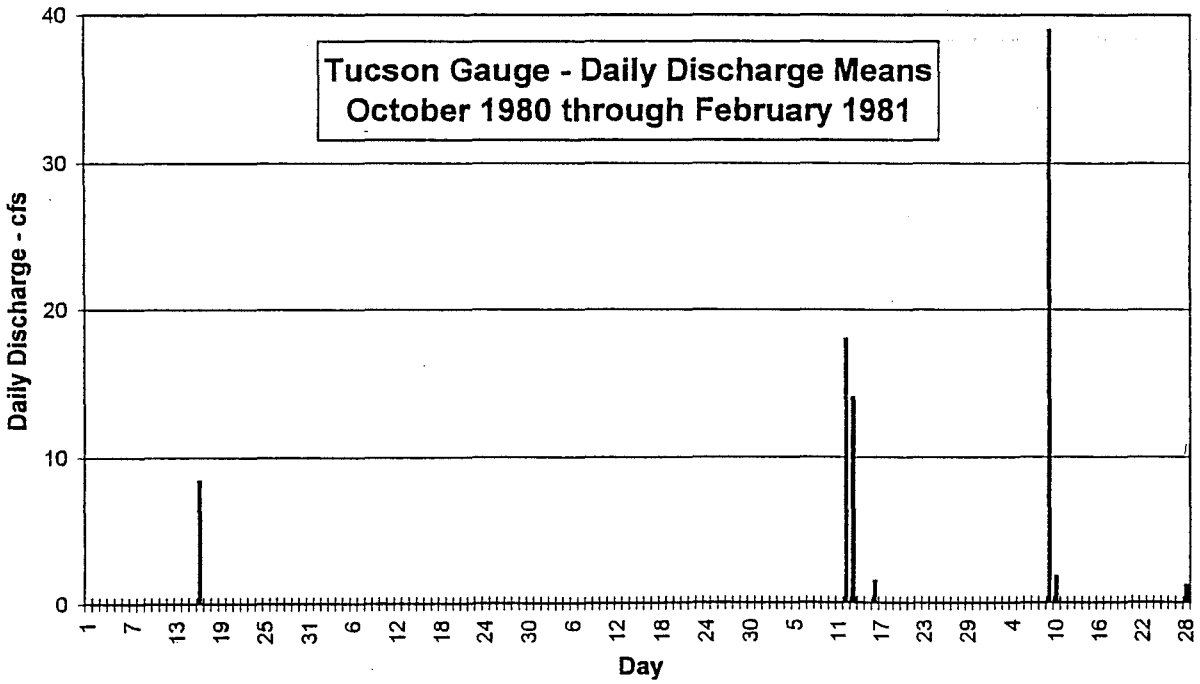
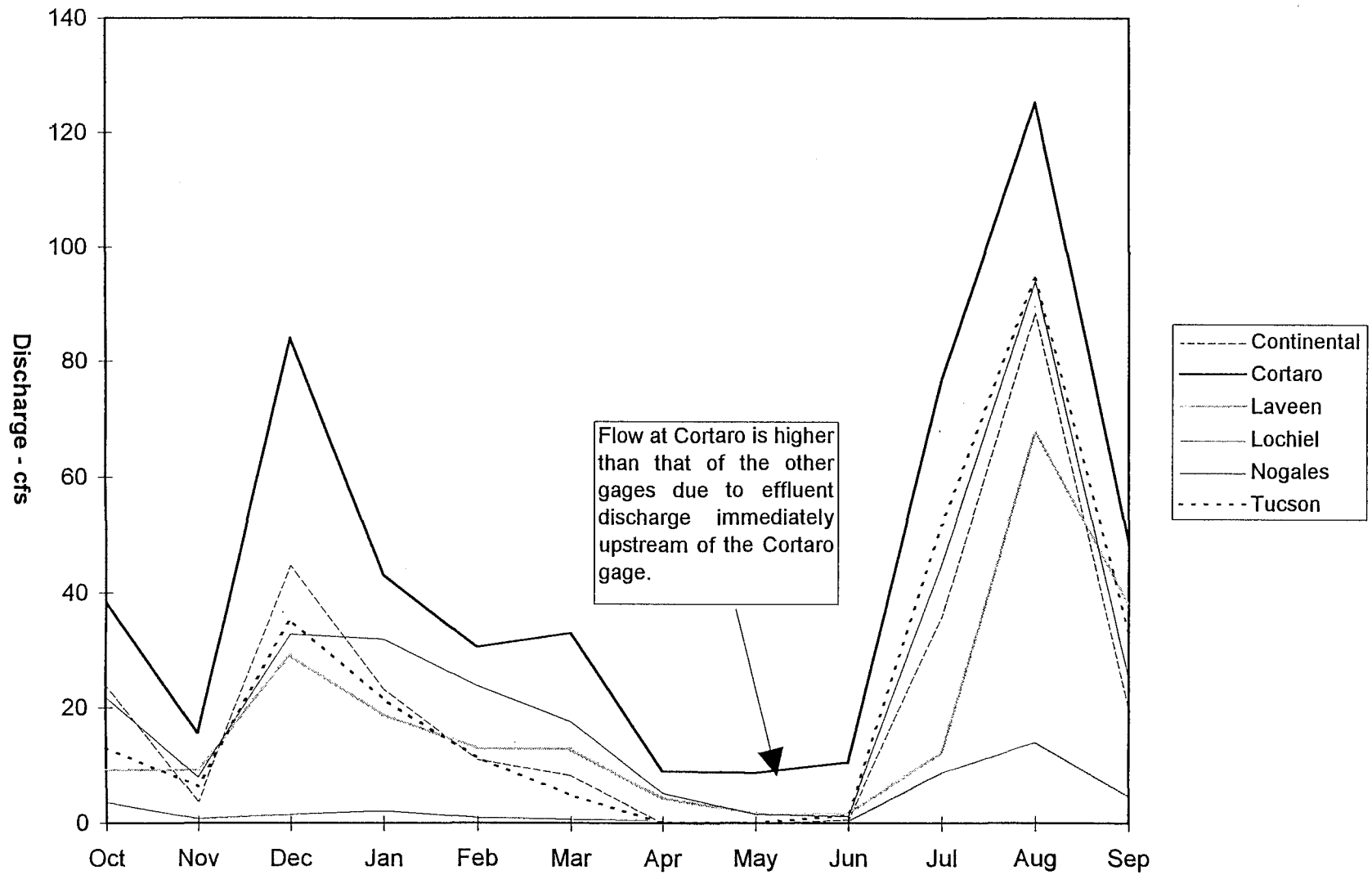


Figure 11. Monthly flow averages at the six gages on the Santa Cruz River.



June. The Cortaro gage records the highest monthly averages during drought months because of the input of discharge from the sewage treatment plants upstream.

Figure 12 compares the average monthly discharge and monthly streamflow variability of the Santa Cruz River at Tucson. It shows that the year-to-year variability is less for the summer months than for the fall, winter and spring seasons. Decadal variability in the monthly averages reflects changes in the peak flow characteristics discussed below and are strongly related to climate change.

Peak Flow Characteristics

Peak flows in the Santa Cruz River typically result from summer monsoon storms, fall tropical storms and/or cutoff lows and winter frontal storms. Hirschboeck (1985) assigned a insert hydroclimatic classification to each flow event occurring at selected gauging stations during the period 1950 through 1980. (See Figure 1 for locations of the streamgages.) For the gage at Tucson, 104 of the 140 flow events analyzed occurred during the monsoon season, 18 were attributed to tropical storm and/or cutoff lows, and 11 were attributed to frontal passages. Of the 119 flows analyzed at the gage near Nogales, 95 were attributed to monsoonal weather patterns, 8 to tropical storms/cutoff lows, and 10 to fronts. At Lochiel, 47 of the 56 flows studied were classified as monsoonal, 4 as tropical storms/cutoff lows, and 3 as frontal in origin.

All six gages measured their highest discharges in the latter portions of their records (Figure 13). Webb and Betancourt (1992) argued that the changes in magnitude and seasonality of annual peak flows resulted from climate change rather than channelization and land-use changes:

> "Although land use and changes in channel conveyance undoubtedly have increased flood discharges to some unknown extent, climatic effects are the only common link between the six gauging stations on the Santa Cruz River... At Lochiel, flows in the Santa Cruz River could not have been affected significantly by land use, yet peak discharges have increased since 1960... The August 1984 flood at Lochiel, the peak of record, was larger than the October 1983 flood, which indicates the apparent changes are not caused by a few isolated large floods. Changes in the hydroclimatology of the basin are reflected by

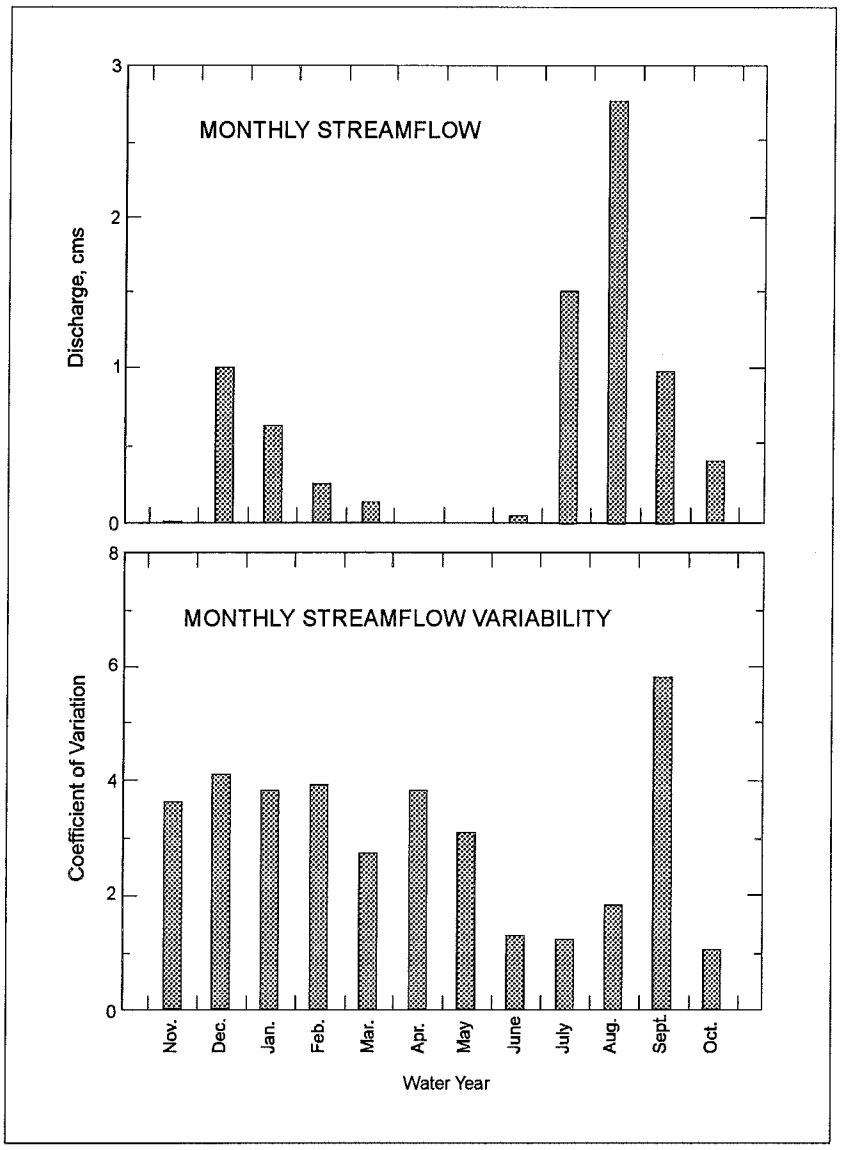
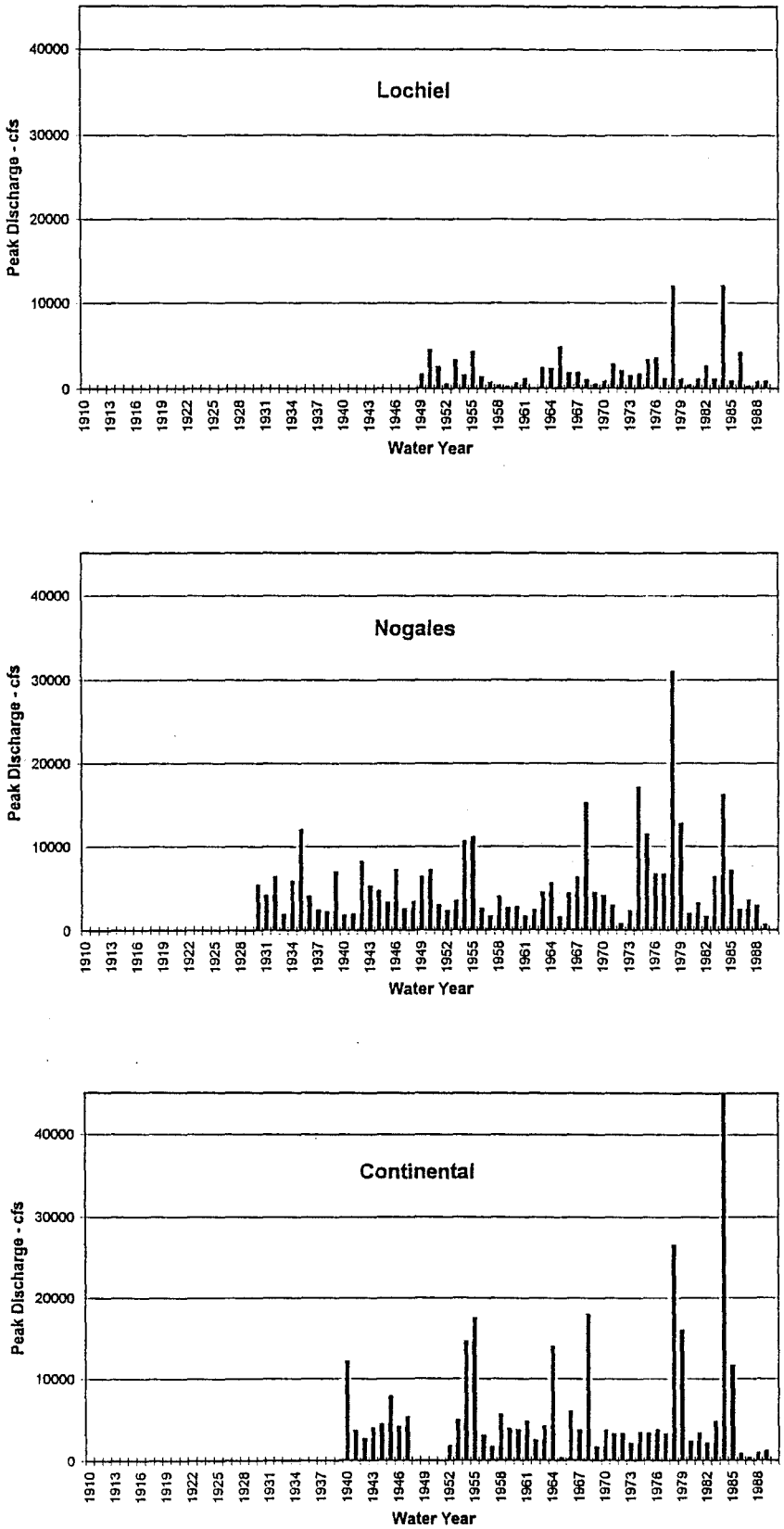


Figure 12. Average monthly streamflow and monthly streamflow variability, Santa Cruz River at Tucson, [Source: Webb and Betancourt, 1992.]

Figure 13a. Annual peak discharges at Lochiel, Nogales, and Continental.



a shift in the seasonality of annual peaks, which is also the most striking symptom of the underlying climatic control of flood frequency." (Webb and Betancourt, 1992, p. 23)

Although flood-frequency estimates for the Santa Cruz River are strongly influenced by the extraordinary October 1983 flood, six of the seven largest floods at Tucson occurred after 1960. Winter and fall floods account for 53 percent of annual peaks before 1930, only 3 percent from 1930 to 1959, and 39 percent after 1960. Seven of the eight largest peaks in the flood series were produced by fall or winter storms, and five of these occurred between 1960 and 1986. Although most of the annual floods at Nogales occurred in summer, four of the six largest floods occurred in fall or winter. Webb and Betancourt (1992) concluded that these changes indicate that the seasonality of flooding is not stationary or random on the Santa Cruz River.

Rhoades (1991) determined that land-use changes in the lower Santa Cruz River basin have affected the peak flood discharges. Since 1962, the construction of flood-control channels in the washes of the lower Santa Cruz basin have resulted in the reduction of floodplain storage and infiltration losses, therefore reducing the *attenuation* -- the downstream decrease of the flood peak -- of peak discharges. Rhoades (1991) compared the input/output volume ratios for the floods of September 1962 and October 1983, both events caused by widespread, heavy precipitation associated with tropical storms. He concluded that attenuation of peak flow was greater during the 1962 flood because water was able to spread out over the broad flow zones in the lower reaches of the Santa Rosa and Santa Cruz washes. In contrast, much of the floodwater during the 1983 flood was efficiently transmitted downstream by the flood-control channels.

CHAPTER 6. GEOMORPHOLOGY

One of the main goals of this study is to determine the nature of channel changes along the Santa Cruz River, especially any changes in location of the channel boundaries since the time of Statehood. To do this, we focused on three objectives: 1) to gather the oldest and most recent aerial photographs and historical and current survey maps of the Santa Cruz River; 2) to compile channel configurations through time (as determined from

the aerial photographs and survey maps) onto a single base map; and 3) to integrate historical accounts, previous channel change studies and channel location data.

The temporal and spatial scales of channel change along the upper and lower Santa Cruz River are dramatically different. Channel change in the upper reaches of the river have been on the order of thousands of feet, and they can be detected through the comparison of aerial photographs for one year to photographs of consecutive years. In contrast, changes in the location of the channel in the lower basin can be measured in miles, and due to the nature of the causes of the changes, the timing spans decades of years. For this reason, we developed different strategies for the mapping of channel locations in the upper and lower reaches. For the upper Santa Cruz River north of the Mexico-United States border, we compiled the channel locations discerned from the oldest survey maps (~1904-1916), the oldest aerial photographs (1936), and the most recent aerial photographs (1995) onto 1:24,000-scale base maps. For the lower Santa Cruz River, we compiled the flow paths of several of the largest flow events that occurred on the Santa Cruz River in this century onto one 1:100,000-scale base map.

The first part of this chapter provides a background of the different types of geomorphic processes that result in changes of a river's channel. Examples from along the upper Santa Cruz River are used to illustrate the different types of channel change. Because of the important role that arroyo formation and change play in defining the character of the upper Santa Cruz River, the second section is devoted to a review of the theories of arroyo development and to descriptions of arroyo formation and change along the Santa Cruz River. The third section documents the disparate courses taken by the flood flows of 1914-15 and 1983, with a focus on the effects of the Greene's Canal construction on the flood paths. Descriptions of channel location changes and arroyo development from the literature are integrated with information gathered from our study of aerial photographs and historical survey maps.

Types of Channel Change

Channel patterns are a result of the interplay between local geology, precipitation and runoff, sediment influx and movement, vegetation and land-use, and the larger context of the drainage basin (Hays, 1984). Parker (1995) thoroughly reviewed mechanisms of channel and arroyo change on the Santa Cruz River in Pima County. He described three types of lateral change: meander migration, avulsion and meander cutoff, and channel

widening. He described two types of vertical change: aggradation and degradation of the channel bed. He determined that the dominant mechanism in each reach depended on channel morphology, channel sediment, bank resistance, and flood magnitude, and he noted that where the channel is entrenched into an arroyo, a combination of fluvial processes and bank retreat mechanisms leads to arroyo change. Table 3 describes the various channel change mechanisms outlined in his review. Hays (1984) noted that soil types bordering the channel reaches affect the stability of channel location, and that banks composed of coarser soils tend to be more prone to erosion than those composed of more cohesive soils containing more silts and clays.

Several human modifications have resulted in channel change on the Santa Cruz River (Hays, 1984; Betancourt and Turner, 1990; Rhoades, 1991; Parker, 1995). Nine different categories of modifications and their effects in the upper and lower Santa Cruz River basin are summarized here. The first six modifications listed have had the greatest effect on channel morphology in the Santa Cruz River basin:

1) **Bank protection and bridge construction** stabilize the position of an alluvial channel by preventing the channel from adjusting its dimensions laterally in response to increased discharge. This results in the artificial concentration of streamflow, increases in stream power, and increased peakedness of flood hydrographs. Bank protection also can remove a major sediment source by preventing bank erosion, thus lowering sediment concentrations of a given discharge and enhancing the erosiveness of streamflows. Bridge construction has locally stabilized channel positions in both the San Xavier and Cortaro reaches.

2) **Channelization** typically shortens stream length, increases stream power and decreases attenuation of flood peaks. Both channelization and bank protection initially cause degradation within and upstream from the altered reach, aggradation downstream from the altered reach, and increased erosion at unprotected sites. Continued degradation may result in a period of channel widening by producing steep banks in unprotected reaches that fail readily, while continued aggradation may result in the plugging of downstream channels and a shifting of channel position by avulsion. Channelization has been implemented in several reaches of the Santa Cruz River, most notably in the San Xavier and Tucson reaches of the upper Santa Cruz River, and throughout the lower Santa Cruz River for the purpose of flood control.

Table 3. Channel Change Mechanisms [Source: Parker, 1995]

MECHANISM	DESCRIPTION
Meander migration:	Lateral shifts of centerline position associated with the inception of meanders and their subsequent downstream translation, lateral extension, or rotation of meander axis.
Avulsion:	An abrupt shift in channel position that occurs when overbank flow incises new channels as other channels aggrade and are abandoned.
Meander cutoff:	An abrupt shift in channel position that occurs at meanders and may or may not involve concurrent aggradation of the abandoned channel segment. Meander cutoff and avulsion tend to occur where channels are shallowly incised, the floodplain is active, and aggradation rates generally are high.
Channel widening:	Results primarily from high flows that erode weakly cohesive banks. It is different from arroyo widening because arroyo boundaries may delineate not only a channel but also a floodplain at the bottom of the arroyo. It is product of corrasion by fluvial erosion during rising flow, or mass wasting by of banks following the flow peak.
Vertical change:	Results from changes in stream power, sediment concentration, or resistance that occur as a result of variation in flood magnitude, sediment availability, channel morphology, or local channel gradient. "Degradation and aggradation occur over years to decades and may reflect climatic changes, adjustments to channel widening or narrowing, sediment storage and episodic transport, and natural or artificial changes in channel-hydraulic properties... Degradation and aggradation can alternate in time and space." [Parker, 1995, p.24]

3) **Artificial diversion of drainage** diverts flow to a different route or to a reservoir for the purpose of: (a) flood control; (b) irrigation, as was the goal of the Greene's Canal project in the lower Santa Cruz River; or (c) protection from erosion, as in the San Xavier reach in the upper basin.

4) **Obstruction of regional drainage lines** alters flood patterns. The construction of roads, highways, and railroads that trend perpendicular to the courses of washes and streams cause such transportation routes to act as barriers to flow, resulting in widespread inundation immediately upstream. Notable examples of this occur in the lower Santa Cruz River basin where Chuichu Road crosses Greene Wash near Chuichu, where Highway 84 and Interstate 8 cross the Santa Cruz Wash, Greene Wash and Santa Rosa Wash west of Casa Grande, and where the Southern Pacific Railroad crosses the Santa Rosa and Santa Cruz washes east of Maricopa (Rhoades, 1991).

5) **Artificial narrowing** (i.e. by emplacement of artificial fill along channel margins) may reduce capacity and armor the banks against erosion, producing the same effects as bank protection and channelization. The incision of the channel bottom at Tucson of 9 to 15 feet after 1946 (Aldridge and Eychaner, 1984) may have resulted from the artificial narrowing of the channel by the dumping of garbage and highway construction debris into the channel and adjacent floodplain (Betancourt and Turner, 1988).

6) **Discharge of sewage effluent into downstream reaches** leads to an increase in vegetation that results in more rapid sediment accretion and stabilization of the channel. The Tumacacori and Cortaro reaches dramatically illustrate the effects of the establishment of riparian vegetation that resulted from the perennial flow maintained by sewage effluent.

7) **Dam and reservoir construction** reduces or eliminates the threat of flooding from runoff. The Tat Momolikat Dam in the upper Santa Rosa Wash, completed in 1974, was constructed to control flows originating from the Santa Rosa basin. As footnoted later in this chapter, the dam has not succeeded in eliminating flooding along the lower Santa Rosa Wash.

8) **Sand-and-gravel operations** within the floodplain.

9) **Channel-maintenance operations**.

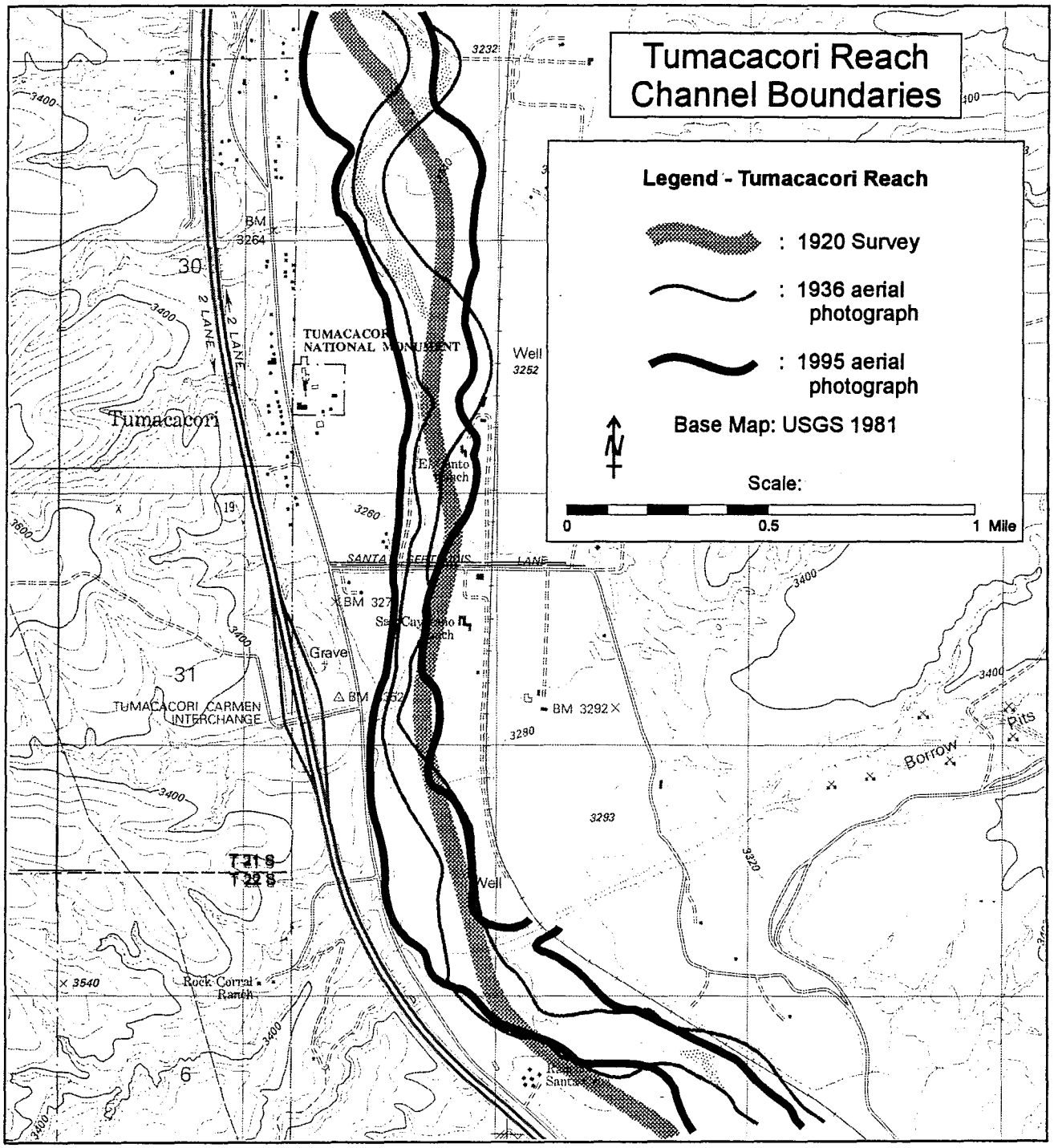
The following sections provide more detailed descriptions of reaches where geomorphic processes and human activities have resulted in dramatic channel change along the Santa Cruz River.

Tumacacori Reach

The reach of the Santa Cruz River near the Tumacacori National Monument (Figure 14) illustrates the effects of channel widening processes. Widening is especially apparent downstream of Tumacacori. Masek and Corkhill (Masek, 1996, personal comm.), using 1954 aerial photographs, observed that the Santa Cruz River in this region was channelized and lacked natural meanders for most of its course downstream of Sonoita Creek. By 1973, Masek and Corkhill observed that the dikes, levees and energy-dissipating structures seen in the 1954 aerial photographs had not been maintained and channel widening had occurred. The flood of October 9-10, 1977, which had a calculated peak discharge of 35,000 cfs at Santa Gertrudis Lane, resulted in several changes in the channel configuration (Applegate, 1981). The flood caused the main channel to become broader and flatter, the low flow channel to change its course in many places, and extensive bank erosion to occur. Applegate (1981) noted that the property owner on the east side built a stone wall to protect his fields, and mechanically widened and cleared the channel for about 1,000 feet of its length. By 1995, the Santa Cruz River had cut new channels, noticeably widened its meanders, eroded farmland, and allowed for the establishment of new cottonwood and willow stands (Masek, 1996, personal comm.).

The Tumacacori reach also illustrates hydraulic and channel changes caused by the re-establishment of riparian vegetation that resulted from the sewage effluent discharge from the International Sewage Treatment plant north of Nogales. Applegate (1981) studied the reach of the Santa Cruz between its confluence with Josephine Canyon and where it crosses Santa Gertrudis Lane, 45 miles south of Tucson and 15 miles north of Nogales. He analyzed large-scale aerial photography that covered the site for ten different time periods from 1965 to 1980 in order to identify channel changes. He found that the average increase in water surface elevation over the reach would have been 2.3 feet for the 10-year flood and 2.0 feet for the 100-year flood from 1967 to September 1977, due to the increased vegetation. After most of the trees were scoured out during the floods of 1977, Applegate estimated that subsequent water surface elevations would have been much lower. Such increases in water surface elevations due to the effects of the increase in vegetation greatly increase the area inundated by flow once the main channel is filled. Figure 15 illustrates the increase in area inundated by the 1967 and 1977 flow events.

Figure 14


Tumacacori Reach
Channel Boundaries
Legend - Tumacacori Reach
: 1920 Survey
: 1936 aerial photograph
: 1995 aerial photograph
Base Map: USGS 1981
Scale:
0
0.5
1 Mile
Tumacacori
TUMACACORI NATIONAL MONUMENT
TUMACACORI CARMEN INTERCHANGE
Well
Grave
Borrow
Pits
Rock Corral Ranch
T 21 S
T 22 S
30
31
6
3400
3260
3280
3293
3320
3540
3232
BM 3264
BM 3292
BM 327
2 LANE

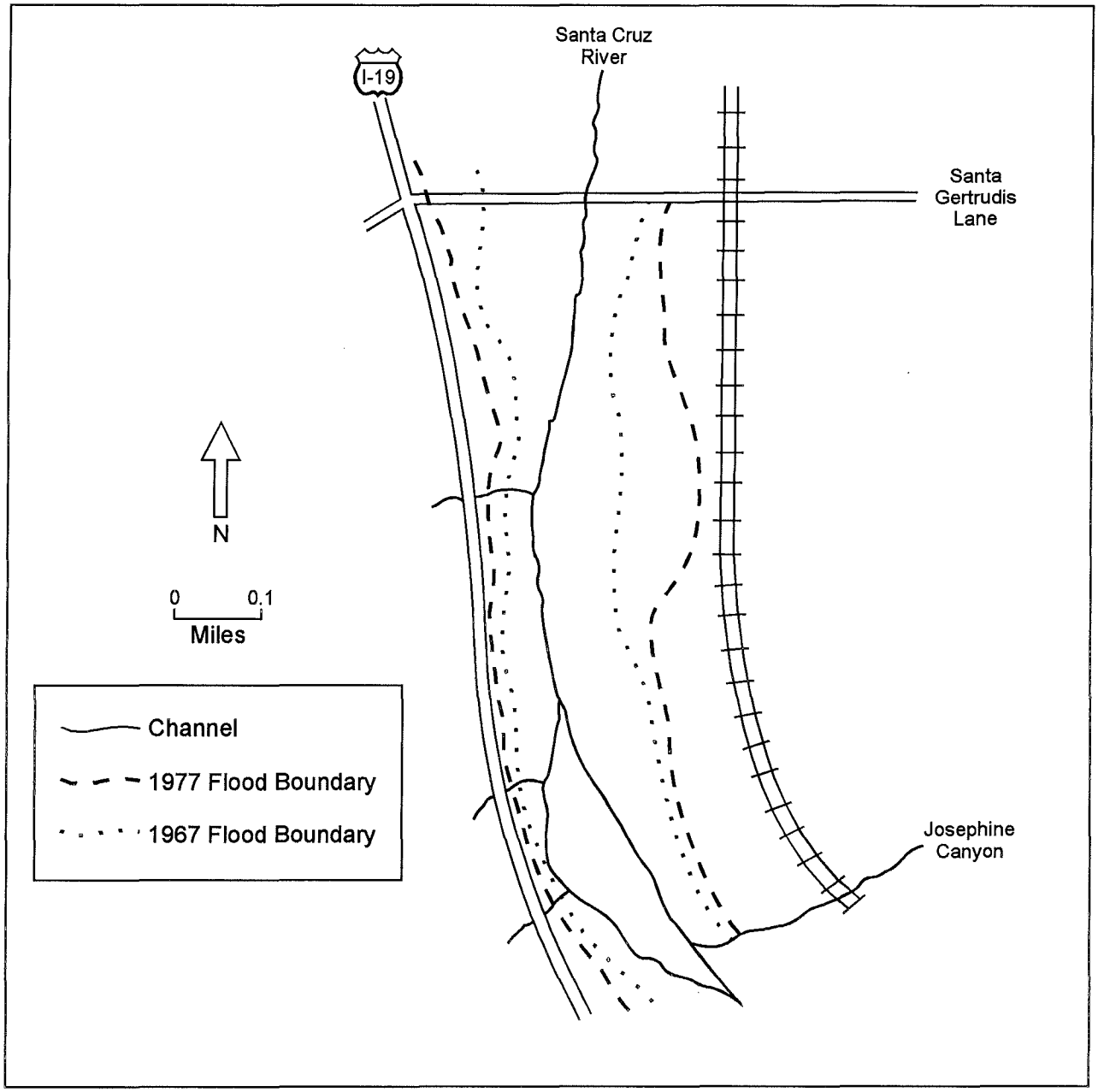


Figure 15. Calculated 100-year flood boundaries for 1967 and September, 1977, for a portion of the Tumacacori Reach of the Santa Cruz River. [Source: Applegate, 1981]

can be seen by the 1995 low flow channel illustrated in Figure 16, input of discharge from the sewage treatment plant not only has resulted in re-establishment of riparian vegetation, but also has restored year-round flow to this historically perennial reach.

Marana and Cortaro Reaches

Substantial aggradation, overbank flooding, and stream avulsions have occurred at the northern end of the Tucson Basin and beyond in recent years. Parker (1995) found that the Cortaro and Marana reaches of the Santa Cruz River had the most complex record of channel change since 1936 of all the reaches he studied in Pima County. Between 1936 and 1986, the Marana reach changed from a wide, braided channel to a compound channel that was less than half the width of the channel in 1936. Before 1966 the Marana and Cortaro reaches were sparsely vegetated ephemeral channels that experienced large, frequent shifts in position. At the turn of the century, the channels of these reaches were relatively narrow (Hays, 1984); they were drastically widened by the winter floods of 1914-1915. (See Table 4 for a comparison of channel widths at different sections in 1895 and 1936.) From 1936 to 1982, a period dominated by summer rainfall, there was an overall decrease in channel width from 418 feet to 236 feet. Hays (1984) noted that, although the downstream end of the study reach remained braided, much of the length of the study reach had developed into a narrow single channel pattern.

In 1970, when flow from sewage effluent discharge from Pima County's Ina Road and Roger Road treatment plants began, channel morphology became controlled by the low, steady base flows, and the channel became generally more sinuous than previously. The channel was also stabilized by vegetation growth, undergoing little change during the large 1977 flood. As a result of the peak flood of record in October, 1983, channel width widened to a mean width of 477 feet, with a range of 100 to 1300 feet. Figure 17 illustrates the boundaries of the 1916, 1936, 1968 (base map) and 1995 channels in the Cortaro reach. The change in channel boundary locations north of Cortaro Road show the meander migration that occurred between 1916 and 1968. The comparatively straight 1995 channel location indicates the meander cutoffs that resulted from the 1983 floods. The series of unconfined meanders in the Cortaro reach have been undisturbed by channelization throughout the historical period (Parker, 1995). Unconfined meanders do

Figure 16

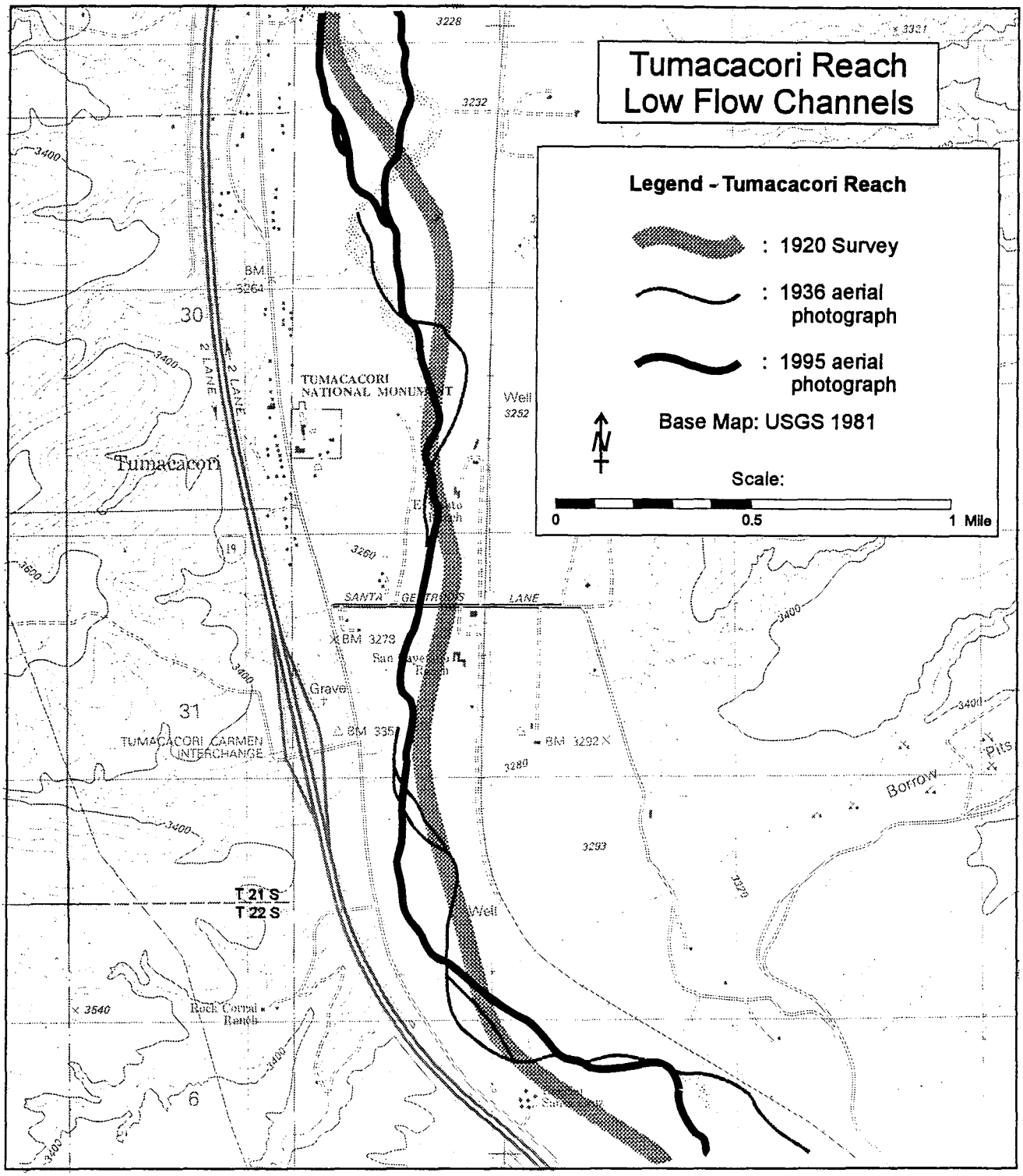
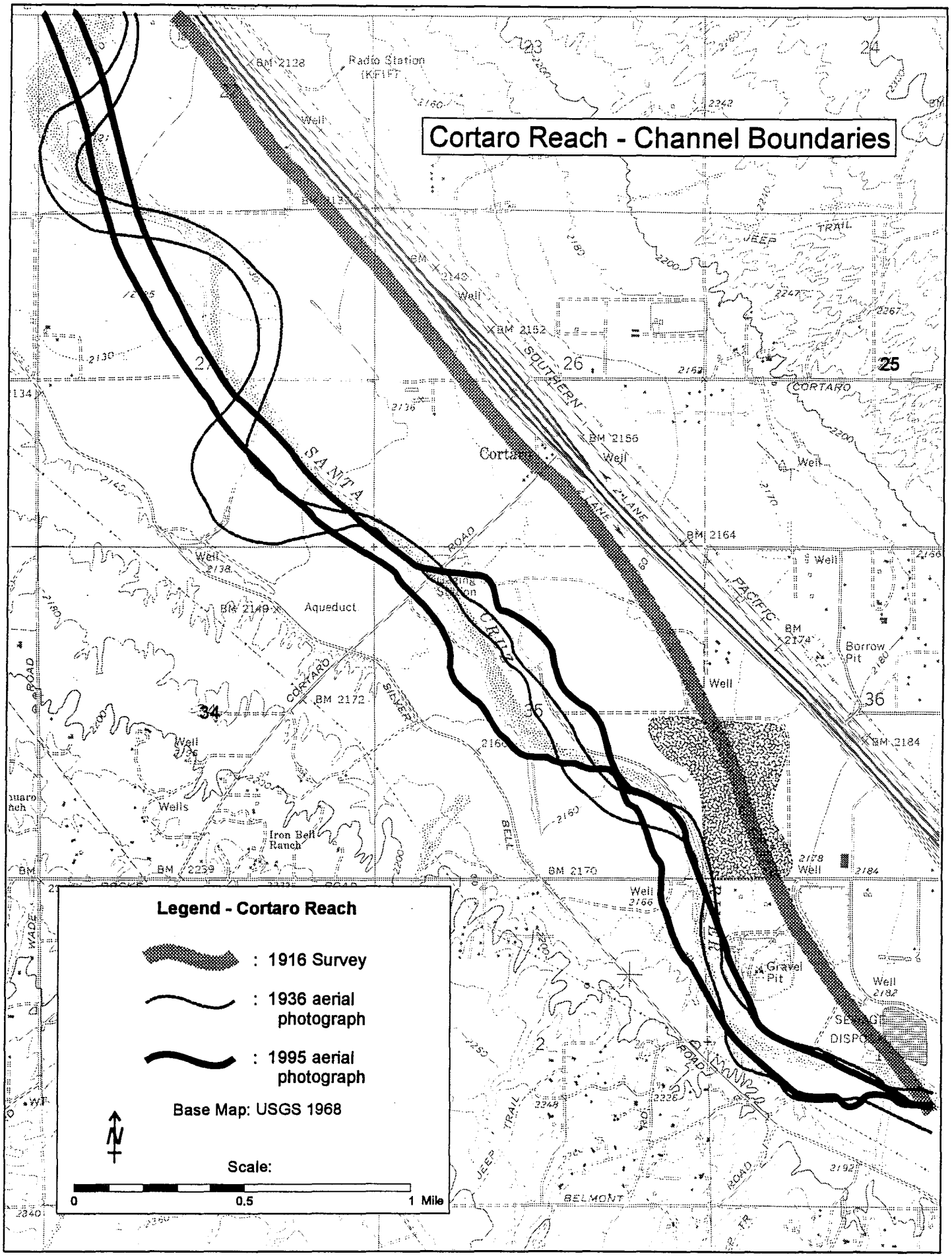

Tumacacori Reach
Low Flow Channels
Legend - Tumacacori Reach
: 1920 Survey
: 1936 aerial photograph
: 1995 aerial photograph
Base Map: USGS 1981
N
Scale:
0
0.5
1 Mile
TUMACACORI NATIONAL MONUMENT
Tumacacori
TUMACACORI CARMEN INTERCHANGE
SANTA GERTRUDIS LANE
Borrow Pits
T 21 S
T 22 S

Table 4. Comparison of 1895 and 1936 channel widths at selected cross sections downstream of the Cortaro reach illustrated in Figure 17. 1895 channel widths were derived from General Land Office Surveys; 1936 data were obtained from aerial photographs. [Source: Hays, 1984.]

Location	1895 Width (feet)	1936 Width (feet)	Percent Change
Between sec. 7 & 8 T.12 S, R.12 E	99	400	+300
Between sec. 6 & 7 T.12 S, R.12 E	79	170	+120
Between sec. 2 & 3 T.12 S, R.12 E	50	350	+610
Between sec. 3 & 34 T.11 S, R.11 E	152	550	+260
Between sec. 32 & 33 T.11 S, R.11 E	462	670	+150
Between sec. 29 & 30 T.12 S, R.12 E	937	950	+1

Figure 17


Cortaro Reach - Channel Boundaries
Legend - Cortaro Reach
: 1916 Survey
: 1936 aerial photograph
: 1995 aerial photograph
Base Map: USGS 1968
N
Scale:
0
0.5
1 Mile
Radio Station (KFIFT)
SANTA CRUZ RIVER
SOUTHERN PACIFIC
Cortaro
Aqueduct
Iron Bell Ranch
Borrow Pit
Gravel Pit
CORTARO
SILVER BELL
BELMONT
JEEP TRAIL
Well
Wells
BM 2128
BM 2152
BM 2156
BM 2164
BM 2149
BM 2172
BM 2184
BM 2170
BM 2239
BM 2174
25
26
34
36

occur on the Marana reach, but they tend to be isolated bends in an otherwise straight channel. These meanders were obliterated between 1976 and 1986 by the flood of 1983.

Channel shifting and widening occurred in the reach near Marana due to overbank flow during fall and winter high flow events (Hays, 1984). During a high discharge, the flood water followed a direct route down the valley, cutting off meander bends. As the flood flow subsided, the low flow channel established itself along the cutoff routes. In contrast, meander migration occurs through bank erosion during the more typical, less extreme flow events that have occurred after several days of continuous discharge. Channel narrowing has been associated with periods dominated by summer flows that tend to be shorter in duration and smaller in volume, and have a higher sediment concentration than winter flow events (Hays, 1984; Pearthree, 1982). Hays (1984) noted that the most stable reaches of the study area were dominated by an alluvium that was more cohesive due to a higher content of silt and clay, than the coarser alluviums that characterized the least stable reaches.

Arroyo Development: Theories and Examples from the Upper Santa Cruz River

Over the last century, several theories explaining the causes for arroyo initiation in the American Southwest have been developed and refined. The following sections review these theories, describe arroyo development along the Santa Cruz River, and provide illustrations showing how the Santa Cruz River arroyos have changed since the time of Statehood. In the convention established by Bryan (1922a) and refined by Antevs (1952), we use the term "wash" where the banks of a river or stream are low and there are multiple channels, and the term "arroyo" when there is a single channel incised in unconsolidated material consisting of clay, silt, sand and some gravel, with banks more than two feet high.

Theories

Antevs (1952) summarized the principal suggested causes of modern trenching given in the literature at that time as:

> "1. Overgrazing, trampling, and human activities, which reduced or destroyed the vegetative cover and made trails, ruts, and ditches,

which, in turn, led to greatly accelerated and concentrated runoff, resulting in violently erosive flash floods after torrential rains.

"2. Increase in moisture, which induced denser vegetation, and longer, steadier, and clearer streams with considerable erosive power in the valleys.

"3. Sudden violent showers followed by unobstructed runoff, together with grazing and forest-cutting.

"4. Increasing dryness of climate, which reduced the vegetation and promoted the runoff, which, in turn, enlarged the magnitude and the erosive and transporting power of floods. (Antevs, 1952, p. 376)"

Through his analysis of ancient and modern channeling and filling in the southwestern United States, Antevs (1952) determined that natural arroyo-cutting takes place during drought periods. However, Antevs noted that the above-normal rainfall from 1905 to 1923 or 1932 did not distinctly improve or restore the plant cover and lead to filling of the trenched channels. He also noted that protection from livestock grazing and trampling did enable the vegetation on the grounds of the Desert Laboratory at Tucson to make a remarkable recovery, even during the 1928-1936 period of average rainfall conditions. Antevs therefore considers the ultimate cause of modern arroyo-cutting in the Southwest to be overgrazing since about 1875.

Cooke and Reeves (1976) made two observations of possible climatic change since 1865 that may have affected the development of arroyos in southern Arizona. They noted that the frequency of light rains was lower and the frequency of heavy rains higher at the end of the 19th century than during the 20th century. The lower frequency of light rains could have resulted in a depletion of grasses and other shallow-rooted plants, causing a reduction in surface cover. Increased runoff at that time may have resulted from the heavy rains. The second observation of climatic change made by Cooke and Reeves (1976) was that droughts are often terminated by relatively wet years. Vegetation probably was depleted during the droughts and did not have time to recover during the following wet periods. As a result, runoff and erosion were increased during the heavy rains at that time.

Cooke and Reeves also noted that while the pattern of droughts followed by wet years was important in the development of arroyos, there was no evidence to prove that this pattern was peculiar to this time period.

Betancourt and Turner (1990) divided explanations for arroyo-cutting into five general categories: livestock grazing, direct and indirect manipulation of streamflow by man, climatic change, extraordinary floods, and intrinsic geomorphic factors. They noted that both erosional and depositional phases have been linked to cyclical drought. The underlying climatic interpretation of the cutting and filling cycles is the assumption that vegetative cover is the immediate factor affecting erosion, which is controlled by precipitation. Several researchers (i.e. Thornthwaite *et al*, 1942; Leopold, 1951; Martin, 1963; Cooke and Reeves, 1976; Bull, 1964; Hansen *et al*, 1977) have addressed the possible effects of changes in frequency of rainfall intensities on plant productivity and alluvial processes. Betancourt and Turner (1990), after summarizing the different hypotheses, found the different rainfall intensity hypotheses to be inconclusive for two reasons: (1) there are uncertainties in how light versus heavy rains affect vegetation across the broad range of ecological settings that experienced arroyo cutting; and (2) secular trends in rainfall intensity may not be unique to the last hundred years; such trends may characterize other times when arroyos failed to develop but we do not have adequate climatic data to define the trends precisely. They did find agreement in the literature that initial downcutting was associated with extraordinary floods. They noted that, over the past century, most channel erosion in the Southwest was accomplished by large floods during the relatively wet periods of 1884-1891, 1904-1920, and 1965-1987. Recent hydrologic analyses of dated slackwater deposits in bedrock canyons suggest that floods of the past century represent the largest events for periods of up to 2000 years (Baker, 1985). On the Escalante River in Utah, such hydrologic analyses indicated that paleofloods recorded by slackwater deposits in bedrock canyons coincide with the formation of paleoarroyos in alluvial reaches (Webb, 1985).

Betancourt and Turner's 1990 survey and synthesis of historical anecdotes establish a link between initial arroyos and human modifications of the floodplain. They also note that, while many authors considered the widespread erosion that occurred during A.D. 1100-1400 to be unrelated to human activity, prehistoric farmers during this period (i.e., Anasazi on the Colorado Plateau and Hohokom in the Sonoran Desert), may have outnumbered the rural population in the Southwest in the late 19th century, and that these

prehistoric farmers harnessed streamflow to grow crops in a similar manner to the Europeans.

Arroyo Development on the Santa Cruz River

The Santa Cruz River system had arroyos no more than a few miles long separated by 12- to 20 -mile-long reaches of unincised alluvium before 1880 (Betancourt and Turner, 1988). For example, the reach below the present site of Valencia Road was described in 1871 as having a channel with vertical banks 60 feet apart and up to 10 feet high (Foreman, 1871, as quoted in Betancourt and Turner, 1988). Since then, a 50-mile-long arroyo through the Tucson Basin has formed, separating relatively unincised reaches upstream and downstream on the Santa Cruz River. Bryan (1925a) and Thornber (1910) place the timing of initial development of large, continuous arroyos on the Santa Cruz River at 1885 to 1890. Thus, arroyo development along the Santa Cruz River began before the time of Statehood.

Schwalen (1942) noted that the deepest arroyo entrenchment is between Continental and Tucson, and a short stretch about a mile and one half above the town of Santa Cruz, Mexico. Betancourt and Turner (1990) noted that the short discontinuous arroyo in Mexico is the only entrenched segment of the river upstream of the Tucson Basin. The Santa Cruz River is entrenched most dramatically within the San Xavier Indian Reservation, with vertical banks up to 30 feet high and 300 feet apart where the river meanders around the base of Martinez Hill.

Cooke and Reeves (1976) note that entrenchment in the lower Santa Cruz River Valley is confined to the arroyo along Greene's Canal and to the 5 to 6 mile-long trench that extends south from the Gila River, which probably resulted from headward erosion following downcutting of the main river (Bryan, 1925b).

San Xavier Reach

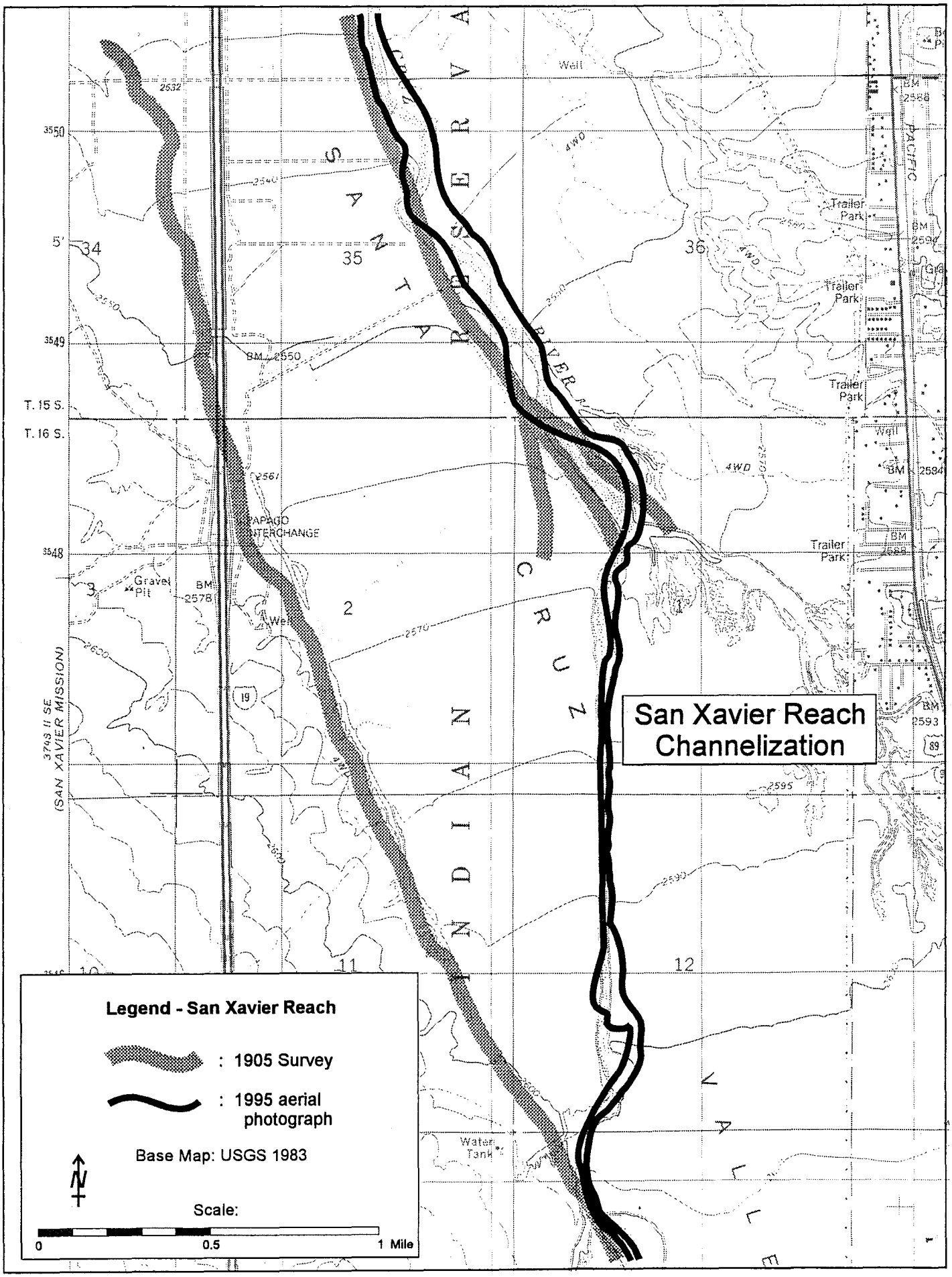
The chronology of channel change along the San Xavier reach of the Santa Cruz River provides examples of arroyo development and of other channel changes such as channelization that are direct results of human activities. Historically, there were two main sources of spring water in the San Xavier reach, the *Agua de la Misión* and *Acequia de la Punta de Agua*, both south of San Xavier del Bac Mission (see Figure 4). Springs at the

Agua de la Misión were destroyed by an earthquake in 1887 and flow was forced to the surface higher up in the valley. Development of this water led to the formation of the *East-Side Barranca*, a channel 100-200 feet wide, 15-20 feet deep, and over two miles long. By 1912, a channel 60-100 feet wide, 6-20 feet deep and about two miles long developed after the construction of an infiltration gallery. This channel came to be known as the *West-Side Barranca* (Cooke and Reeves, 1976). Both the *West-* and *East-side Barrancas* were initiated by 1882 (Cooke and Reeve's, 1976) and dried up periodically, which led them to be deepened and extended artificially (Berger, 1901).

The most serious erosion on the San Xavier Indian Reservation resulted when overbank flow crossed from the west to the east side of the valley, and cascaded into the *East-Side Barranca* near the base of Martinez Hill. In 1915, the Santa Cruz River did not have an entrenched channel near the south boundary of the San Xavier Indian Reservation. However, during the 1914-1915 floods, a headcut eroded to a point south of Martinez Hill, destroying the marsh at the source of the Spring Branch. In 1915, engineers acting on behalf of the Papago Indians implemented C.R. Olberg and F.R. Schank's 1913 plan (Olberg and Schank, 1913) to build an artificial channel that connected the Santa Cruz River channel with the head of the entrenched Spring Branch. The headcut migrated rapidly along the artificial channel and continued upstream so that by the 1930s, a continuous arroyo defined the river's course for a distance of 35 to 45 miles in the Tucson Basin (Betancourt and Turner, 1988). The channel of the Santa Cruz River still follows the route of the 1915 dike into the former course of the Spring Branch (Figure 18) and is now 18 to 24 feet deep (Betancourt and Turner, 1990).

The downstream section of the San Xavier reach, especially the portion above Martinez Hill to Valencia Road, has undergone the most extensive and continuous arroyo widening on the Santa Cruz River. The channel was incised as much as 30 feet in silt and sand of Holocene age, and about 1,200 feet of widening occurred at some places between 1936 and 1986. Mean arroyo width of the entire San Xavier reach increased from 200 feet in 1936 to 500 ft in 1986 (Parker, 1995). Meyer (1989) determined that channels in which bedload transport is significant and bed material are predominantly gravels, such as the Santa Cruz arroyos (i.e. near Nogales, Amado, and I-19), initially widen their arroyos by meandering. Figure 19 illustrates the meandering of the low flow channel within the arroyo walls in the San Xavier reach between 1972 and 1983, while Figure 20 graphs the widening that occurred. Flows undercut weakly indurated, oversteepened arroyo walls, or

Figure 18


San Xavier Reach Channelization
Legend - San Xavier Reach
: 1905 Survey
: 1995 aerial photograph
Base Map: USGS 1983
Scale:
0
0.5
1 Mile
SANTA CRUZ RIVER
INDIAN
Trailer Park
Well
Gravel Pit
Water Tank
T. 15 S.
T. 16 S.
(SAN XAVIER MISSION)

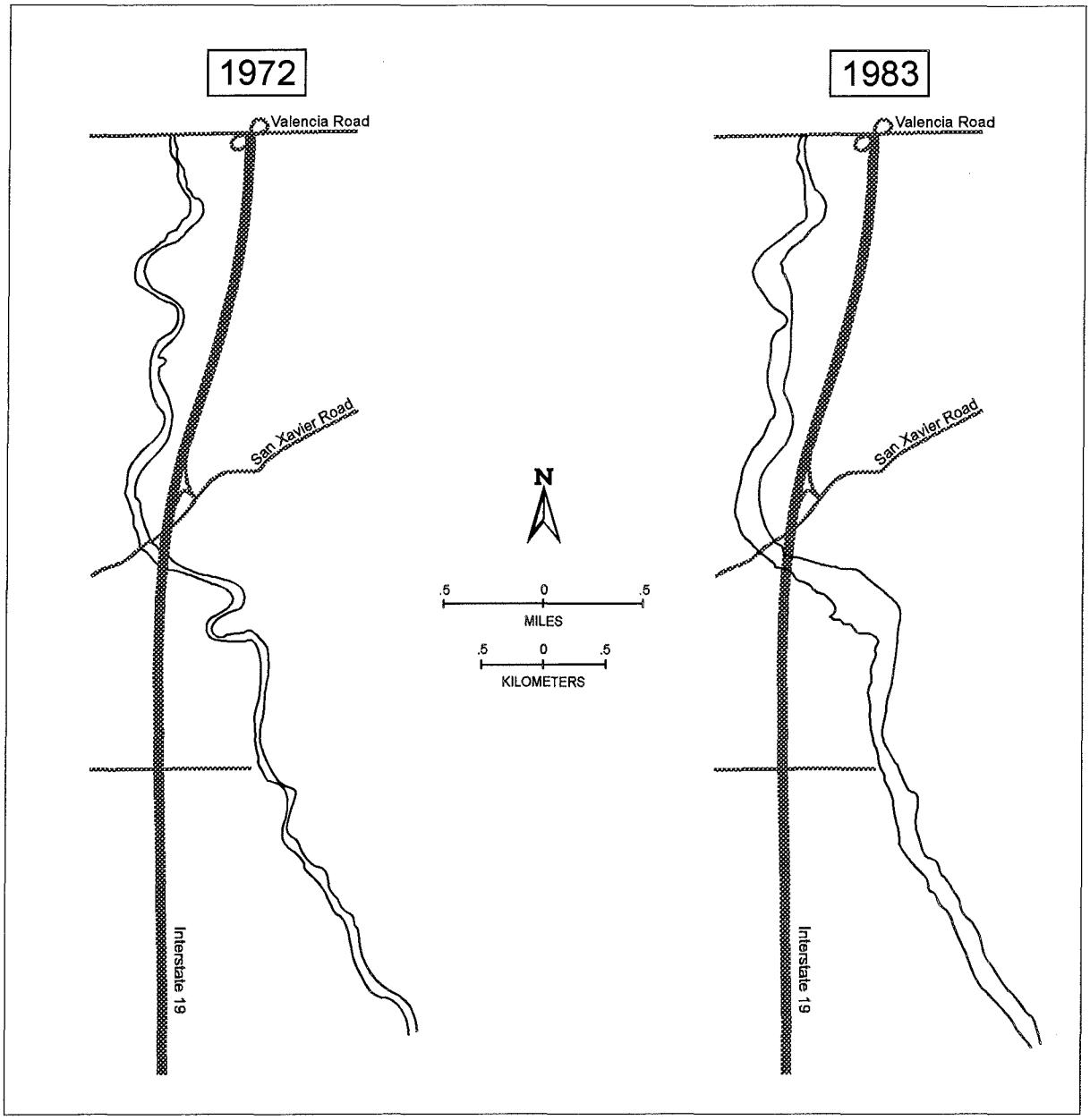


Figure 19. Low flow channel boundaries within the Santa Cruz arroyo in the San Xavier reach. Channel boundaries are represented by solid black lines; roads are indicated by dark grey lines. Boundary data was obtained from aerial photographs. [Source: Guber, 1988.]

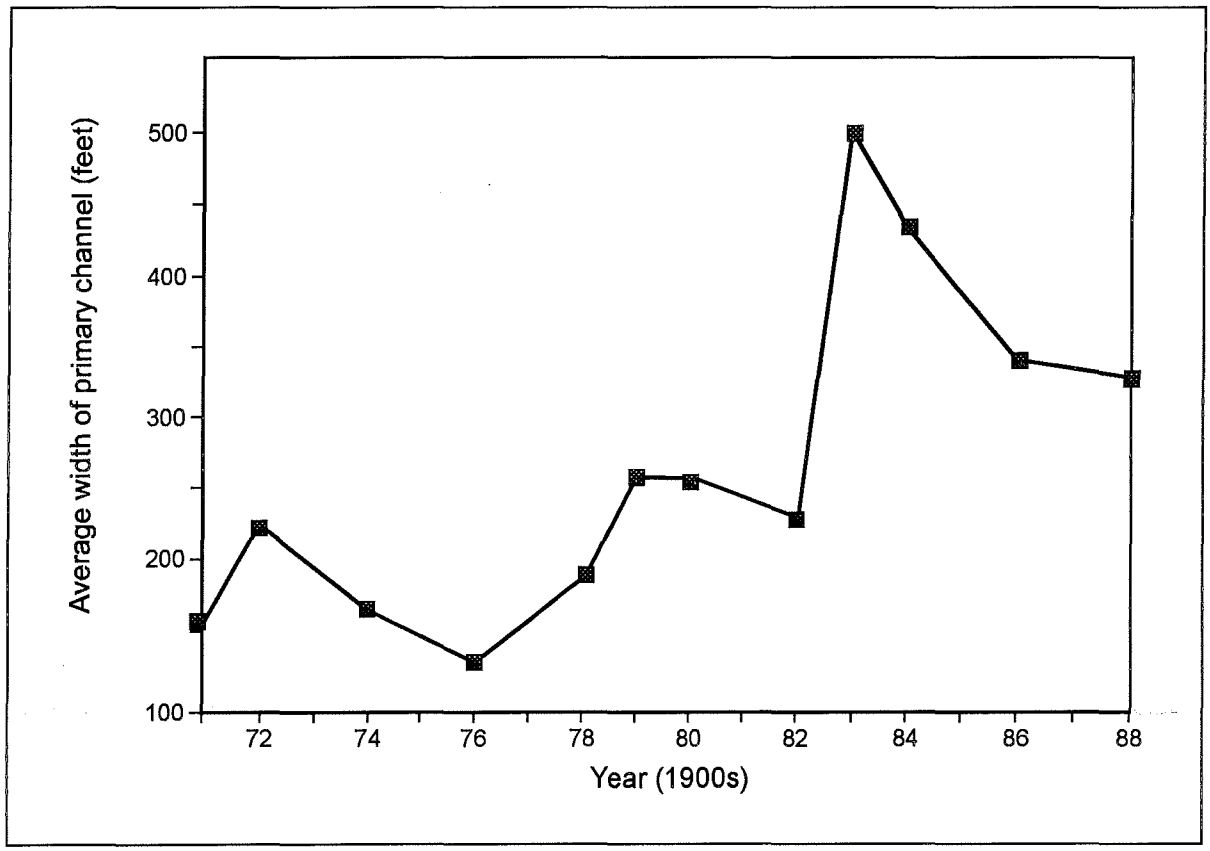


Figure 20. Average width of the primary flow channel within the San Xavier arroyo. Each box in the graph represents a measurement made from an aerial photograph. [Source: Guber, 1988.]

return flow of bank storage to the channel causes seepage erosion at the base of the walls (Parker, 1995). Figure 21 provides a dramatic time-elapsed view of arroyo widening along the reach upstream of San Xavier Road. Once arroyos widen to the point they no longer constrain flood-channel width, they become braided. The rate of arroyo wall erosion then decreases because the low flow and flood channels can shift freely within the arroyos and only rarely impinge upon the arroyo walls. The arroyos eventually become relatively stable; former floodplains become terraces and arroyo floors become floodplains (Meyer, 1989). Unlike channel widening, the process of arroyo widening is not readily reversed on large systems such as the Santa Cruz River (Parker, 1995).

Channel Changes in the Lower Santa Cruz River Basin

Change in channel form and pattern on the lower Santa Cruz River is less understood and documented than the upstream reaches. The fluvial system of the lower Santa Cruz River is distinctly different from its upstream counterpart and such changes are more challenging to document and describe. Only during large floods does significant streamflow from the upper Santa Cruz River extend through the lower Santa Cruz River to the Gila River. This hydrological discontinuity is mirrored by a geomorphological discontinuity wherein the basic form of the river transforms from a relatively deep, well-defined channel to a broad, flat, extensive alluvial plain with only intermittent channels. Prior to human disturbance, this transition occurred in the Marana area. Due primarily to the effects of Greene's Canal (discussed in the following section), the Santa Cruz River now has a fairly well-defined channel to Chuichu area. (Refer to Figure 1 and Figure 2 for locations.)

Broad sheetflow that is characteristic of large floods on the lower Santa Cruz River is associated with deposition of abundant sediment that remains in storage for long periods of time between large floods. The widespread sedimentation during large streamflow events and the low gradient of this part of the system are conducive to large scale changes in channel position. However, the low frequency of the recurrence of large floods influences the timing of these changes such that they occur only over long time spans. The evidence for significant changes (primarily in channel position) is present in the regional geomorphology and the spatial distribution of geologically young (i.e. 1000 to 5000 years) alluvial deposits in the area. However, because of data limitations and the long time scale

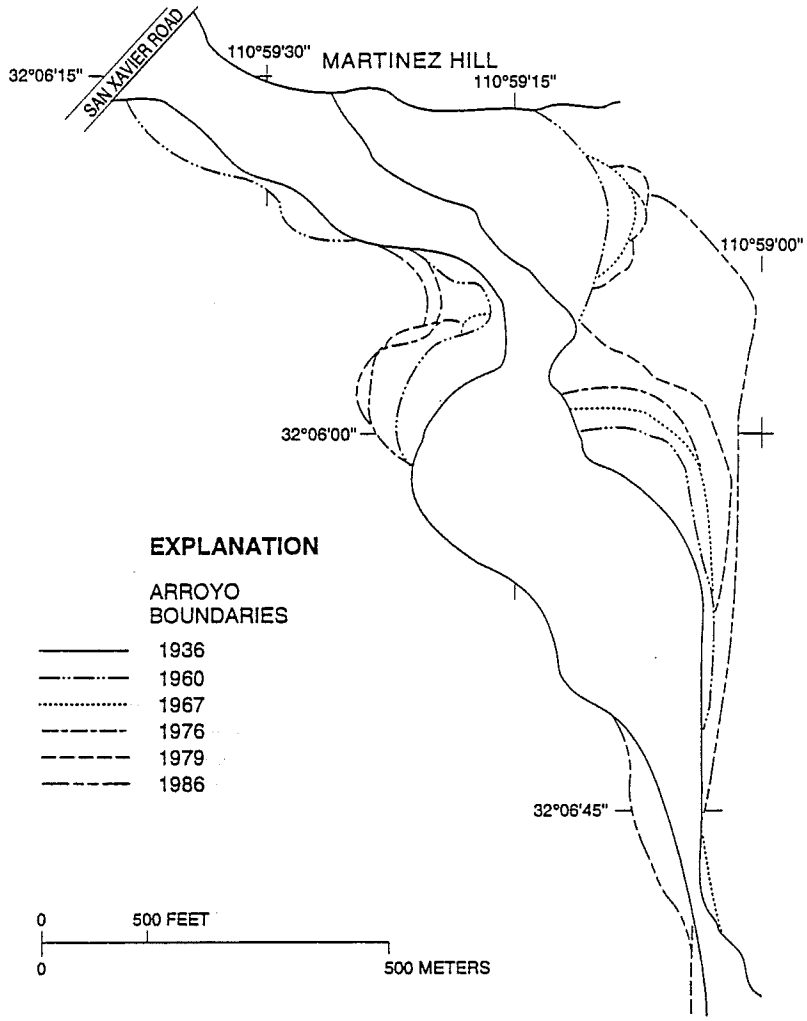


Figure 21. Arroyo widening caused by migration of entrenched meanders in the San Xavier reach at Martinez Hill, 1936-86. Data from U.S. Soil Conservation Service, 1936; Cooper Aerial Survey, 1960, 1967, 1979, 1986; Kucera and Associates, 1976. [Source: Parker, 1995.]

Flood Flow Patterns in the Lower Santa Cruz River Valley

Greene's Canal flows west-northwest to the site of the abandoned reservoir for which the canal was originally constructed. The reservoir outlet, now Greene Wash, flows towards the north-northwest. Northwest of Casa Grande, Greene Wash is joined by the Santa Rosa Wash and the North Branch of the Santa Cruz River (refer to Figure 1). The North Branch of the Santa Cruz Wash is an east-west flowing tributary between the town of Casa Grande and the piedmont of the Sacaton mountains to the north. This drainage currently receives runoff from the southern side of the Sacaton Mountains. Flow in the Santa Rosa Wash and the Santa Cruz Wash intermingle during large runoff events because agricultural modification of the landscape has removed the effective drainage divide between the two systems[2] (Rhoades, 1991).

Detailed mapping of flow paths on the lower Santa Cruz River is possible because two of the largest flood events on the Santa Cruz river this century followed distinctly different paths and have been mapped in reasonable detail at various scales. Previous flood mapping in this area has been combined and compiled on a 1:100,000-scale base map of the lower Santa Cruz River area (Plate 1, in pocket). Lines have been drawn to indicate: 1) the spatial extent of the winter flood of the 1914-15 as discerned from Smith's 1938 and 1940 publications and the General Land Office (GLO) surveys; and, 2) the distribution of floodwaters of the 1983 flood event, as published by Roeske *et al* (1989).

Smith's mapping was transferred directly to the 1:100,000-scale base map by enlarging the original map. Smith's 1940 publication indicates only areas "overflowed by floods (not complete)." The 1938 map claims to show the 1914-1915 flood swath, thus it is possible that Smith's maps indicate areas overflowed by earlier (or subsequent) events, i.e. the 1905 flood event. The data sources for the maps by Smith are unknown. No verbal description of methods compilation, data sources, or likely evolution of the flow path depicted for the 1914-1915 map is available. Smith's mapping can only be taken as a somewhat rough depiction of inundation; however, Smith's delineation of one branch of the flow swath extending through Eloy and towards the northwest is consistent with the

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[2] An interesting and somewhat unfortunate consequence of the floodwaters crossing the drainage divide between the Santa Cruz Wash and the Santa Rosa Wash, combined with the effects of Greene's Canal, is that it nullifies much of the flood-control effect of the Tat Momolikat Dam on the Santa Rosa Wash (Rhoades, 1991). The dam was constructed in 1974 to protect communities in the floodplain of the lower Santa Rosa Wash. These areas are now subject to inundation by floods on the Santa Cruz River, which are historically more frequent than floods on Santa Rosa Wash.

of the processes involved, we cannot provide an assessment of long-term channel change. In terms of channel change in the 20th century, description of the effects of Greene's Canal and documentation of the disparate courses taken by two large floods provide interesting and useful perspectives on the behavior of the Santa Cruz River in this unique environment.

Greene's Canal

The modern Santa Cruz River has a relatively distinct channel from its headwaters to just upstream of Greene's Canal. Greene's Canal is a man-made feature that has dramatically influenced the evolution of the lower Santa Cruz River. In 1908 the Santa Cruz Reservoir Company developed a plan to concentrate water from the Santa Cruz River into Greene's Canal, transfer the water to a reservoir, and distribute it for the irrigation of farm land near Toltec (Cooke and Reeves, 1976). A diversion dam and canal were constructed in 1909-10 under the leadership of Colonel William C. Greene. The irrigation scheme was temporarily halted when Colonel Greene died in 1911 and then reactivated in 1913 (Sonnichsen, 1974). However, during the floods of 1914-1915, the diversion dam was destroyed and the canal was eroded to a depth of about 12 feet (Cooke and Reeves, 1976).

Greene's Canal, and headcuts migrating upstream from the canal, have continued to capture and concentrate extensive sheetflow in the upstream area during subsequent floods of this century. This unintended flow diversion had the effect of restricting the vast majority of flood runoff to the western Santa Cruz Flats. Prior to the diversion, floodwaters apparently flowed in a more northerly direction, inundating areas that are now covered by Eloy, Toltec, and Casa Grande. Following the diversion by Greene's Canal, these areas have not been affected by significant flooding from the Santa Cruz River. In 1983, a tongue of floodwater extended to the outskirts of Eloy, apparently following part of the old path. Thus, Greene's Canal has become the dominant conduit for flows from the upper Santa Cruz River. The large floods in 1914-1915, 1977, 1983, and 1993 have transformed what was once a relatively small canal into a deep, wide arroyo that bears a strong resemblance to portions of the Santa Cruz River channel upstream.

position of the Santa Cruz River and Santa Cruz Flats as mapped by the GLO surveyors. Lines that represent interpretations of channel positions made by various survey parties also were transferred from the original GLO plats to the 1:100,000 base map.

Roeske *et al* (1989) mapped the distribution of floodwaters from the flood of 1983 using high altitude aerial photography, field reconnaissance, and flood reports. Their rendering is probably considerably more precise than Smith's mapping. The path of the 1983 flood was first transferred from Roeske *et al*'s high altitude aerial photograph to a 1:130,000 scale aerial photograph, and then overlain on the 1:100,000-scale base map. In a few places, flow paths of the 1977 flood on the lower Santa Cruz River mapped by Aldridge *et al* (1984) were added to refine the mapping of likely flow paths of the 1983 event where imagery was not available. This addition was done under the assumption that the general flow paths were the same, although the extent of the 1983 flood was likely greater.

The effect of Greene's Canal can be seen by the comparison of the strikingly different flood paths illustrated in Plate 1. According to both the GLO surveys and Smith's map, the North Branch of the Santa Cruz River near Casa Grande was an important element of the Santa Cruz system. According to Smith (1938, 1940), the floodwaters in 1914-1915 also crossed the low divide near the southeastern corner of the Sacaton Mountain Piedmont between the North Branch and McClellan Wash, the principal drainage of the Picacho Basin. This resulted in the Santa Cruz River flowing along both the east and west sides of the Sacaton Mountains and entering the Gila River at two points separated by more than 20 miles. The very low gradient in the region explains the apparent variability of flow paths through this area. Also evident in Smith's map are broad areas of inundation associated with flow down Greene's Canal and along the western margin of the lower Santa Cruz River Valley. This flow path became the main flow route during the 1983 and 1993 floods.

The low-relief characteristic of the area and the widespread distribution of geologically recent alluvial deposits indicates that much of the area in the lower Santa Cruz River basin has conveyed flow at some point during the last few thousands of years. Only in a few areas are there relatively high standing surfaces (aside from the isolated mountains) that obviously have been free from any inundation. Since the construction of Greene's Canal and the development of the arroyo it initiated, the main flow of the Santa

Cruz no longer follows its former paths down the North Branch and McClellan Wash. Instead, it follows the western route via Greene's Canal.

CHAPTER 7. MAPPING OF LOW AND HIGH WATERMARKS

To aid the Arizona Navigable Stream Adjudication Commission in its determination of the potential navigability of the Santa Cruz River, the ordinary low and high watermark boundaries were mapped for the Santa Cruz River and Greene's Canal/Greene Wash for all the reaches that have a defined channel. Several qualitative and quantitative procedures have been developed to delineate high and low watermark boundaries (GVSCE, 1996a). The ANSAC Technical Review Committee determined that a three-level approach should be utilized (GVSCE, 1996b). The first level is a boundary determination based on the qualitative assessment of physical evidence identified during field checks of different reaches of a given Arizona river. The second level incorporates additional physical evidence collected from the interpretation of aerial photographs and topographic maps. Field observations are used to verify the information gathered from the aerial photographs and maps. The third level, the analysis of flow duration data published by the USGS for gaged streams, is to be undertaken "where there is justifiable need and sufficient data exists" (as cited in GVSCE, 1996b).

In accordance with the approach outlined above, information gathered from field checks, aerial photographs and topographic maps was utilized to delineate the low and high watermark boundaries in the Santa Cruz River basin. Aerial photographs of the Santa Cruz River area in Pima and Santa Cruz counties were produced by Landiscorp Aerial Surveys in March of 1995 and have a scale of ~1:24,000. Aerial photographs of the Santa Cruz Flats region in Pinal County were produced by Aerial Mapping Company, Inc., and had photograph dates ranging from September, 1994, to March, 1995, with a scale of ~1:7200. Color copies of the Santa Cruz County aerial photographs and blue-line copies of the Pinal County photographs are indexed and archived at the Arizona Geological Survey. Field checks of the aerial photographs and topographic maps were conducted in late September and early October, 1996. Photographs taken of different sites at ground level are indexed and provided in Appendix A.

The ordinary low watermark, per ARS § 37-1101, is defined as "the line on the banks of a watercourse created when the water recedes at its regularly recurring lowest

stage in normal years without reference to unusual droughts" (as cited in GVSCE, 1996a). Although this definition is fairly straightforward when used to describe rivers with a baseflow, ambiguity arises when applying such a definition to the Santa Cruz River because it is intermittent or ephemeral in the majority of its reaches. First, physical markers on the landscape left by low flows tend to be quickly erased by periodic high flows. Second, even if there were a statistical definition of the ordinary low watermark based on hydrological records, much of the Santa Cruz River is not gaged. For these reasons, low watermark boundaries were mapped only in the reaches in which there was water at the time the most recent aerial photographs were taken. The low watermark boundaries discerned from the 1994 and 1995 aerial photographs were transferred to USGS 7 1/2' topographic quadrangles using a zoom-transfer projector and marked in blue pencil. Figure 22 provides an index of the topographic maps that were used in this study and submitted to ANSAC. In most reaches, the low watermark boundaries were too close together to draw separately. Therefore, one line was drawn, the width of which approximately matches the width of the low flow channel. The existence of surface flow as seen in the aerial photographs was verified by field-checking and the analysis of daily synoptic weather maps and topographic maps.

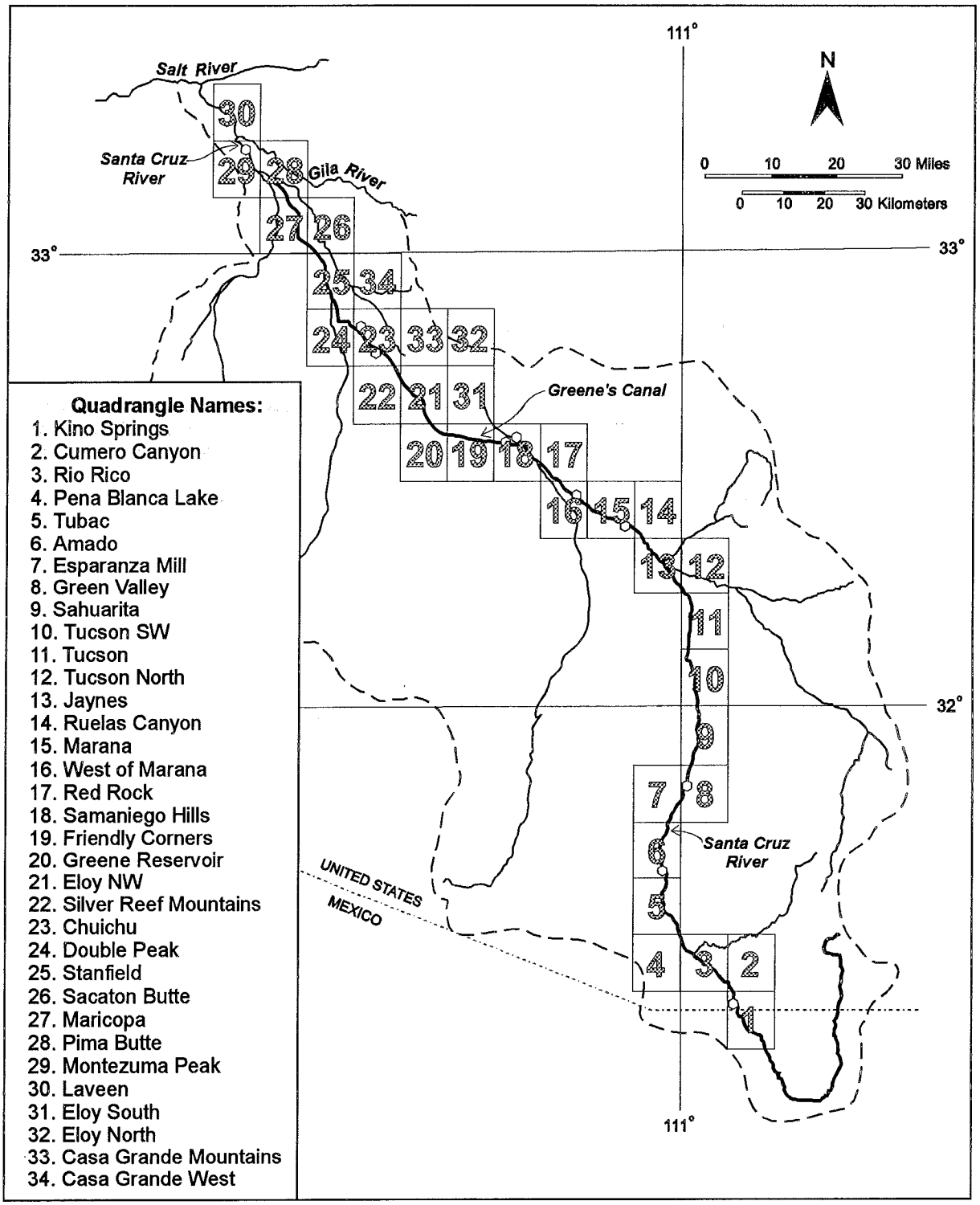
The ordinary high watermark is defined as "that line on the bank established by the fluctuations of water and indicated by physical characteristics such as a clear, natural line impressed on the bank, shelving, changes in the character of the soil, destruction of terrestrial vegetation, the presence of litter and debris, or other appropriate means that consider the characteristics of the surrounding areas." (33 CFR, Part 328.(e), as cited in GVSCE, 1996a). We mapped high watermark boundaries in all reaches that had any combination of: defined channel banks, channel surfaces cleared of vegetation, changes in vegetation type from riparian to terrestrial, and changes in soil type. Figure 23 is an annotated aerial photograph of the reach of the Santa Cruz River one mile north of the USGS gage near Nogales. The channel surfaces cleared of vegetation appear as bright white or light tan in the original color photographs (white in this black and white image) and provide relatively straightforward evidence of the high watermark boundaries. The water-filled low flow channel appears as a darker tan color (darker gray in this image) and delineates the low watermark boundaries.

In some reaches, the high and low watermark boundaries are the same, as evidenced by the lack of vegetation-cleared surfaces adjacent the low flow channel.

Figure 22. Index of USGS topographic quadrangles used in the mapping of high and low watermarks.

Legend:

- Rivers
- Main Flow Route since ~1915
- Santa Cruz Basin Boundary
- Ground Photograph Location
- 30 - USGS Topographic Quadrangle. (The number refers to the name of the quadrangle listed in the box below.)



Quadrangle Names:

1. Kino Springs
2. Cumero Canyon
3. Rio Rico
4. Pena Blanca Lake
5. Tubac
6. Amado
7. Esparanza Mill
8. Green Valley
9. Sahuarita
10. Tucson SW
11. Tucson
12. Tucson North
13. Jaynes
14. Ruelas Canyon
15. Marana
16. West of Marana
17. Red Rock
18. Samaniego Hills
19. Friendly Corners
20. Greene Reservoir
21. Eloy NW
22. Silver Reef Mountains
23. Chuichu
24. Double Peak
25. Stanfield
26. Sacaton Butte
27. Maricopa
28. Pima Butte
29. Montezuma Peak
30. Laveen
31. Eloy South
32. Eloy North
33. Casa Grande Mountains
34. Casa Grande West

Areas where recently deposited river sediments were observed beneath riparian vegetation cover (i.e. mesquite *bosques* and large cottonwood trees) were included within the high watermark boundaries. The location of the high watermark boundaries were transferred from the aerial photographs to the USGS 7 1/2' topographic quadrangles on which the low watermark boundaries were mapped using a zoom-transfer projector and marked in green pencil. A dashed green line on the topographic maps indicates areas that were recently (i.e. during the 1983 floods) cleared of vegetation and, as of the 1995 aerial photographs, were experiencing re-vegetation. Figure 24 shows the high and low watermark boundaries mapped near Cortaro, north of Tucson.

The review of aerial photographs and topographic maps indicated that the current locations of the high and low watermark boundaries has remained approximately the same since the 1983 floods. However, there have been notable changes in the location of the high and low flow channel boundaries since the time of Statehood. These channel changes were discussed in great detail in the earlier chapter on geomorphology. A more detailed narrative of the mapping of the low and high watermark boundaries is provided below. If the narrative describes features mapped on the USGS 7 1/2' topographic quadrangles, the italicized names of those quadrangles are provided in parentheses.

Low Watermark Boundary Delineation

Low watermark boundaries were mapped in two reaches of the Santa Cruz River: 1) from the U.S.-Mexico border to south of Green Valley; and 2) from south of Jaynes to north of Marana. Figure 25 highlights the locations of these reaches. Most of the surface water results from the discharge of secondary-treated municipal effluent from the Nogales International Wastewater Treatment Plant, and the treatment plants at Ina Road and Roger Road just north of Tucson. Refer to Figure 25 for the locations of the treatment plants and to the earlier chapters on hydrology and geomorphology for a more detailed review of the effects of effluent in these areas.

The aerial photographs taken on March 27, 1995, indicated that the channel *upstream* from the Nogales treatment plant also contained surface water (*Kino Springs*, *Cumero Canyon* and *Rio Rico* quadrangles). This section of the Santa Cruz's channel is often dry due to the lowered water table and depleted subflow that has resulted from increased groundwater extraction and diversion of the river's flow in this region during the

Figure 24

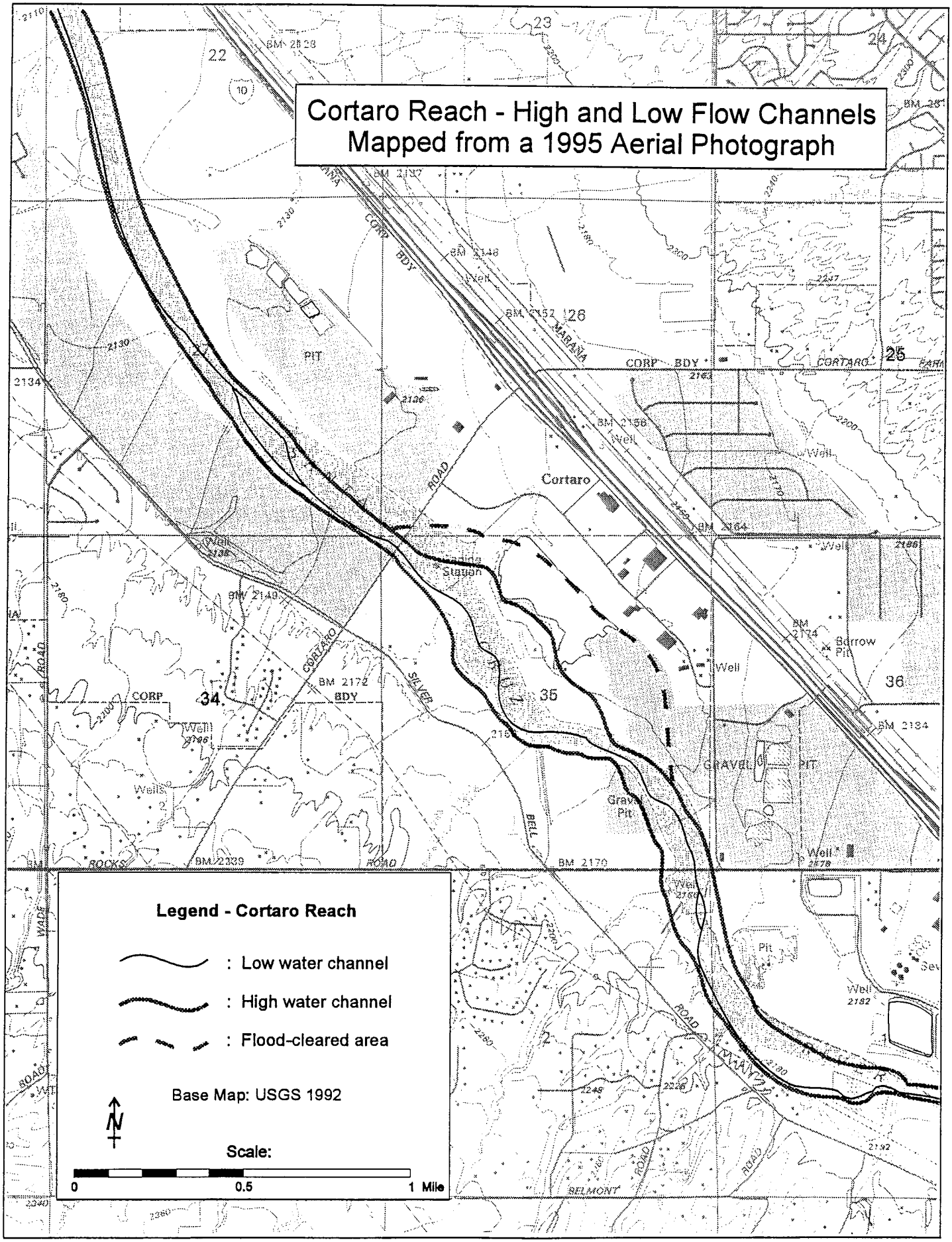

Cortaro Reach - High and Low Flow Channels
Mapped from a 1995 Aerial Photograph
Legend - Cortaro Reach
: Low water channel
: High water channel
: Flood-cleared area
Base Map: USGS 1992
N
Scale:
0
0.5
1 Mile
Cortaro
CORP BDY
MARANA
CORTARO
SILVER
BELL
ROAD
PIT
GRAVEL PIT
Gravel Pit
Borrow Pit
Well
Wells
22
23
24
25
26
27
34
35
36

Figure 13b. Annual peak discharges at Tucson, Cortaro, and Laveen.

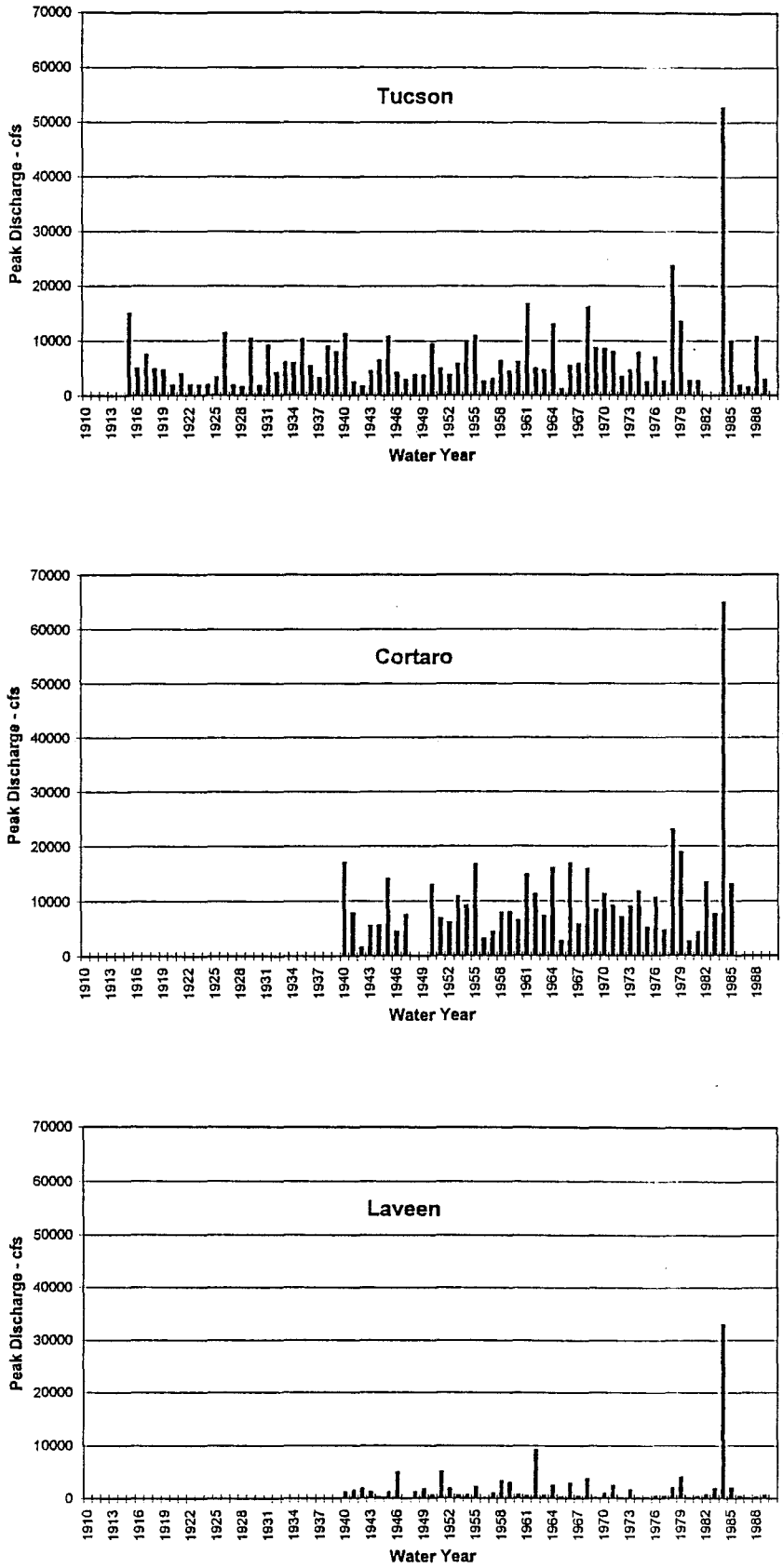
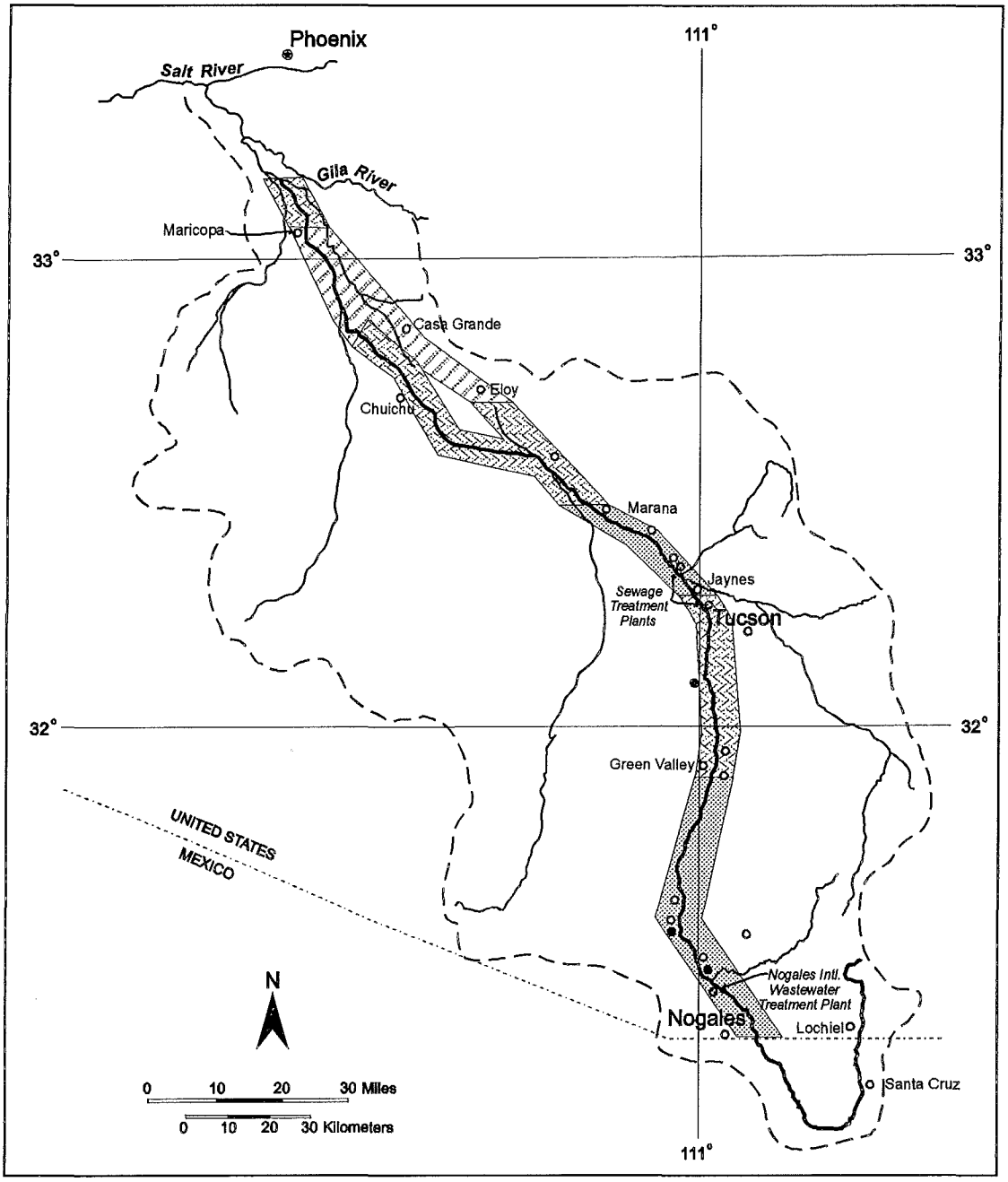


Figure 25. Santa Cruz River Basin: Mapping of ordinary high and low watermark boundaries.

Legend:

- o - Populated Places
- ● - Historical Sites
- ⊗ - Sewage Treatment Plants
- ~ - Rivers
- ~ - Main Flow Route since ~1915
- - - Santa Cruz Basin Boundary
- - High and low watermark boundaries mapped from aerial photographs.
- - High watermark boundaries only mapped from aerial photographs.
- - 7 1/2' maps supplied for this region. No high or low watermarks are mapped.



last few decades. A review of the daily synoptic weather maps determined that three fronts had passed over or near the upper Santa Cruz River within the ten days before the aerial photographs were taken, bringing both isolated and widespread rain showers that would have resulted in flow in the channel. Field checks in late September, 1996, a week after several intense monsoon showers, found evidence of either surface water or water just beneath the channel surface in this same reach.

We also conducted field checks to determine where the surface water terminated downstream of the treatment plants. Surface flow that had its source from the Nogales treatment plant ceased just south of Amado. Surface flow that had its source from the Ina Road and Roger Road treatment plants ceased about one mile west of downtown Marana. The surface flow in the reach downstream from the Nogales treatment plant ended south of the termination location discerned from the aerial photographs. Most likely, both the aerial photograph interpretation and field observations are valid. During the cooler winter/spring season in which the aerial photographs were taken, there would be less evaporation from the water surface and less withdrawal of water by the vegetation adjacent the channel. Hence, surface flow would continue farther downstream than during the hotter summer months.

High Watermark Boundary Delineation

The entire upper Santa Cruz River had a well defined channel for which high watermark boundaries could be mapped from the aerial photographs in a straight-forward manner. There were a few sections of the river that had dense mesquite *bosques* in or immediately adjacent the channel. Where the *bosques* led to ambiguity in the exact watermark boundary location in the aerial photographs, field observations and an analysis of the topographic maps provided clarity.

The Santa Cruz has a well defined channel until four miles southeast of the Santa Cruz/Greene's Canal split (*Samaniego Hills Quadrangle*). A distinct channel appears again about two miles south of the Santa Cruz/Greene's Canal split. A headcut begins about one and a half miles upstream of this split and the Santa Cruz is deeply eroded with steep banks until the Greene's Canal junction. Field checks discovered two interesting channel features in this reach. First, a 1500 foot levee has been constructed within the main channel that diverts flow down Greene's Canal and away from the Santa Cruz branch. Second, a low flow channel has incised itself about five feet into the main channel where

the channel's flow has been directed. Figure 26 provides both an aerial view of this reach and a cross-sectional view of the main channel where the Santa Cruz channel splits from Greene's Canal. The aerial view illustrates how the levee has redirected flow from the Santa Cruz, as evidenced by the denser vegetation growth in the southern section of the main channel. The aerial view also shows how narrow the Santa Cruz channel becomes downstream of its split from Greene's Canal, with only a very thin portion of its channel cleared of vegetation. The cross-sectional view illustrates the vertical relationship between the Santa Cruz channel and the channel features within Greene's Canal.

Field checks indicated that the shrubs and trees that fill the channel of the Santa Cruz immediately downstream of the split are dead. The death of the vegetation probably resulted from the Santa Cruz being cut off from the water flow in the main channel. Less than a mile downstream of the split, the narrow Santa Cruz channel is completely filled with living vegetation. This reach of the Santa Cruz receives water only from the drainage of the local fields rather than from upstream of Greene's Canal. In the aerial photographs, field checks and topographic maps, the Santa Cruz channel ends in the irrigated croplands north of the village of Friendly Corners, south of Eloy (*Friendly Corners Quadrangle*).

The Santa Cruz Wash is mapped again just north of Chuichu by USGS surveyors (*Chuichu Quadrangle*). It appears in the aerial photographs as a region of slightly denser vegetation. Field checks and aerial photographs taken during the floods of 1992-93 indicate that this was a region of extensive sheet-flow rather than channeled flow during the recent large floods; no defined channel banks were observed in the field checks. North of Interstate 8 and southwest of Casa Grande, the Santa Cruz Wash becomes completely constrained by levees. The channeled Santa Cruz Wash is routed through the croplands until north of Maricopa where is spreads out into multiple braided channels that are densely vegetated.

Evidence gathered from field checks, aerial photographs and the mapping of historical floodwaters indicates that Greene's Canal has become the main flow route during the latter part of this century. For this reason, we have mapped Greene's Canal in addition to the Santa Cruz Wash. Unlike the Santa Cruz Wash, Greene's Canal, which flows into Greene Wash, can be mapped throughout its course. From its split with the Santa Cruz Wash to its confluence with Greene Wash (*Greene Reservoir Quadrangle*), Greene's Canal is deeply incised with steep channel banks..

Greene Wash has braided channels except where levees have been constructed near Chuichu (*NW Eloy* and *Chuichu* quadrangles). Field checks and the aerial photographs indicate that, like the neighboring Santa Cruz, this reach of Greene Wash is an area of sheet-flow rather than channeled flow (*Chuichu Quadrangle*). However, Greene Wash is more distinct in the landscape than the Santa Cruz in this region. For example, while breaks in the Santa Rosa Canal were created for both Greene Wash and Santa Cruz Wash, Greene Wash has a more defined, wider channel in that area and more vegetation (i.e. both shrubs and dense grass growth that was green at the time of the field checks). Three miles northwest of Chuichu, Greene Wash is constrained by levees. Less than one mile northeast of Stanfield (*Stanfield Quadrangle*), the channeled Greene Wash joins with the channeled Santa Rosa to become a second branch of the Santa Cruz Wash. This branch of the Santa Cruz also is constrained by levees and routed through the croplands until north of Maricopa, where it spreads out into multiple channels. The multiple branches of the Santa Cruz join three miles southeast of the village of Santa Cruz (*Pima Butte Quadrangle*). This vegetation-filled channel continues northeast five miles to where it joins the Gila River (*Laveen Quadrangle*).

Unlike the upper Santa Cruz River, the Santa Cruz Wash in the Santa Cruz Flats region often did not meet the criteria for mapping high watermark boundaries. The following scenarios occurred:

1) Channels were completely filled with dense vegetation (i.e. no cleared surfaces were apparent in the aerial photographs); such channels were mapped on the topographic quadrangles using a green shading that filled the entire channel area rather than two lines denoting exact watermark boundaries. If only a narrow line of vegetation denoted the location of the wash in the aerial photograph, a single green line was mapped on the topographic quadrangle.

2) Channel boundaries were completely constrained by berms and levees, or were labeled as canals; such channels were not mapped using aerial photographs, but topographic maps were compiled for such reaches and annotated.

3) Channel boundaries were not seen in the aerial photographs or from ground observations; such channels were not mapped using aerial photographs, but topographic maps were compiled for these reaches and annotated.

In several of its reaches, Greene Wash matched scenarios #1 and #2 listed above.

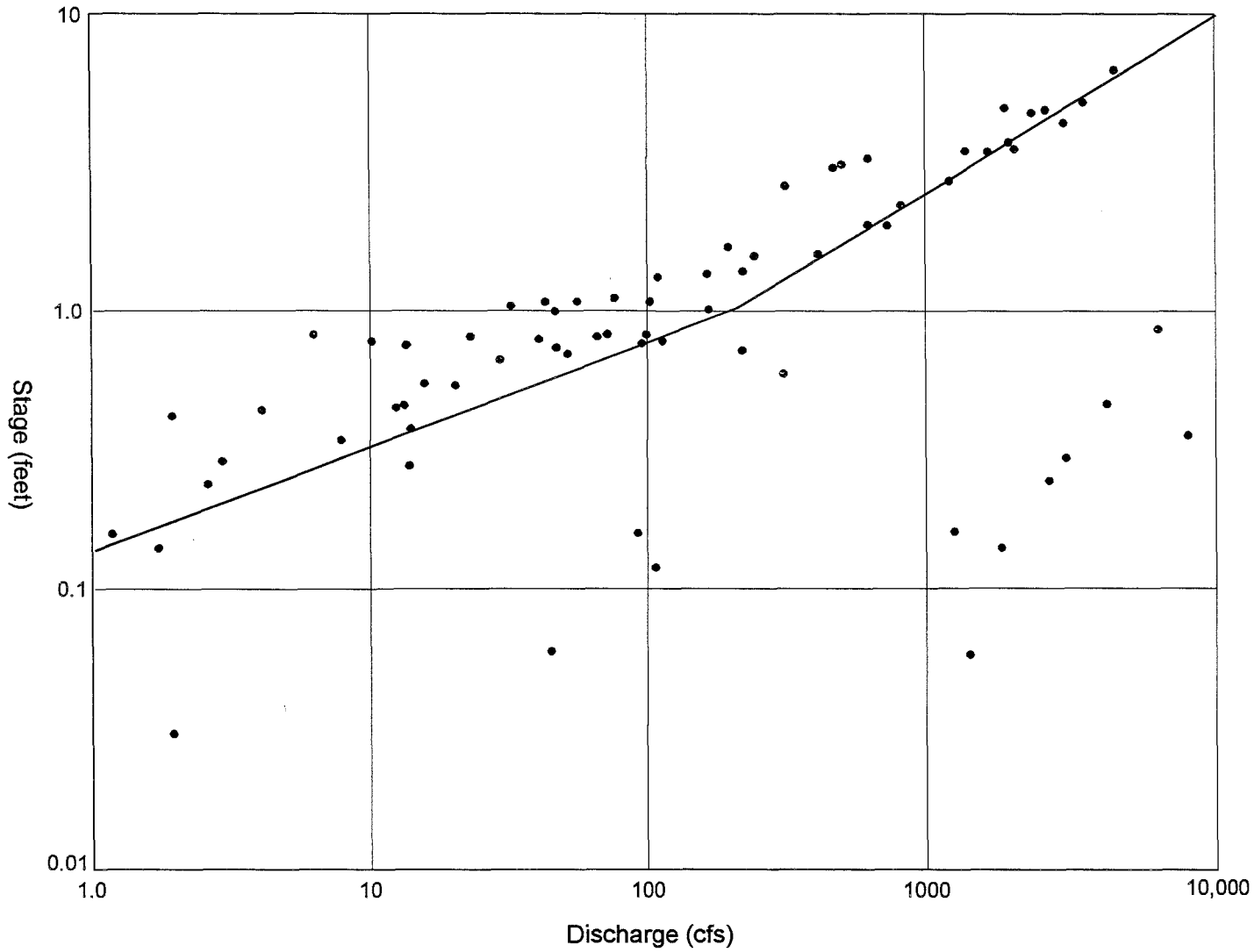
CHAPTER 8. STAGE-DISCHARGE RATING CURVES FOR THE SANTA CRUZ RIVER

A stage-discharge rating curve is a graphical plot that shows the relationship between the monitored water level at a gaging station (the *stage*) and the corresponding flow rate (the *discharge*). The establishment of a reliable stage-discharge relationship is essential at all river gauging stations when continuous-flow data are needed from the continuous stage record (Shaw, 1988). While stage-rating curves are most often used to convert stage data to discharge values, the curves can also be used to do the reverse. Stage-discharge rating curves are provided in this appendix so that the Arizona Stream Navigability Commission may determine the water heights that correspond to the discharge values given in earlier chapters. Below is a brief background of the meaning and use of stage-discharge rating curves for the gages at Tucson and near Nogales, the gages for which the oldest and most complete data were obtainable.

The stage-discharge relationship is dependent on the nature of the channel section and the length of channel between the site of the gage and the cross-section where the discharge was measured. Channel conditions in natural rivers tend to change over time; hence, stage-discharge relationships also tend to change over time, especially after flood flows. Typically new discharge measurements are made throughout a range of stages on a regular basis by the hydrologists responsible for maintaining USGS streamflow records. The hydrologist plots the discharge measurements against the corresponding stage measurements on log-log graph paper and draws a best fit line through the points. Because the data are plotted on log-log paper, the data points tend to group in a more linear fashion that makes relationships more apparent to the hydrologist. If the data were plotted on regular arithmetic graph paper, the data points would group into a curve; hence the name "rating curve" is given to the hand-drawn line through the data points. Each time new measurements are collected, a new stage-discharge rating curve is created. That rating curve is then used until the next time new discharge measurements are made.

Figure 27 is an example of such a stage-discharge plot using a log-log scale created for the Santa Cruz River at Tucson from data gathered during the period 1955-1961. There is a great amount of scatter in the data points' location; that is, the points do not cluster close together. Such scatter often occurs in data collected from rivers with channels composed of sandy, unconsolidated materials. Rivers with bedrock channels

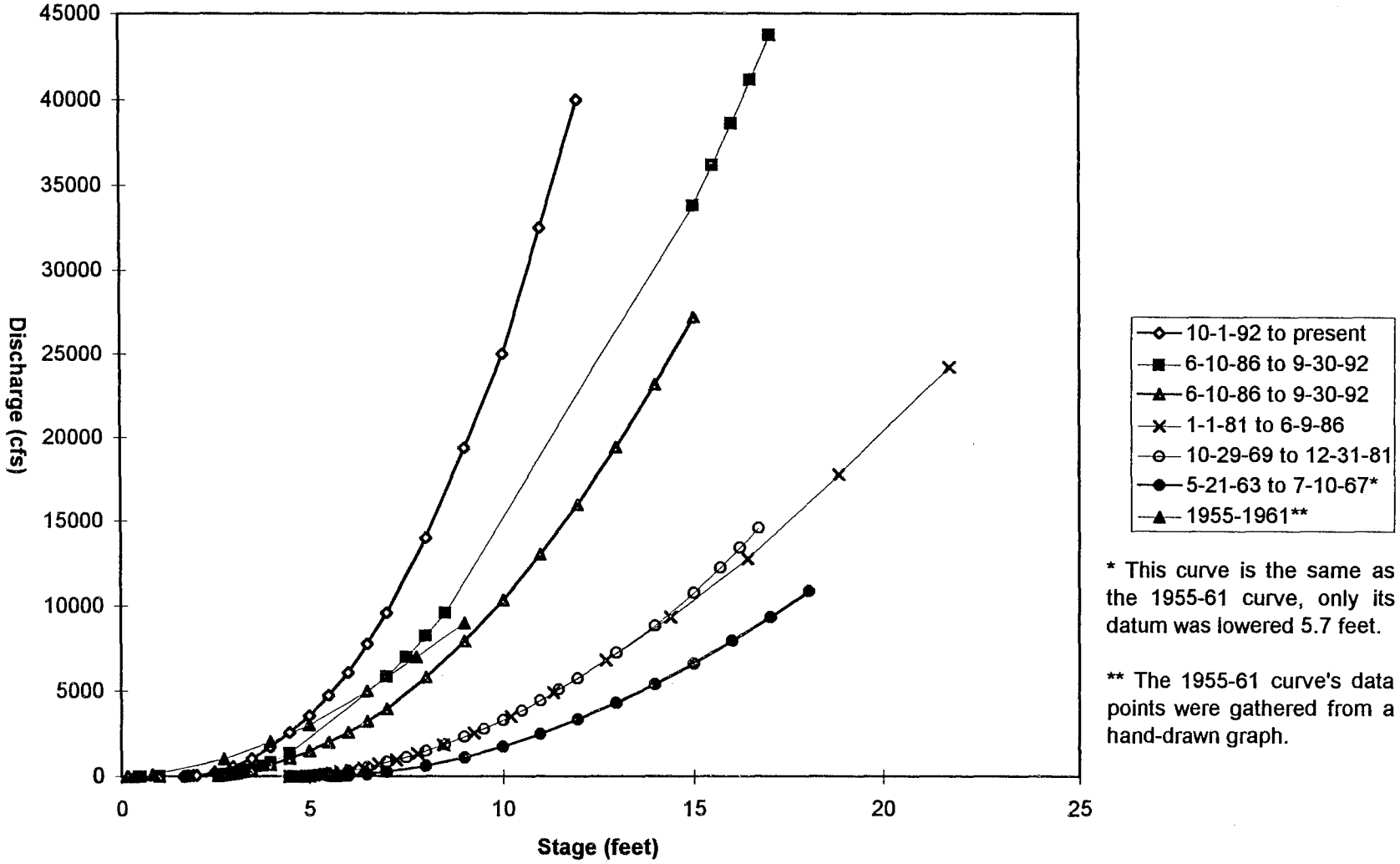
Figure 27. Stage-rating data for the Santa Cruz River at Tucson, Arizona.
Data points are plotted on a log-log scale.
Discharge measurements were gathered 1955-1961.



tend to have flows that remain in a fixed location with a fixed channel geometry; therefore, their stage-discharge points plot closer together. In contrast, channels in unconsolidated materials tend to shift their locations and dimensions through such processes as channel scour and deposition and meander formation and cut-off. (Refer to the section on channel change mechanisms in Chapter 6 of this report for a more detailed review.) Channel changes may occur even as a hydrologist is taking the discharge measurements (D. Ufkes, USGS-Water Resources Division, Tucson, personal communication, 1996). The change in the slope of the line drawn through the data points in Figure 27 at the stage height of about one foot indicates that there was a change in the channel control governing the stage-discharge relationship in this reach (i.e. there may have been a change in the slope of the river banks). In rivers where flood flows overfill the channels and spill onto flood plains, there may be another break in the slope of the line at higher discharges because the stage-discharge relationship of the within-bank flow may be very different from the stage-discharge relationship of the floodplain flow.

Once a USGS hydrologist establishes a satisfactory rating curve, a rating table is constructed from values of stage and discharge read off the line drawn through the data points. We retrieved the rating tables used for different time periods from the USGS-Water Resources Division office in Tucson for the gages at Tucson and near Nogales. We plotted the data as curves on an arithmetic scale rather than as straight lines on a log-log scale to make the graphs easier to read. Figures 28 and 29 illustrate how the stage-discharge relationships at these sites have changed over time. While most of the differences between the curves are a result of changes in the channel characteristics, some result from the use of different methodologies in obtaining discharge measurements. For example, the two curves in Figure 28 plotted for the period June 10, 1986, to September 30, 1992, result from different data collection methodologies. Figures 30 and 31 are enlargements of the same curves in Figures 28 and 29 that better show the stage-discharge relationships for lower stage heights.

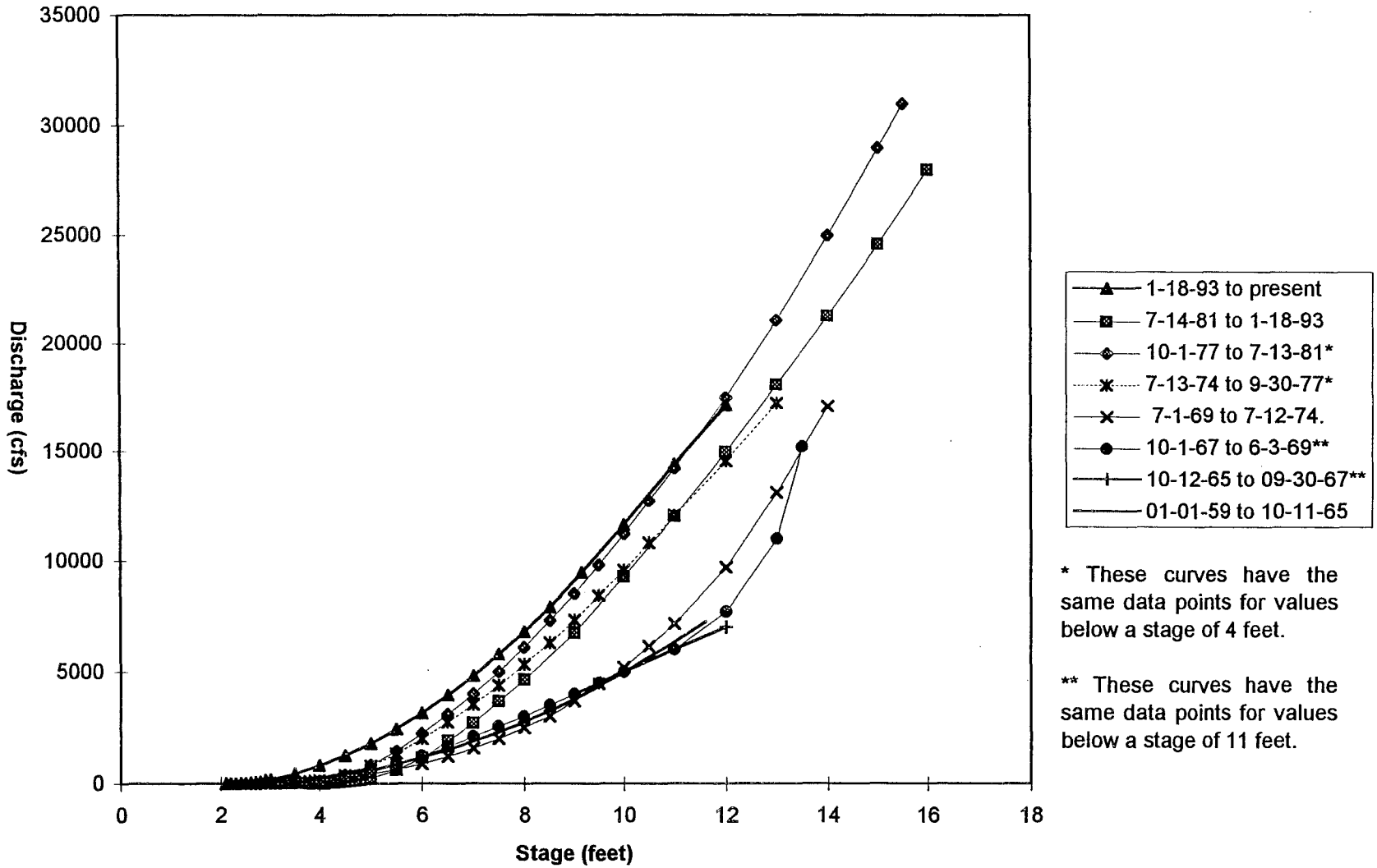
Figure 28. Stage-rating curve for the Santa Cruz River at Tucson.
Each line represents the stage-discharge relationship for a different period.



* This curve is the same as the 1955-61 curve, only its datum was lowered 5.7 feet.

** The 1955-61 curve's data points were gathered from a hand-drawn graph.

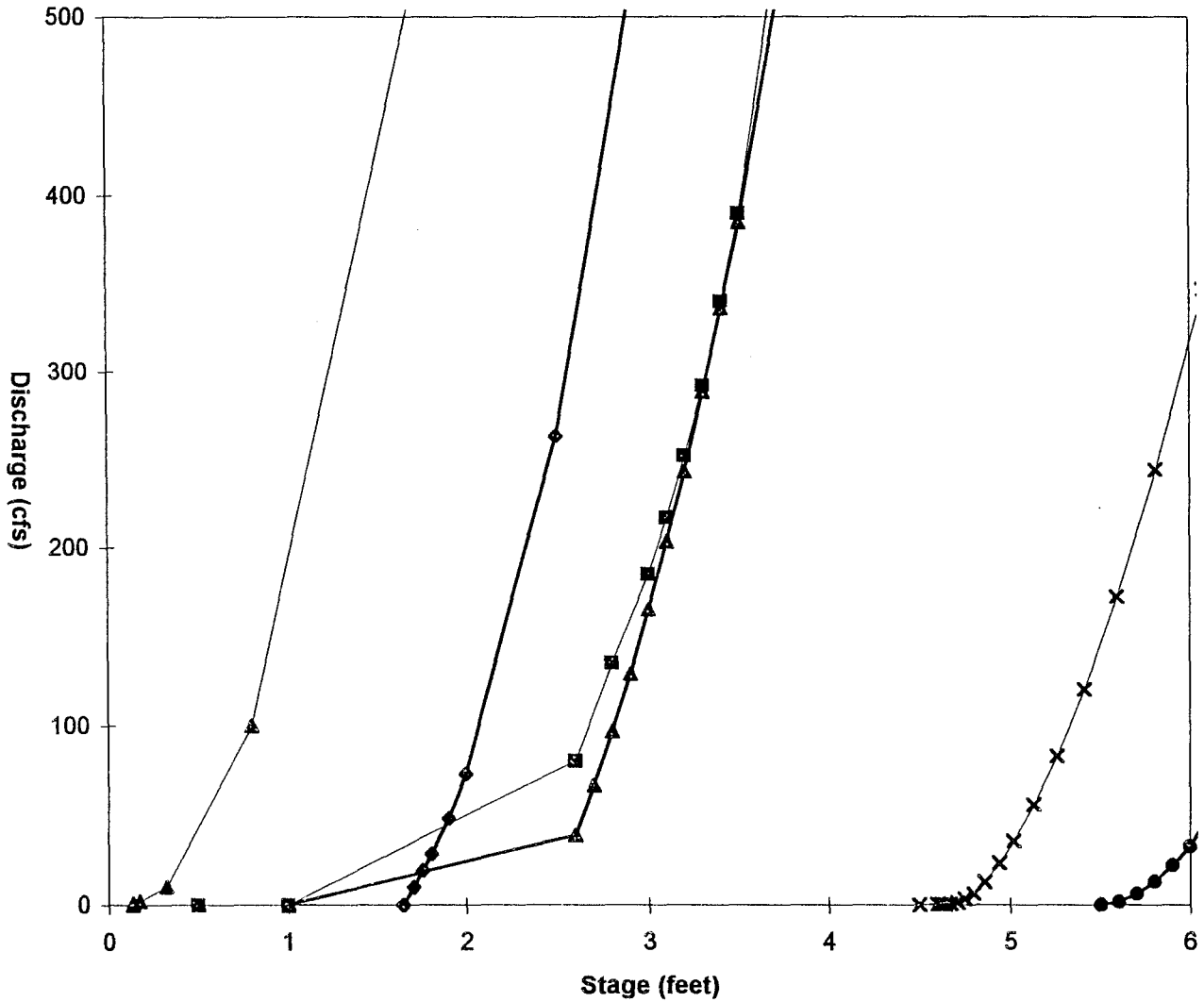
Figure 29. Stage-rating curves for the Santa Cruz River near Nogales
Each line represents the stage-discharge relationship for a different period.



* These curves have the same data points for values below a stage of 4 feet.

** These curves have the same data points for values below a stage of 11 feet.

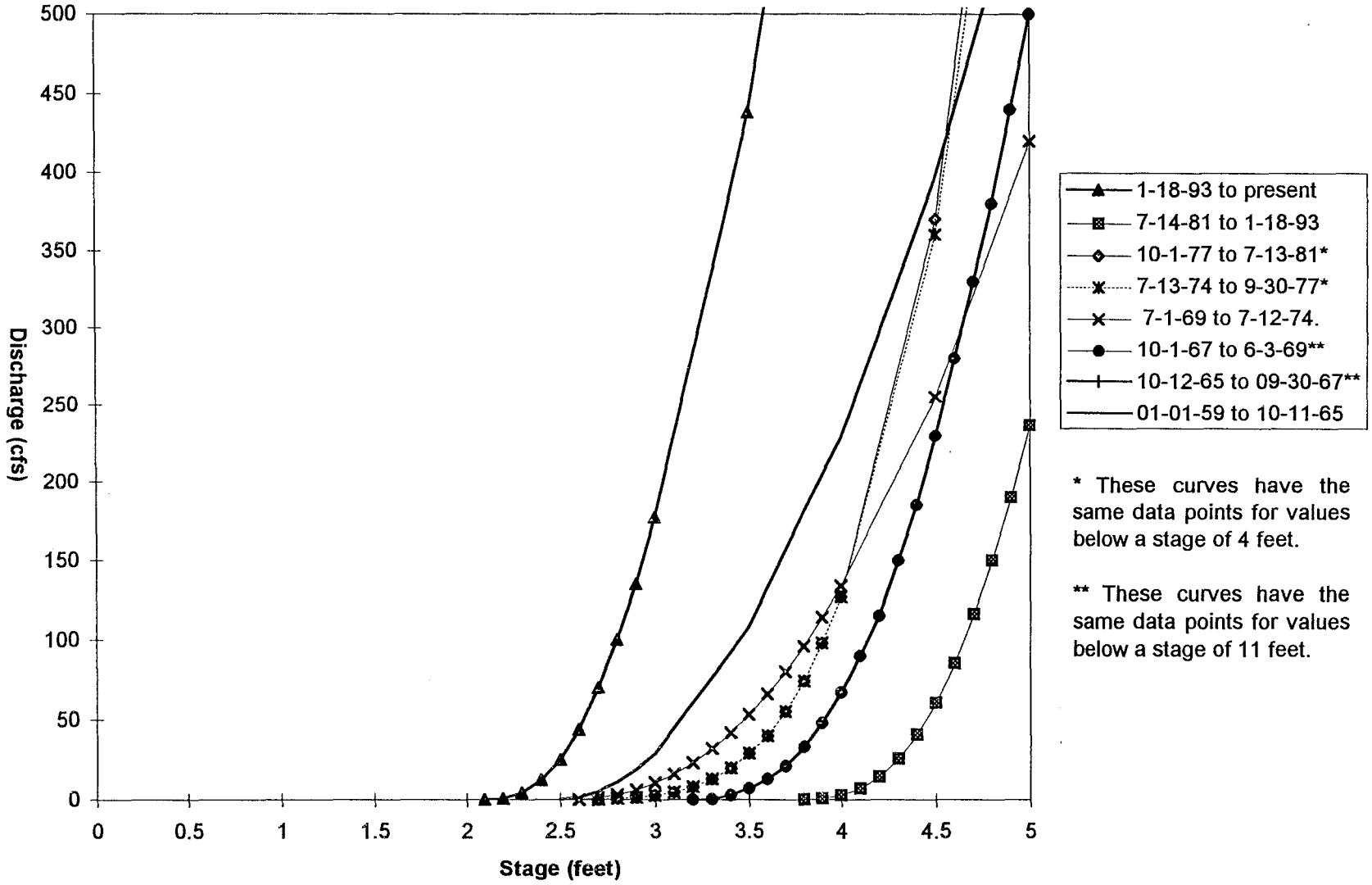
Figure 30. Stage-rating curve for the Santa Cruz River at Tucson.
Enlarged view of the stage-discharge relationship at low flows for selected periods.



* This curve is the same as the 1955-61 curve, only its datum was lowered 5.7 feet.

** The 1955-61 curve's data points were gathered from a hand-drawn graph.

Figure 31. Stage-rating curve for the Santa Cruz River near Nogales.
Enlarged view of the stage-discharge relationship at low flows for selected periods.



* These curves have the same data points for values below a stage of 4 feet.

** These curves have the same data points for values below a stage of 11 feet.

The following is an example of how to extract information from these rating curves. Figure 10 shows that the Santa Cruz River at Tucson experienced a daily discharge mean of 18 cfs on January 12, 1981. Figure 30 contains an enlarged illustration of the rating-curve used for the period January 1, 1981, to June 9, 1986. According to this rating curve, a discharge of 18 cfs would have a corresponding stage of 4.9 feet. Because a discharge of zero corresponds to a stage of 4.5 feet, the actual water depth for a discharge of 18 cfs would be 0.4 feet (4.9 minus 4.5 feet) in the channel. [Note: it is common for a discharge of zero *not* to correspond to a stage of zero (GVSCE, 1996a).]

The earliest rating tables we retrieved from the USGS date to the mid-1950's. Because of the multitude of channel changes that have occurred in the upper reaches of the Santa Cruz River in the early part of this century, the reader is advised not to use the 1950's curves to determine the stages corresponding to earlier discharges presented in this report except to get very rough estimates of stage. Also, these rating curves do not represent the stage-discharge relationships that exist at the Lochiel, Continental, Cortaro and Laveen gage sites. The table below provides a comparison of the estimated stage-discharge values for the gages at Tucson and near Nogales. Although the stage-rating curves in Figure 30 and Figure 31 appear to be very different because of the lowering and raising of the stage datum, the stage values derived from these curves that correspond to low discharges remain about the same over time. The stage values that correspond to higher discharges are markedly different.

Table 5. Comparison of the Estimated Stage-Discharge Values for the Gages at Tucson and near Nogales.

DISCHARGE (cfs)	STAGE (feet)			
	Nogales		*Tucson*	
	early 1900's	late 1900's	early 1900's	late 1900's
10	0.3	0.3	0.2	0.1
100	1.0	0.7	0.7	0.4
1000	3.3	2.1	2.6	1.9

CHAPTER 9. SUMMARY

The hydrology and geomorphology of the Santa Cruz River have experienced both subtle and dramatic changes in their character since the time of Statehood. These changes have resulted from a combination of climate change, human activities and geomorphologic processes. In this concluding chapter, the characters of the Santa Cruz River at the time of Statehood and the Santa Cruz River of the last decade are described and contrasted.

Hydrology

Historically (~1890s), the Santa Cruz River was perennial from its source to Tubac. Climate change since the turn of the century, combined with the extensive groundwater pumping for irrigation and the flow diversion for municipal use that began near the International Border during the 1930 to 1950 drought period, has resulted in no flow in the channel in Sonora, Mexico, and in discontinuous flow in the channel near Nogales, Arizona. The 1913 gage record at Nogales (the earliest in that region), indicates that by the time of Statehood, the Santa Cruz River at Nogales was no longer perennial, but instead had continuous flow during the winter and occasional flow during the spring, summer and fall. The winter discharge averaged about 15 cubic feet per second (cfs) except for an increase caused by a rainfall event that ranged from 35 to 174 cfs. A survey of the daily data for the rest of the Nogales record indicated that, during unusually wet years, there were only a few days of no-flow conditions. During dry years there were entire months that passed with no flow recorded in the channel. At present, naturally occurring perennial reaches occur only in the uppermost part of the river in the San Rafael Valley. Perennial flow in the reach near Nogales results from the discharge of sewage effluent from the Nogales International Wastewater Treatment Plant that began in 1972.

The Santa Cruz River historically had several springs and marshes (*cienegas*) within its channel from Tubac to Tucson, and a marsh existed at its confluence with the Gila River near Laveen. Even in the historical record, only the very largest floods were sustained from the headwaters to the confluence with the Gila River. A review of the daily discharge record indicated that there was some semblance of baseflow with an average of about 12 cfs during the fall and winter of 1912-1913 at the Tucson gage. Such continuous flow for months at a time was not seen again in the years that followed, although there

were periods of several weeks that experienced continuous or nearly continuous flow during very wet winter seasons. The Laveen gage recorded nearly year-round flow from its beginning date (1940) until June, 1956, when it began to measure zero flow for weeks at a time. During the 1940 to 1956 period, the daily flow averaged about 3 cfs during low flow conditions and had peaks as high as 5060 cfs during wet periods. By 1960, the Santa Cruz at Laveen was experiencing no-flow conditions for months at a time.

Not only have the locations of surface flows changed since the time of Statehood, but also the seasonality and magnitude of flows in the Santa Cruz River have changed in response to shifts in the hydroclimatology of the region. Although the majority of flow events occur during the summer season, the magnitude and number of annual peak discharges that occurred in the fall and winter were higher before 1930 and after 1960 than during the 1931-1959 period. For example, six of the seven largest floods at Tucson occurred after 1960, indicating that the magnitude of flood peaks has increased in the past few decades.

Human activities as well as climate change have had notable effects on the peak flows of the Santa Cruz River, especially in the lower Santa Cruz River basin. Since 1962 the construction of flood-control channels in the washes of the lower Santa Cruz River basin have resulted in the reduction of floodplain storage and infiltration losses, therefore reducing the *attenuation* (the downstream decrease of the flood peak) of peak discharges. For example, the attenuation of peak flows was greater during the 1962 floods than during the 1983 floods because water was able to spread out over the broad flow zones in the lower reaches of the Santa Rosa and Santa Cruz washes. In contrast, much of the floodwater during the 1983 floods was efficiently transmitted downstream by the flood-control channels.

Geomorphology

The geomorphology of the upper Santa Cruz River is quite different from that of the lower Santa Cruz River. The river has a well-defined, often entrenched channel in its upper reaches that contrasts strongly to the ill-defined system of braided channels that exist north of the northern end of the Tucson Mountains near Marana. Both the upper and lower reaches of the Santa Cruz River have experienced dramatic changes resulting from a combination of both natural geomorphic processes and human activities. Three types of lateral change have occurred: meander migration, avulsion and meander cutoff, and

channel widening. Two types of vertical change have occurred: aggradation and degradation of the channel bed. While arroyo development is the most obvious type of channel change to occur since the 1890s in the upper Santa Cruz River, most of the initial channel incision occurred before the time of Statehood. Since 1912, various reaches of the upper Santa Cruz River have been dominated by such processes and activities as meander migration and cutoff, channel widening, arroyo widening, channelization, and the vegetational effects of sewage effluent discharge. The channel locations in different reaches have changed spatially on the order of a few feet to a few thousand feet, depending on the processes that resulted in the change, and often change could be detected from one year to the next.

The lower Santa Cruz River experienced changes of a completely different magnitude from the upper Santa Cruz River. Changes in the location of the channel in the lower basin can be measured in miles, and the timing of changes spans decades. Before the construction of Greene's Canal in 1910, the river transformed from a relatively deep, well-defined channel to a broad, flat, extensive alluvial plain at a point in the Marana area. Now that transition point occurs near Chuichu, Arizona. The construction and subsequent flood damage of Greene's Canal has resulted in dramatic geomorphic changes. Prior to and during the floods of 1914-1915, flood flow had the opportunity to follow routes down the North Branch of the Santa Cruz Wash and McClellan Wash. After the development of the arroyo in Greene's Canal, subsequent flood flows have had westerly paths *via* Greene's Canal.

GLOSSARY

adobe flats: defined in Bryan (1922a) as broad flats that are formed by deposition from sheet floods and are floored with sandy clay, also called "adobe."

aquifer: a permeable geologic formation, group of formations, or part of a formation which stores and transmits water.

arroyo: a river or stream with a single, definite channel incised in unconsolidated material consisting of clay, silt sand and some gravel, with banks more than two feet high.

basin: an extensive depressed area into which the adjacent land drain. The Tucson Basin is the northward-trending, structural depression of about 2600 km^2 into which the adjacent land drains.

cienega: term applied to riparian marshlands by Spanish explorers.

ephemeral stream: a stream or portion of stream which flows only in direct response to precipitation. It receives little or no water from springs and no long continued supply from snow or other sources. Its channel is at all times above the water table.

flow-duration curves: cumulative frequency curves that show the percentage of time specified discharges are equaled or exceeded in a given period.

groundwater: that water which infiltrates the earth's surface, percolates downward, and is stored in the saturated zone of a geologic stratum.

infiltration: the process whereby water passes through an interface, such as from air into soil.

infiltration rate: the rate at which soil can absorb water.

intermittent stream: a stream with reaches that flow only during wet weather or during part of the year.

percolation: the process whereby water passes through fine openings in porous stones.

perennial stream: a stream or portions of a stream that flow throughout the year.

phreatophytes: deep-rooted plants that obtain water from the ***water table*** or the layer of soil just above it.

recharge: inflow to a ***groundwater*** reservoir. ***Aquifers*** may be recharged from ***infiltration*** of water from adjacent mountains, direct penetration of precipitation on valley floors, infiltration of waters used for irrigation, water rising from depths as fault or fracture springs, and ***underflow*** from outside the basin. Water is discharged from aquifers by underflow into a downstream basin, evaporation, transpiration, spring discharge, and pumping.

riparian: refers to that which is related to or located or living along a watercourse whether natural, man-made, ephemeral, intermittent, or perennial.

subflow: see ***underflow***.

underflow: a term used interchangeably with ***subflow*** throughout this report to describe the groundwater underlying the surface of a stream's channel. Sykes (1939) noted that these words imply continuous forward movement of water beneath the stream-bed, which probably seldom occurs in a stream channel like that of the Santa Cruz River. Sykes instead describes the "underflow" as being a series of semi-isolated sub-surface reservoirs, which retain most of the seepage water received from local precipitation, or channel flow, and only intercommunicate when the sub-surface layers of the stream bed become supersaturated.

wash: a river or stream with low banks and numerous channels.

water table: the plane which forms the upper surface of the zone of ***groundwater*** saturation. Should the water table rise so that it intersects the ground surface, a spring results.

xerophytes: plants that are structurally adapted for life and growth with a limited water supply.

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Appendix A. Ground Photographs

The ground photographs provided in this appendix illustrate key differences between the different reaches of the upper and lower Santa Cruz River. Figure A-1 indicates the locations of the photographed reaches. All photographs were taken in 1996. For a review of historical photographs of the Santa Cruz River, refer to Tucson's Santa Cruz River and the Arroyo Legacy.[3]

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[3] Betancourt, J.L. (1990). Tucson's Santa Cruz River and the Arroyo Legacy. Tucson, The University of Arizona, Ph.D. dissertation, 239 p., and,
Betancourt, J.L., and Turner, R.M. (1990). Tucson's Santa Cruz River and the Arroyo Legacy. To be submitted to the University of Arizona Press, Tucson, as a book manuscript, 239 p.

Figure A-1. Locations of ground photographs provided in this appendix.

Legend:

- Rivers
- Main Flow Route since ~1915
- Santa Cruz Basin Boundary
- Ground Photograph Location

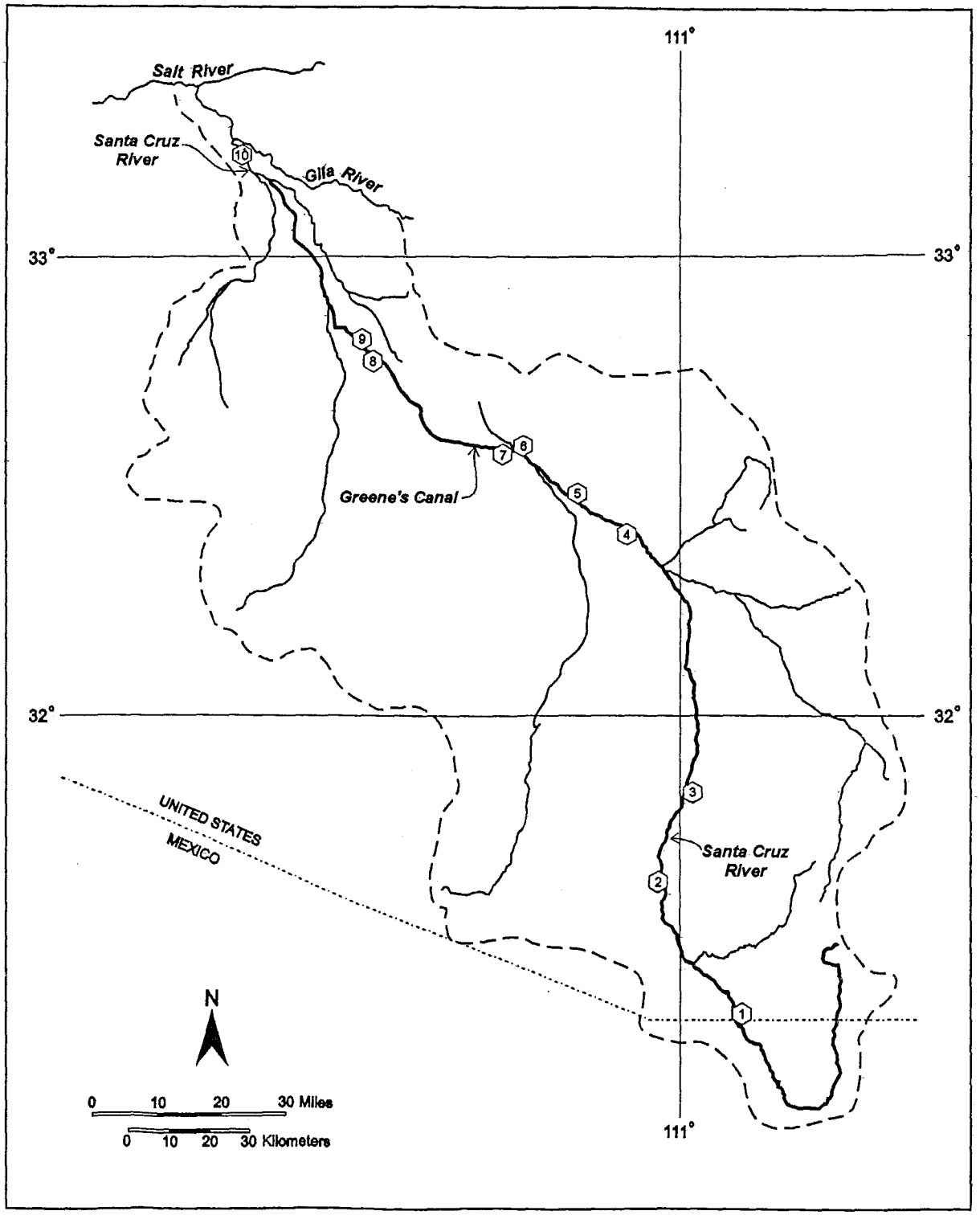
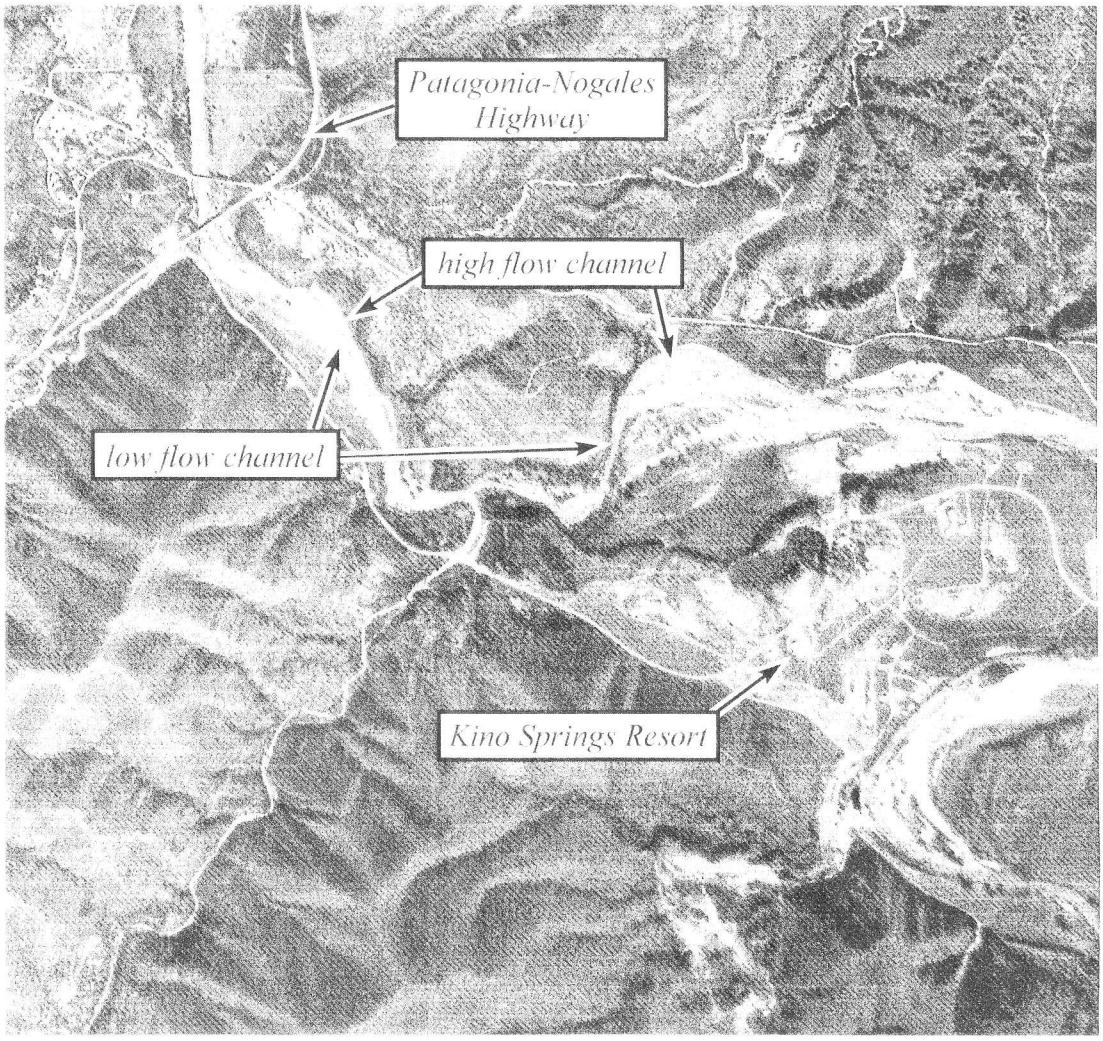
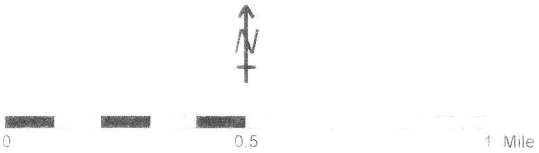
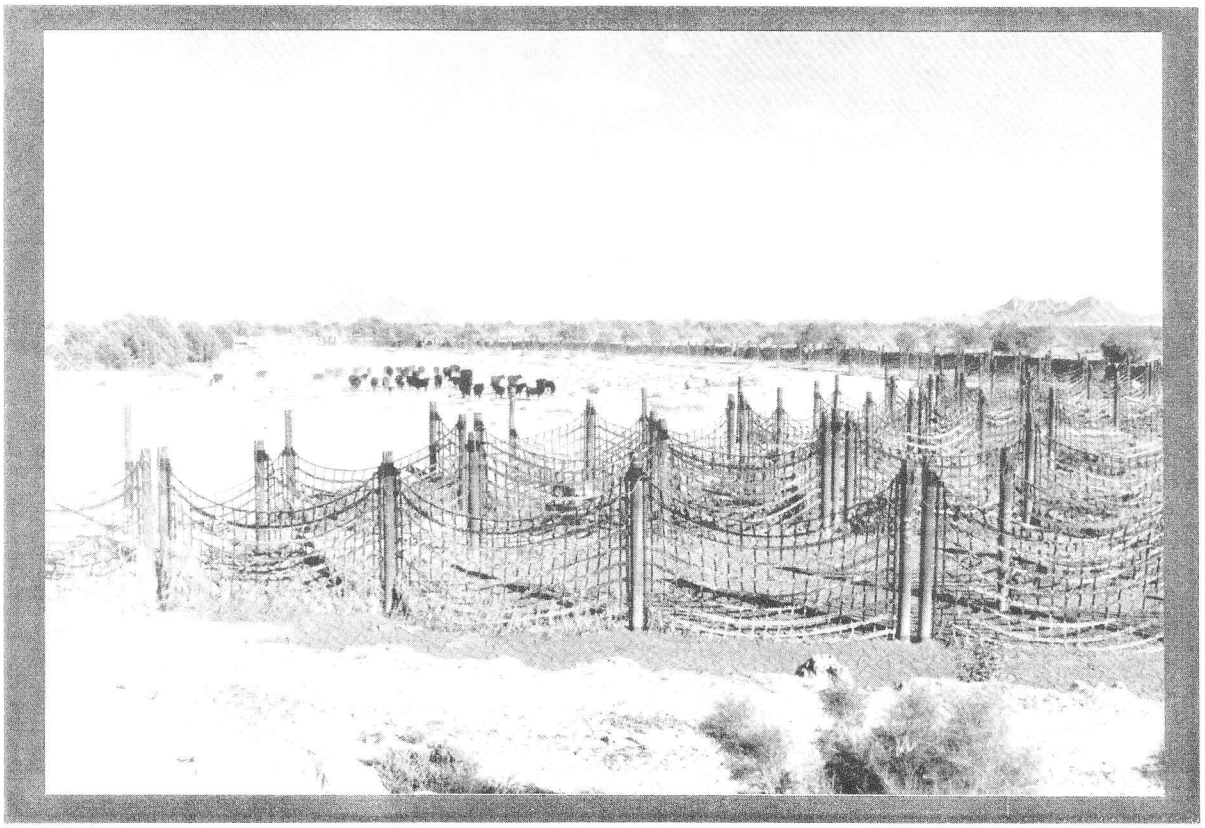
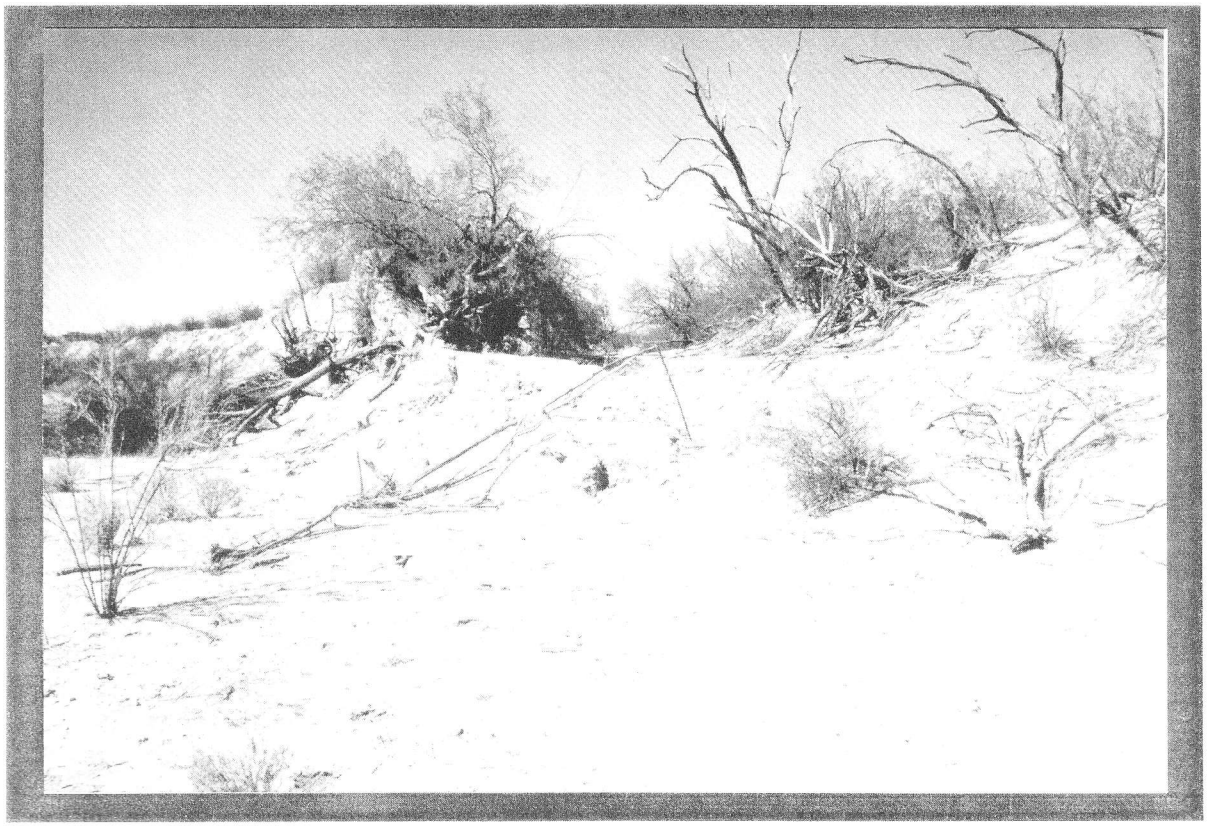


Figure 23. Annotated aerial photograph of the Kino Springs reach of the Santa Cruz River.





5. Upstream view from Trico-Marana Rd. crossing of the Santa Cruz River with erosion control structures. (9/18/96)



6. Downstream view of the Santa Cruz where it splits from Greene's Canal. Note, the base of the Santa Cruz channel is perched above the base of Greene's Canal. (10/7/96)