RICHARD HEREFORD AND
JULIO L. BETANCOURT

Historic Geomorphology of the San Pedro River

TWELVE

ARCHIVAL AND PHYSICAL EVIDENCE

Introduction

The need to explain and manage arroyos, or water-carved gullies, in the western United States has been a dominant theme in American geomorphology since the turn of the twentieth century. To date, no single explanation satisfies widespread and almost synchronous arroyo formation around the turn of the century. Is this dramatic episode of erosion unique, or has it repeated itself both in kind and in magnitude during past millennia? Surprisingly, attempts to explain arroyos far outnumber efforts to characterize their initiation and subsequent history.

The San Pedro River is cited often in reference to historic arroyos (Bryan 1925, Antevs 1955, Hastings 1959, Hastings and Turner 1965, Martin 1963, Melton 1965, Rodgers 1965, Cooke and Reeves 1976, Dobyns 1981, Hendrickson and Minckley 1984), but neither the archival nor physical evidence has received more than cursory attention. Unlike the heavily urbanized floodplains along the Santa Cruz River at Tucson, floodplain surfaces and cutbank stratigraphy remain relatively unspoiled along the San Pedro River, particularly in its upper reaches.

When arroyos expanded into the upper San Pedro, they exposed the remains of mammoth in association with Clovis, notably at the Naco, Lehner, and Murray Springs sites. Investigation of these sites has led to an unusually complete record of late Quaternary alluvial history (Haynes 1968, 1987) that contrasts with our haphazard understanding of the more recent floodplain history. We correct for this oversight by evaluating both archival and physical evidence for floodplain evolution before and after historic arroyo cutting on the San Pedro.

In this study, we used archival evidence from the lower and upper basins, but field mapping was limited to the upper San Pedro. The primary objectives of the archival research were to describe general floodplain conditions before arroyo cutting and to establish timelines for major floods and cutting episodes. The physical evidence was marshaled to determine rates and causes of channel widening once the arroyo developed, as a prerequisite for understanding how alluvial channels might progress towards equilibrium after entrenchment (Hereford 1993).

Archival Evidence

Historical studies of environmental change must depend on documentary sources of variable quality. Standard observations made at regular time intervals, such as those obtained at a stream gage or weather station, usually are unavailable for the periods of interest; for example, neither weather nor discharge measurements exist for the San Pedro River during the critical period of arroyo initiation. In the Southwest, the field notes of the cadastral surveys made by the General Land Office consistently record the width of stream channels but mention channel depth only sporadically (both before and after arroyo initiation occurred). Were there significant differences between cross sections where channel depths are mentioned and where they are omitted, or is any reference to depth purely whimsical? Can we infer unincised floodplains where the surveyor failed to mention depth, as Bryan (1928a) did on New Mexico's Rio Puerco? In 1873, Theodore White, one of the first land surveyors in southern Arizona, surveyed the San Pedro River Valley from St. David to just below the Narrows. From the journals of itinerants, we know that the river was entrenched at St. David, Tres Alamos, and below the Narrows (fig. 12.1), with perpendicular banks 3 to 6 m deep as early as the 1850s. White failed to record any channel depths at these same localities (Cooke and Reeves 1976). Was White making a distinction between terraces formed during an earlier erosional episode and active channel depths, a distinction that escaped the itinerants?

Historical sources, such as newspapers, provide descriptions of extreme and rare episodes, most importantly floods. These accounts serve the environmental historian well, because degradation of alluvial stream channels occurs catastrophically during extreme flows. The erosional work done by floods often is described in great detail, as was the case with headcut migration in the Santa Cruz River Valley at Tucson in summer 1890 (Hastings

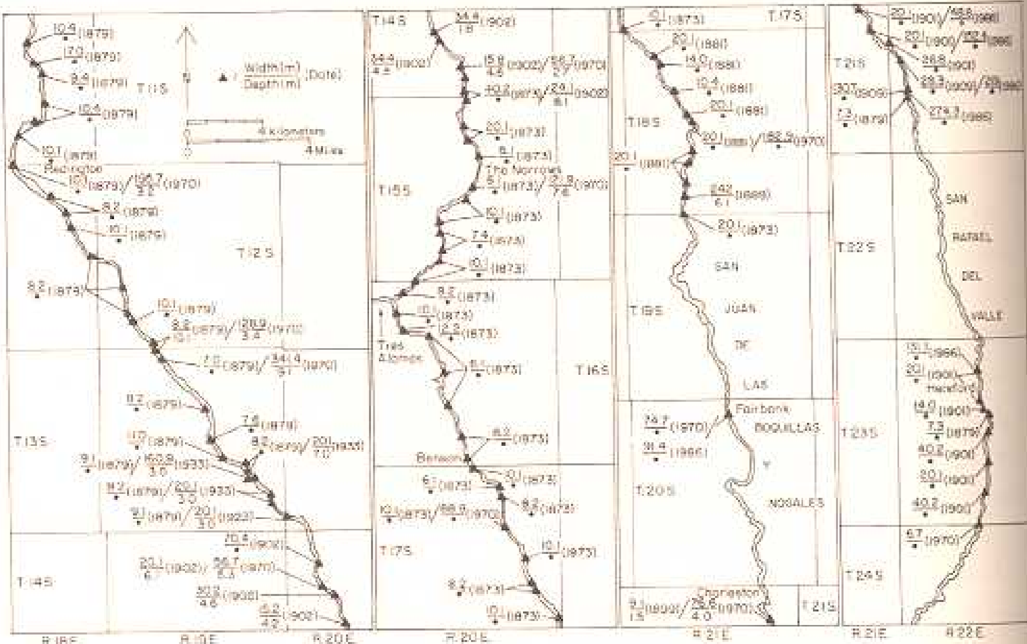

Fig. 12.1. Maps showing width and depth observations from cadastral surveys 1873–1933, amended from Cooke and Reeves (1976).

1959, Betancourt 1990). The degree of detail given in the accounts corre-lates well with distance to large settlements, and coverage of flood damage is patchy, giving the false impression that some reaches were more afflicted than others.

For the San Pedro River, we relied on a variety of primary and secondary sources. The earliest relevant observations are those related to administration of the Presidio of Santa Cruz de Terrenate, established in 1742 in the headwaters of the San Pedro and moved to Quiburi near Fairbank (fig. 12.2) in 1772 (Kessell 1966). Many of the documents pertaining to this presidio are contained in the Archivo General de Indias in Seville, Spain (Beers 1979). The next period for which documentation exists involves the early years (1820s–1830s) following Mexican Independence, when four land grants—the San Ignacio del Babocomari, the San Rafael del Valle, the San Juan de las Boquillas y Nogales, and the San Pedro (fig. 12.2)—were sought, surveyed, and approved (Mattison 1946). A fifth grant was ceded at Tres Alamos in 1852. For the post–Civil War period, we relied mainly on local newspaper accounts.

PRE-ENTRENCHMENT CONDITIONS

The inability to accurately portray pre-entrenchment conditions has plagued historic arroyo studies. The written record just prior to arroyo formation is patchy and incomplete. In the case of the San Pedro, gaps in written observa-tions can be bridged by stratigraphic records from critical localities.

These records can help resolve two questions about pre-entrenchment

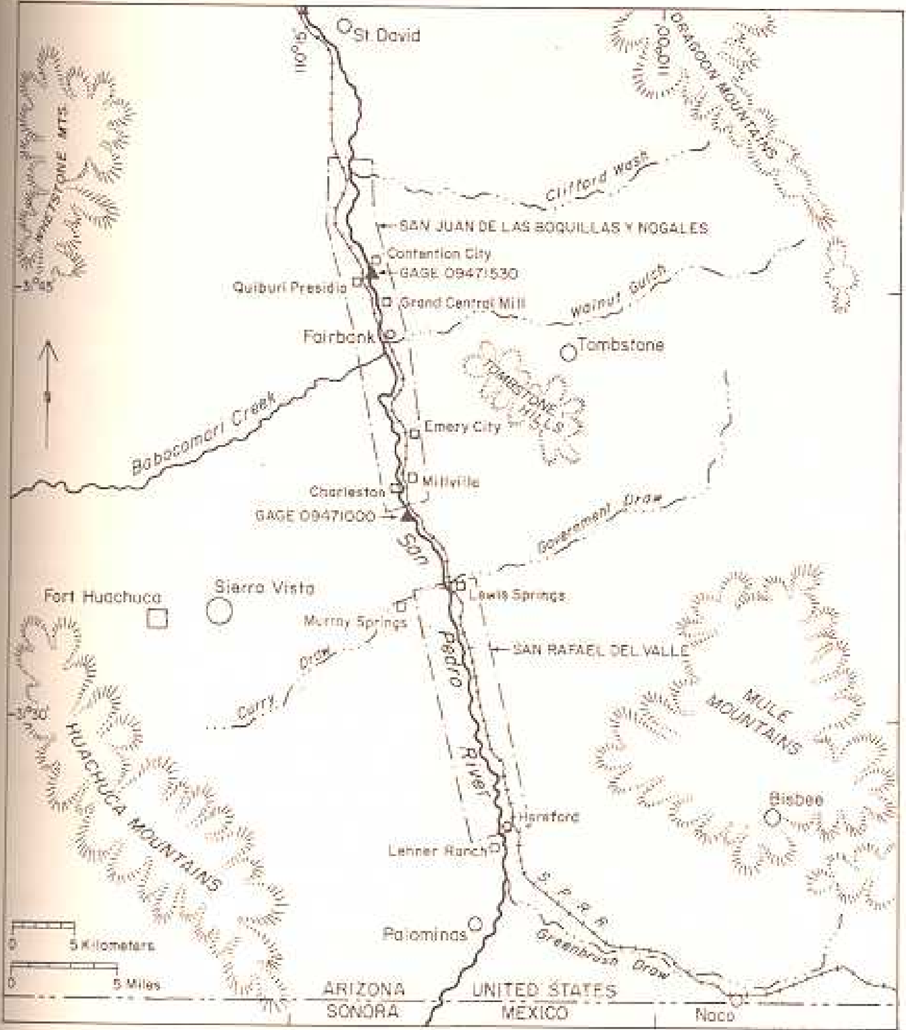

Fig. 12.2. Map of upper San Pedro River Valley showing locations of current and historical features. Illustration credit: Chuck Sternberg.

conditions: (1) which reaches of this interrupted stream had perennial surface flow and which did not, and (2) does evidence exist for unincised floodplains and contemporaneous discontinuous arroyos? In the case of discontinuous arroyos, the evidence could be ambiguous because the observer usually was unaccustomed to making subtle distinctions between inset and superimposed stratigraphic relations between alluvial deposits. Such a distinction is critical to geomorphic interpretation. Figure 12.3 illustrates the difference between inset and superimposed relations. These relations result from two or more cut-and-fill cycles in which the younger longitudinal gradient is the steepest. A superimposed relation is typical of the area upstream of Lewis Springs; an inset relation occurs locally from Charleston downstream to Fairbank (see fig. 12.2 for locations). A steep terrace rise near the river,

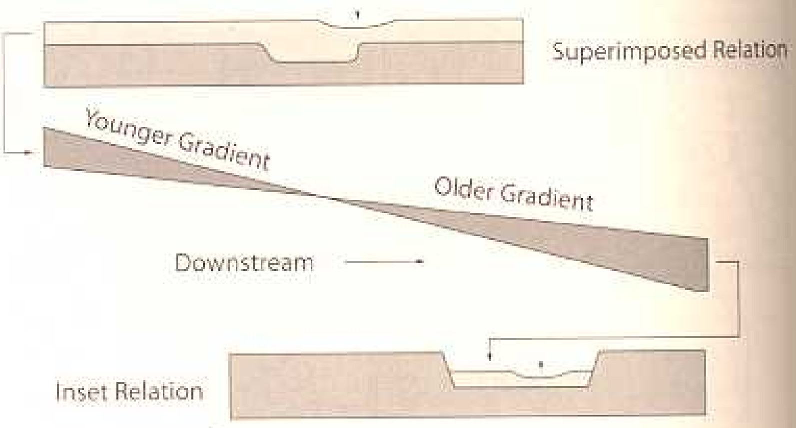

Fig. 12.3. Superimposed and inset stratigraphic relations and their geomorphic expression.

which perhaps had to be "cut down" to help wagons cross the river, could represent an earlier entrenchment, unrelated to current base level, and with an inset stratigraphic relation.

1600s and 1700s. The accounts of Kino, Manje, and Bernal (Karns 1954) in the 1690s and those of Velarde in 1716 contain few relevant observations about channel or flow conditions in the valley, other than the fact that irrigation was practiced on swampy land near Quiburi (near Fairbank).

1820s and 1830s. Attempts to settle the San Pedro increased in the 1820s after Mexican Independence, when several settlers filed for land grants in the bottomlands. This happened at a time when beaver ponds dotted the lower reaches of the San Pedro River Valley (Pattie 1905). The State of the West law, adopted by Mexico in 1825, limited grants to ranchers to 4 square leagues or *sitios* (ca. 2784 ha). The price of a sitio with running water was $60; the price for dry rangeland was $10. In 1832, Don Ygnacio Elias y Gonzales was issued title for eight sitios, six with water, along Babocomari Creek, where he ran about 40,000 head of cattle and a large herd of horses and mules (Christiansen 1988). He and Juan Nepomucino Felix were also granted four sitios with water along the San Pedro (the San Juan de las Boquillas y Nogales Land Grant) in 1833. The Boquillas Land Grant was a narrow strip of land on both sides of the river, from Charleston to just south of Fairbank. In 1833, Rafael Elias Gonzales was granted four sitios, again with water, along the San Pedro. This was the San Rafael del Valle Land Grant with its southern boundary between Hereford and the Lehner Ranch and extending north to Lewis Springs (fig. 12.2). Gonzales also received title to the San Pedro Land Grant, another four sitios along the San Pedro straddling the international boundary. A selling price of $60 for each sitio along the Babocomari and San Pedro Rivers suggests that relevant reaches of these streams were perennial in the 1830s. The San Pedro remains perennial today from Hereford to Fairbank, while the Babocomari contains two perennial reaches, one near the Brophy Ranch headquarters and another just downstream of the grant's eastern boundary (D. Brown et al. 1981).

1840s to 1860s. Accounts during this period generally indicate marshy and commonly treeless conditions throughout the upper San Pedro, with intermittent flow below Tres Alamos and the Narrows and discontinuous arroyos below the Narrows, at Tres Alamos, and near St. David (Hastings 1959, Hastings and Turner 1965, Dobyns 1981, Hendrickson and Minckley 1984). In 1849, Eccleston (1950) noted that below the Narrows, the river "is lined with a poor growth of swamp willow and other brush, so that it cannot be seen until you come within a few feet of it; then the bank is perpendicular." Five years later, in the same reach, Parke (1857:24–26) noted that: "The valley bottom is generally smooth and open, with the streambed curving through it, sometimes a few inches, and at others as much as fifteen feet below the surface of the meadow. At Tres Alamos, the stream is about fifteen inches deep and twelve feet wide, and flows with a rapid current over a light sandy bed, about fifteen feet below its banks, which are nearly vertical. The water here is turbid, and not a stick of timber is seen to mark the meanderings of its bed. In the gorge below (the Narrows) and in some of the meadows, the stream approaches more nearly the surface, and often spreads itself on a wide area, producing a dense growth of cottonwood, willows and underbrush, which forced us to ascend and cross the outjutting terraces. The flow of water, however, is not continuous." Hutton (1859) gave a similar description for the reach just below Tres Alamos in 1857: "The San Pedro has a width of about twelve feet and a depth of twelve inches, flowing between clay banks, ten or twelve feet deep, but below it widens out, and from beaver dams and other obstructions overflows a large extent of bottomland, forming marshes, densely timbered with cottonwood and ash." Another apparent arroyo just below St. David was described by Bartlett (1854) and Graham (1852) of the International Boundary Commission.

LATE NINETEENTH-CENTURY FLOODS AND ARROYO CUTTING

1870s to 1890s. Settlements along the San Pedro were first established in the 1870s, with the arrival of Mormons at St. David and the discovery of silver near Tombstone (Fulton 1966). In 1884, the anthropologist Adolph Bandelier visited ruins along the San Pedro and described the arroyos near Tres Alamos and St. David: "[At Tres Alamos] the river, now rendered muddy by the washings of the mines worked on its upper course near Contention and Charleston, runs in a cut which is from eight to twelve feet deep . . . [at St. David] the river runs in a cut with abrupt sides. This cut is 10 to 15 feet deep, and about 25 feet wide" (Bandelier 1892:475–478). This also agrees with McClintock's (1921) account that the first Mormon settlers encountered an entrenched channel of the San

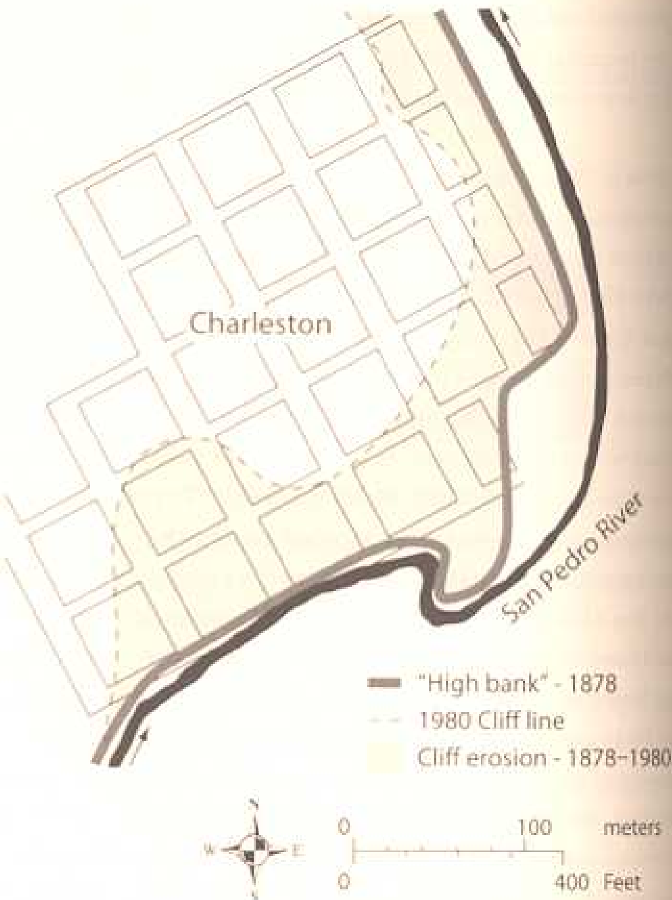

Fig. 12.4. Plat of Charleston in 1879 by A. J. Mitchell. Adapted from K. Tiller (1982).

Pedro below St. David in 1877. Hastings and Turner (1965) suggest that extensive mesquite thickets existed where the floodplain was entrenched. Mesquite also dominated in the lower reaches where the flow was intermittent.

In 1879, the town of Charleston (a planned community) and a mill site were founded on opposite sides of the San Pedro, with the intent of using the river's permanent flow for processing ore from the newly created Tombstone Mining District (fig. 12.4). Early photographs of Charleston (fig. 12.5) again beg the question about discriminating between superimposed and inset relations for steep "banks" bordering the San Pedro. Figure 12.5 is an upstream view of Charleston from Millville showing the position of the inner channel between two older terraces. The date of the channel cutting that produced these erosional terraces remains uncertain. However, major flooding at any time before establishment of Charleston could have formed these terraces and caused valley widening.

The first mention of active arroyo cutting is from the reminiscences of Mary Wood, published in the *Tombstone Epitaph* in 1929. Wood recalled that a flood in August 1881 destroyed the small dam near Millville, and the banks of the river were widened and deepened. The years 1881, 1882, and 1883 had

Fig. 12.5. (top: 12.5a): Photograph of Charleston taken by Carleton Watkins in 1883 looking southwest toward Huachuca Mountains. The San Pedro River runs from left to right through well-defined channel. (bottom; 12.5b): Same view in 1960. Photo credit: Rod Hastings, U.S. Geological Survey Desert Laboratory Photo Archive.

unusually wet summers, the only three consecutive years to produce more than 20 cm of rainfall in June–August at Tucson (Betancourt 1990). The wet summer of 1881 produced enough runoff to cause overflow of the active channel and erosion of the terrace on which Charleston was built. The 1883 photograph of Charleston indeed shows some evidence of recent undercutting of the west terrace (fig. 12.5).

Bryan (1925:342), in an often-cited statement, maintained that "the trench on San Pedro River was cut progressively headward between 1883, when the arroyo formed at the mouth of the river, and 1892, when the headwater fall cut through the boundaries of the Boquillas grant 200 km upstream." He cited a report then in preparation (Bryan et al. 1934), but this manuscript contains no further reference that would warrant an 1883 date for initiation of a headcut at the mouth, or that arroyo development progressed from mouth into the upper San Pedro in less than a decade (Hastings 1959, Rodgers 1965, Cooke and Reeves 1976). Bryan apparently thought that headcut migration was enhanced by increased longitudinal surface slope in each successive subbasin, contrary to normal steepening upstream exhibited by most streams. Bedrock outcrops at Charleston and the Narrows produce independent base levels in each subbasin. Over the short term, these outcrops should have restricted propagation of headcuts or coalescence of discontinuous arroyos from one subbasin to another.

Large floods also occurred on the San Pedro River in the summers of 1886 and 1887 and the summer and fall of 1890. The newspapers reported overbank flooding in 1886 and 1887, but no mention was made of channel erosion. Hastings (1959), however, cites testimony in a court case that the bed of the river near Tres Alamos was lowered 4 m between 1885 and 1889.

1890s to 1900s. Though in other reaches arroyos might have developed in the 1880s, 1890 does appear to mark the beginning of extensive degradation in the lower San Pedro. In August and September 1890, floods on the San Pedro and Santa Cruz Rivers received unusual attention in southern Arizona newspapers. On the San Pedro, most of the bridges were swept downstream. At Dudleyville, the San Pedro "caved within 5 meters of Cook's place," indicating extensive channel widening. On October 2, the *Arizona Daily Star* described deepening of the channel near Mammoth by 9 m.

In the winter of 1891, flooding again affected the San Pedro River Valley, eroding valuable land in some areas and silting other land downstream. Damaging floods occurred again in August 1893, 1894, and in July, August, and September 1896. Above-normal summer rains preconditioned the watershed to excessive runoff during a generalized storm in the fall of 1896. This storm produced the third greatest September-October rainfall at Tucson. In October 1896, streams originating in the Whetstones flooded the Benson area; near the mouths of these streams, channels were deepened by as much as 9 m. This storm persisted for two weeks and caused significant damage to settlements and farms along the San Pedro.

It was probably during the 1896 flood that a channel almost 244 m wide and 6 m deep developed at the northern end of the Boquillas Land Grant, as recorded in an 1899 survey (fig. 12.1). A survey in 1873 recorded a width of no more than a chain (ca. 20 m) in the same area (Cooke and Reeves 1976).

Yet, a channel only 9 m wide and 1.5 m deep defined the river's course at the southern end of the grant near Charleston in 1899. We speculate that in 1899 there was an active headcut somewhere in the 25 km reach between the northern and southern boundaries of the Boquillas Land Grant. In 1909, J. B. Wright recorded a channel width of 130 m at Lewis Springs (fig. 12.1), which may suggest that the headcut progressed to the northern end of the San Rafael del Valle Land Grant between 1899 and 1909, possibly during the floods in the winter of 1904–1905.

1910s and 1920s. According to several accounts, neither the main stem nor tributaries became entrenched upstream of Charleston until the 1910s. Ranchers at Hereford told Haury et al. (1959) that between 1910 and 1914 the river channel was narrow and only 0.5–1.0 m deep. The channel from Fairbank to Hereford, a reach of more than 32 km, was probably entrenched in less than 18 years. Haynes (1987) states that Curry Draw on the Murray Ranch became entrenched along the ruts of a wagon road in 1916.

Channel widening and further degradation in the San Pedro River Valley occurred in September 1926, when floods produced peak discharges of 2780 m^3s^{-1} at Charleston. This is three times greater than the next highest peak in the 69-year gaged record at Charleston from 1916 to 1987. The 1926 flood is one of the better-documented floods in the early twentieth century. Numerous occurrences of channel erosion at bridges were reported from the international boundary to the Gila. The river overflowed its 6-m-deep channel at Benson. At St. David, the channel, which was 18 m wide in 1918 and 46 m wide in 1922, widened to 107 m. The second largest gaged flow occurred in August 1940, but by then the channel could accommodate larger flows.

Over the length of the river, the areas of extensive channel widening are near Redington and Benson, where arroyos cut to the greatest depths in the floods of 1890–1926. Degradation and channel widening persist in these areas. Elsewhere, tributaries have been aggrading in recent decades, as have reaches of the main stem, particularly below Mammoth (near the confluence with the Gila) and above Benson.

Factors Contributing to Entrenchment

HUMAN SETTLEMENT

Overgrazing, trampling of springs and marshes by cattle, eradication of beavers, draining of marshes through ditch diversions, and fuel harvesting in the 1870s and 1880s may have preconditioned the watershed to arroyo cutting in the 1890s. Bahre and Hutchinson (1985) estimate that about 80,000 cords of fuelwood, including mesquite from the floodplains and oaks and junipers from the uplands, were consumed in the Tombstone Mining District between

1879 and 1886. By 1890, upland and floodplain vegetation had been seriously reduced by grazing and fuelcutting. A number of new ditches, which concentrated drainage and used ciénegas as their source, had been dug in the valley (Bryan et al. 1934, Rodgers 1965). Railroad construction involved lengthy embankments along the San Pedro, which may have impeded sediment contributions from the adjacent *bajadas*. More significantly, flow was constricted at bridges (Cooke and Reeves 1976, Dobyns 1981).

EARTHQUAKE

Another factor that may have preconditioned the valley to widespread arroyo cutting was the 1887 earthquake. On May 3, 1887, an earthquake rocked southern Arizona, northern Sonora, and northwestern Chihuahua (DuBois and Smith 1980). Hydrologic effects were noted within a 160-km radius of Bavispe (Dubois and Smith 1980). The upper San Pedro River Valley was within the fissured zone, with several reports of liquefaction from Charleston to Tres Alamos. A fissure 32 km long was reported along the San Pedro River north of Benson and issued a considerable stream of water. Some springs went dry, others doubled in flow, and there was a rise of 1 m in the flow depth of the San Pedro, this during the driest month of the year. The earthquake leveled Charleston, while at St. David, it alerted settlers to the presence of artesian water (Fulton 1966, Fulton and Bahre 1967, Tiller 1982).

According to Tevis (1954), a similar earthquake affected the San Pedro River Valley in 1800–1810. References to unincised floodplains in the 1850s suggest that if this earlier earthquake occurred, it had no large-scale effects on subsequent channel histories in the San Pedro River Valley. However, it cannot yet be discounted that geohydrological phenomena associated with the 1887 earthquake set the stage for arroyo initiation. The earthquake conceivably could explain the remarkable synchroneity of arroyo cutting throughout southern Arizona and northern Sonora. One might expect channel adjustment to a 32-km fissure in the floodplain or to the changed configuration of groundwater surfaces. The immediate withdrawal from artesian aquifers probably produced changes in head that might have accelerated rates of compaction by reducing buoyant forces. The same effect, perhaps not as catastrophic, can stem from pressure losses in artesian aquifers during extremely dry periods. Regardless, investigation of the possible links between the 1887 earthquake and subsequent channel trenching is long overdue. A first step would be to examine evidence for fissures in the 1937 aerial photos of the San Pedro River Valley, provided that arroyo cutting did not eliminate such evidence.

WATER TABLE FLUCTUATION

There is fair agreement that a period of major channel cutting in southern Arizona took place in the middle Holocene (Haynes 1968, Waters 1985, Haynes 1987), but great discordance over the number and timing of cut and fill cycles during the late Holocene (Waters 1985). Waters (1985) argues that in the late Holocene, streams responded to geomorphic controls irrespective of regional climates. Haynes (1987) maintains that drought-induced fluctuations in regional water tables determined late Holocene cutting and filling. He also suggests that the historic arroyo is just the modern expression of frequent cutting and filling in the late Holocene, which would have happened eventually without human impact. Few would argue that simultaneous cutting and filling on ephemeral streams could lead to ambiguity in the alluvial record. However, there is also danger in assuming that zones of aggradation and degradation migrate systematically to flush sediment from the system, completely out of step with climatic trends (Patton and Schumm 1981). It would be equally difficult to discount the role of a falling water table in promoting arroyo cutting or that of a rising one in enhancing aggradation.

Floodplain Evolution after Arroyo Cutting in the Upper San Pedro: Physical Evidence

The channel and floodplain of the San Pedro River, through time, were mapped from Hereford to the northern boundary of the Boquillas Land Grant, an area that encompasses much of the San Pedro Riparian National Conservation Area (SPRNCA). The age of the various channel and floodplain deposits was estimated from analysis of aerial photography taken at five different times and scales (Soil Conservation Service, April 1937, 1:30,000; USGS, January 1955, 1:20,000; U.S. Air Force, October 1970, 1:55,000; Soil Conservation Service, October 1978, 1:25,000; U.S. Bureau of Land Management, September 11, 1986, 1:6,600). Ages were assigned by the first appearance of a particular deposit in the photographs. The area of the entrenched channel (here defined as the area between the walls of the post-entrenchment terraces) was mapped on sequential, stereoscopic small-scale aerial photography to evaluate rates of channel widening. The channel walls are readily identifiable in stereoscopic aerial photographs because the walls form a nearly vertical, continuous feature that separates two broad surfaces of different elevation.

PRE-ENTRENCHMENT ALLUVIUM

Late Holocene (4,000 YBP to present) alluvium, inset against the St. David Formation, can be divided into pre-entrenchment alluvium, which forms a terrace that occupies most of the inner valley, and post-entrenchment alluvium, which represents the active floodplain of the San Pedro River (fig. 12.6). Near Hereford, the pre-entrenchment alluvium forms a two-stepped terrace separated by 0.5 to 1.0 m of relief. Lenses of dark, carbonaceous sediments, or ciénega deposits, mark the former heights of the water table in the pre-entrenchment alluvium. The pre-entrenchment alluvium correlates with the

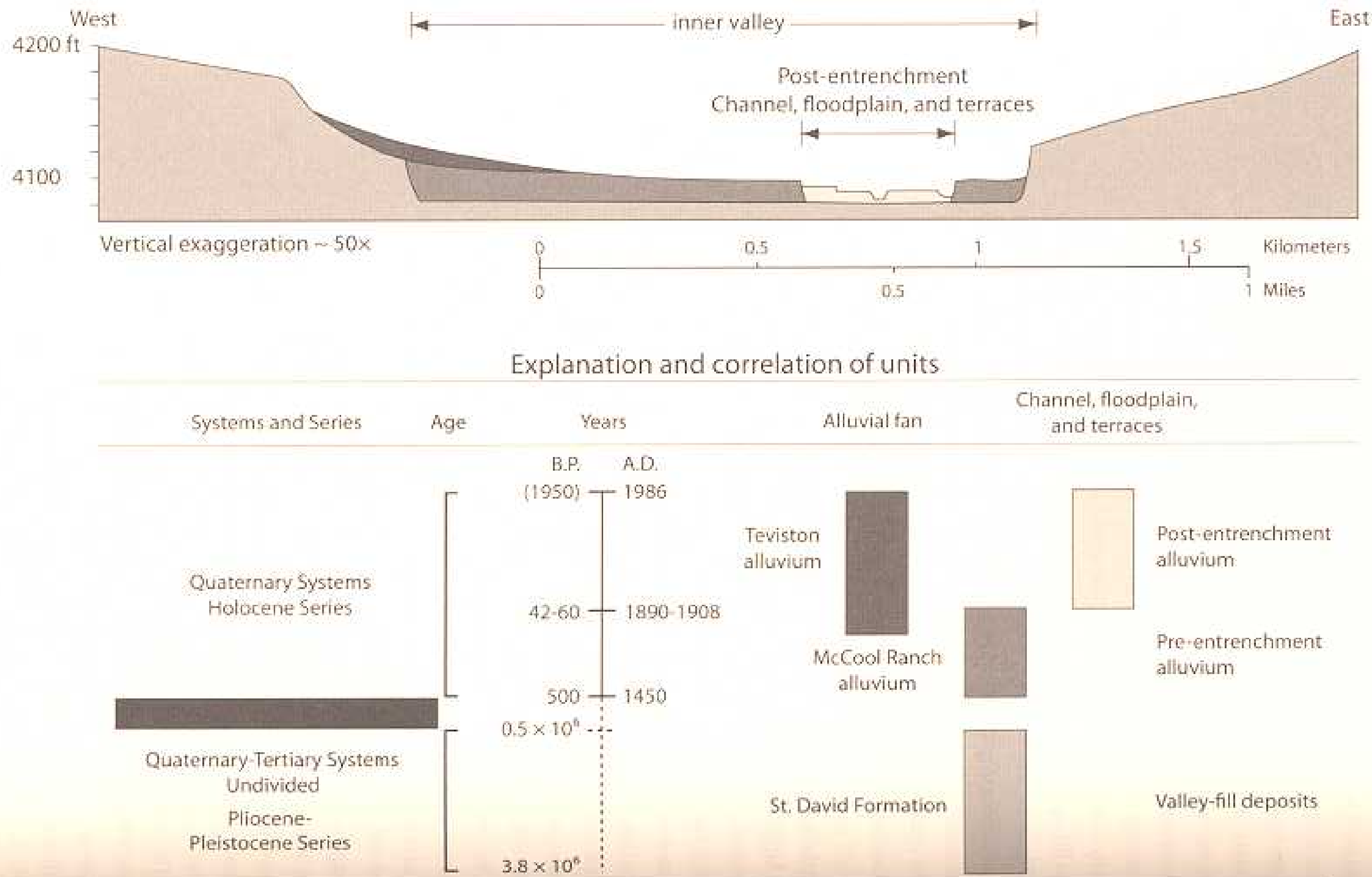

Fig. 12.6. Geologic cross section showing correlation of surficial deposits and geomorphology of the inner valley of the San Pedro River in the vicinity of Lewis Springs. The geologic relations, geomorphology, and deposits are typical of the upper San Pedro.

"Escapule Ranch formation" of Haynes (1987), which can be traced from Curry Draw into the inner valley near Lewis Springs. Near Hereford a sinuous abandoned channel (1 m deep and 10–20 m wide) on the lower terrace was probably the active channel of the San Pedro River before arroyo cutting.

POST-ENTRENCHMENT ALLUVIUM

From youngest to oldest, the post-entrenchment alluvium consists of the active channel, floodplain, and terrace of the San Pedro River, although alluvial fans have formed contemporaneously. The active channel is inset from 1 to 10 m below the pre-entrenchment terrace. Entrenchment in the SPNRCA is greatest below Lewis Springs where it ranges from 5 to 10 m deep. Upstream of Lewis Springs, the river is entrenched only 1 to 5 m below the pre-entrenchment terrace.

Deposition of the alluvial fans and sheetwash deposits began slightly before entrenchment of the San Pedro River. The deposits are cut by the entrenched channel of the San Pedro River, suggesting that deposition began before channel entrenchment. At Walnut Gulch, historic artifacts dating from the turn of the century occur at the basal contact, and artifacts are present locally within the Teviston alluvium. Deposits of similar age are also present in Curry Draw (Haynes 1987). In short, the Teviston alluvium and its correlatives in the inner valley resulted from tributary stream entrenchment and increased hillslope erosion that began before the entrenchment of the main channel.

RATE OF CHANNEL ENLARGEMENT

The spatial distribution of the post-entrenchment alluvium (fig. 12.7) indicates clearly that the area of the channel and floodplain have enlarged since initial entrenchment around the turn of the century. In an alluvial system with a strong component of lateral accretion such as the San Pedro River, progressively younger floodplains form as the channel migrates (see chap. 13). Channel migration simultaneously erodes the pre-entrenchment alluvium, while providing space for subsequent floodplain deposition. Two important questions emerge regarding this process: what is the rate of widening of the high-flow channel, and is the process complete? The process of channel widening is poorly understood. Thus, it is not known whether the widening process is self-limiting or controlled by external factors such as climate or land use.

Figure 12.8 illustrates expansion of the channel from pre-entrenchment to 1986 in a 2-km reach of the river beginning 3.2 km downstream of the Hereford Bridge. Channel area increased rapidly from entrenchment to 1955, but the rate of enlargement slackened since then as shown in figure 12.9, which illustrates the cumulative area of the entrenched channel as a function

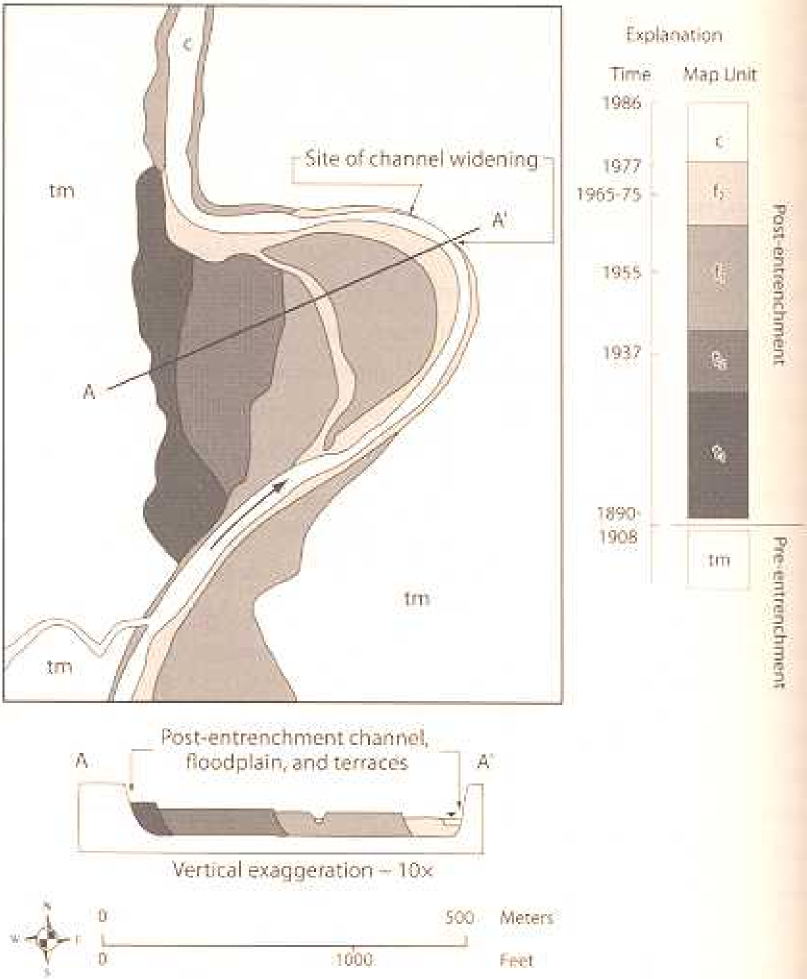

Fig. 12.7. Geologic map and cross-section of the post-entrenchment alluvium exposed on a point bar north of Hereford.

of time. The increase of channel area is approximately an exponential function of time and follows a "rate law," which describes the time-dependent adjustment of many disturbed physical systems (Graf 1988a). Considering the entire area and assuming that entrenchment occurred by 1900, the estimated rate of enlargement from 1900 to 1955 was 0.109 $km^2\ yr^{-1}$, and from 1956 to 1986 the rate was only 0.024 $km^2\ yr^{-1}$. Thus, the rate of channel enlargement has declined in recent years. This probably signifies stabilization of the channel and the end of significant widening.

FLOODS AND CHANNEL WIDENING

The morphology of the channel is controlled largely by the frequency of channel-forming floods (the control variable). The annual flood series at Charleston (see chap. 16) shows a clear pattern of relatively frequent large floods (defined as events in the upper quartile of all flows) during the first part of the twentieth century. Seventeen floods equal to or greater than the

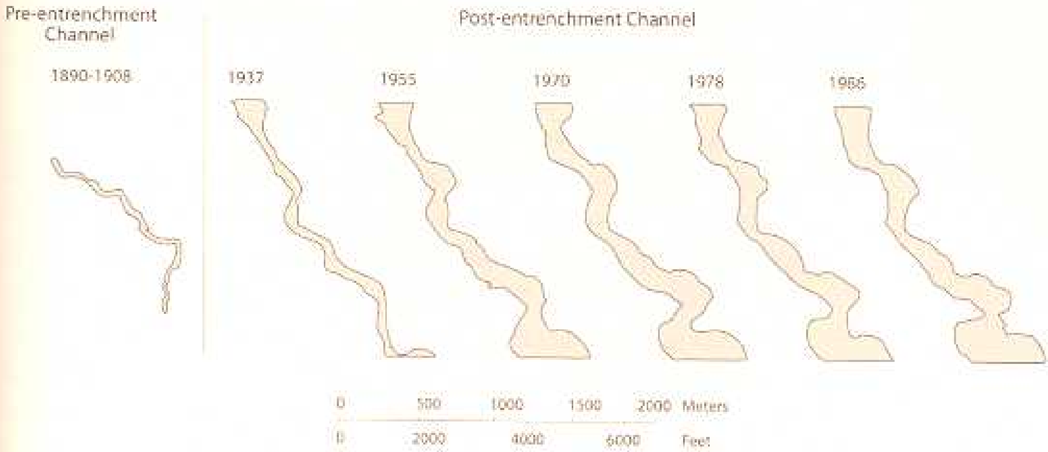

Fig. 12.8. Maps showing the pre-entrenchment channel and expansion of the post-entrenchment channel as compiled from sequential aerial photography since 1937, and from cadastral survey notes and plats at the turn of the century.

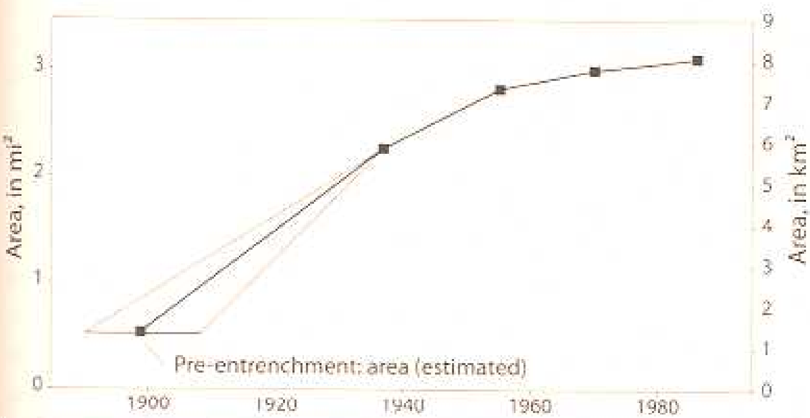

Fig. 12.9. Time series showing cumulative area of the entrenched channel. Channel expansion slowed appreciably by at least 1955.

75th percentile occurred between 1916 and 1955, an average rate of about one such flood every 2.4 years. This period includes the flood of record in 1926. Most of these large floods occur during the summer runoff season.

In contrast, only four floods larger than the upper quartile occurred from 1956 to 1987, an average rate of one such flood about every eight years. Only one of these four floods, the flood of October 9, 1977, was comparable in size to the largest floods of the earlier period. Reduced frequency of large floods on the San Pedro after 1955 runs counter to trends noted in adjacent watersheds, notably the Santa Cruz River (Webb and Betancourt 1992). Less-frequent large floods after 1955 probably stem in part from increased channel storage due to greater channel areas and sinuosities, which seem to have stabilized during the last five decades, as well as perhaps to increased revegetation of the watershed.

CHANNEL WIDENING AND EQUILIBRIUM

Widening of the San Pedro River channel could not continue indefinitely. Once the channel cross section is capable of transporting the water and sediment load of the post-entrenchment discharge regimen, it should stabilize and cease to widen. The negligible rate of channel enlargement since about 1955 indicates that the widening process has ended or slowed greatly (Hereford 1993). In terms of geomorphic equilibrium, the river system has adjusted to the entrenchment disturbance and has probably attained a new equilibrium with a quasi-stable channel configuration.

This transition from pre- to post-entrenchment equilibrium is analyzed diagrammetrically in figure 12.10. The effect of an increase in flooding is to increase the channel area after a reaction or lag time. Thus, the pre-entrenchment equilibrium was disturbed by a change of flood frequency probably beginning in the early 1880s, when destructive floods were first described in the upper San Pedro River Valley. An additional disturbance with unknown effect was the 1887 earthquake. The reaction time to these disturbances began about 1880 and lasted until entrenchment began between 1890 and 1908. The period of disequilibrium and rapid increase of channel area is the relaxation time, or the time it takes to attain a new quasi-stable equilibrium. The relaxation time was about 55 years, assuming that entrenchment began by 1900 and that the channel was essentially stabilized by 1955.

The relaxation time for channel stabilization was probably controlled by factors influencing the frequency of channel-forming floods. This variable is affected by feedback mechanisms, climate, and land use. The feedback is between vegetation and the expanding channel. As the channel expands, more room is provided for riparian vegetation, which has the effect of reducing peak-flood discharge (Burkham 1972). In addition, larger channel area increases transmission losses, compounding the influence of vegetation. This feedback process shortens the time to stabilization, because vegetation increases boundary shear stress, eventually minimizing further bank erosion. Climate directly controls flood frequency through rainfall variations and indirectly controls flood frequency through its effect on vegetation both within and out of the channel.

Changes in grazing practices and development of tributary water-retention structures probably shortened the time required for channel stabilization. Generally, these changes served to reduce runoff and peak flows. The number of cattle grazing in the upper basin decreased since entrenchment from a historic high of 36,000 cattle in 1890 to 7,500 by 1964, well within grazing capacity (Wagoner 1962, Rodgers 1965). In addition, numerous small water-

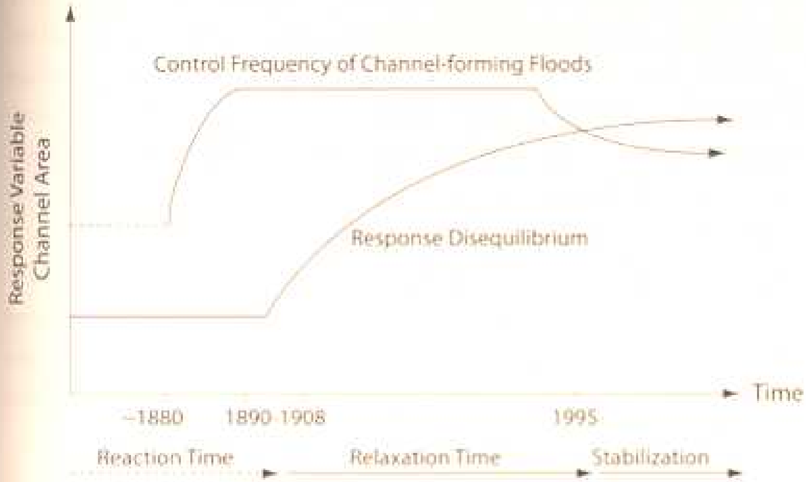

Fig. 12.10. Conceptualization of channel equilibrium in terms of control and response variables, based on Graf (1988a) and Knighton (1984).

retention structures have been built in small tributaries of the river. Although their overall effect is unknown, they were designed to reduce runoff.

Summary

The historical record suggests that in the mid-nineteenth century the San Pedro was a continuously perennial stream from its source near Cananea to just beyond the Narrows. Flow was interrupted (spatially intermittent) in the lower reaches, with the dry discontinuities outdistancing limited surface flow from groundwater outcroppings. Apparent discontinuous arroyos up to 6 m deep at St. David, Tres Alamos, and below the Narrows transitioned a short distance downstream into cienegas dammed by beaver. Mesquite thickets occupied dry and incised reaches, while mostly treeless conditions characterized the unincised, marshy floodplains particularly in the upper basin. Treeless conditions could imply permanently saturated soils, where reducing conditions would limit tree growth and favor graminoids (Hendrickson and Minckley 1984).

The exact timing of arroyo initiation is still uncertain. Bryan's (1925) statement that arroyos started at the mouth in 1883 and progressed headward 200 km to the Boquillas Land Grant by 1892 cannot be substantiated. Though in other reaches arroyos might have developed in the 1880s, 1890 does appear to mark the beginning of extensive degradation in the lower San Pedro. Extensive erosion in the upper San Pedro apparently did not occur until the early 1900s. Newspaper accounts, survey records, and other written records describe extensive channel erosion in association with the series of large floods that occurred near the turn of the nineteenth century.

Today on the San Pedro River, post-entrenchment alluvium deposits occupy the lowest topographic level of the inner valley, which is 1 to 10 m below the pre-entrenchment terrace. A widespread, locally dense riparian forest has developed simultaneously with deposition of the post-entrenchment alluvium. The nature of post-entrenchment deposits imply an entrenched, meandering, low-sinuosity alluvial system. The post-entrenchment alluvial deposits are successively younger across the floodplain surface, indicating that the channel has widened since initial entrenchment. Channel area of the upper San Pedro increased rapidly from initial entrenchment until at least 1955; since 1955, channel area has increased only slightly. Peak-flood discharge of the San Pedro River declined substantially after 1955. Our conclusions are that the channel in the upper basin is largely stabilized and that equilibrium or near-equilibrium conditions exist.