ECOLOGY AND CONSERVATION OF THE SAN PEDRO RIVER

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Contents

SECTION 1 **Vegetation of the Riparian Ecosystem**

SECTION 2 Animals of the Riparian Ecosystem

SECTION 3 The Geomorphic Template

SECTION 4 The Hydrologic Template

SECTION 5 **Conservation and Management**

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The Land and the People

ELEVEN

The San Pedro basin has a long and rich human history. The goal of this chapter is to provide a general overview of human activities in the San Pedro River and its watershed. This history provides important context for understanding the changes, described in other chapters, that have occurred in the river's hydrology, geomorphology, and biotic communities.

Chronology of Settlement

EARLY HISTORY OF THE SAN PEDRO RIVER VALLEY

The first evidence of human occupation of the area comes from remains of hunting groups that lived in temporary camps starting about 12,000 YBP (years before present). Archaeological evidence points to human hunting of mammoths that lived there, along with other megafauna such as the saber-toothed tiger and giant ground sloth (Wright and Martin 1967, Haynes and Huckell 2007). After a gap in the archaeological record, evidence of human settlement in the area again appears, showing that people made a gradual transition from a hunting and gathering lifestyle to an agricultural one augmented by hunting and gathering at least 3,000 years ago. The northern parts of the river were influenced by Hopis and Zunis starting about 1100 AD, a period of drought throughout the Southwest when population shifts occurred

(Anyon 1999, Ferguson et al. 2004). These people lived alongside the Hohokam and Tohono O'Odham tribes already in the region. The Sobaipuri were well established by the time the first Spaniards arrived, using irrigated agriculture along the San Pedro River and tributaries such as the Babocomari.

SPANIARDS AND APACHES

The sixteenth and seventeenth centuries were times of major change. Spaniards arrived from the south about the same time Apaches arrived from the north at a time of upheaval in the region. The indigenous civilization throughout the area had declined by the mid-fifteenth century for reasons still debated, including drought, salination of irrigation systems, and overuse of resources. Spaniards introduced cattle, horses, goats, sheep, donkeys, wheeled vehicles, iron tools, and new crops. They constructed a major wagon road, the Camino Real, which traversed the upper basin going from the Rio Grande to the Colorado River and California. Spanish military encampments and missions were short-lived, except in the Mexican portion of the watershed (Officer 1987).

Apaches primarily occupied upland areas, with periodic travels into and through the lowlands mainly of the upper basin. Most of the Sobaipuri Indians (a Piman tribe), unable to compete with the Apaches, moved to the Santa Cruz basin in the 1760s at Spanish instigation. Apaches challenged Spanish and Mexican attempts to farm and ranch the region and did limited farming in addition to hunting and gathering native plants. At the time of American settlement, Apaches strongly resisted incursions into what they considered their territory. After the American Civil War when the American army mobilized throughout the American West, it took less than five years to end Western Apache domination of the region and to send the survivors to reservations in Arizona and elsewhere (Seymour 2001).

THE AMERICAN PERIOD

The first Americans in the area were beaver trappers, followed by "'49ers" moving though the area on their way to the California gold fields. War between the United States and Mexico ended in 1847 when the San Pedro was still part of Mexico. Just six years later, the United States purchased land from Mexico in the Gadsden Purchase, moving the border south to its present location. Significant products of the subsequent border surveys included biological inventories of the areas crossed (e.g., Emory 1858–1859). Following the American Civil War in the 1860s, the U.S. Army sent hundreds of troops to defeat the Apaches and make American mining and settlement possible. By the 1870s, prospectors had established claims in many parts of the Sa Pedro region. Arrival of the railroad in the mid-1870s increased the pace o development. In the United States, the Homestead Act (1862) and the Dese

Land Act (1877) opened lands for ranching and farming. As the land was surveyed, it became available for purchase at very little cost (Sheridan 1995).

By 1912, when Arizona became a state, gold and silver mining had declined, but copper mining was on the rise. Ranching, copper mining, and farming were the predominant land uses in both the Sonoran and Arizona parts of the valley. After World War II, urbanization began to predominate in the Fort Huachuca area but had little influence in the Sonoran and lower basin parts of the region.

History of Land Uses

BEAVER TRAPPING

Famed trapper James Ohio Pattie passed through the San Pedro area in the 1820s and named this watercourse "Beaver River," reportedly procuring 200 pelts near the Gila River confluence. In the late 1800s, European travelers, prior to floodplain entrenchment, commented on numerous beaver dams and associated ponds (Hastings 1959, Rodgers 1965:16, Bahre 1991). Beavers were nearly extirpated along the San Pedro River by 1900 as they were killed in an effort to drain local wetlands caused or enhanced by their dams, or because they interfered with irrigation systems. They persist today near the Gila River confluence and in the San Pedro Riparian National Conservation Area (SPRNCA), where they were introduced in the 1990s (see chap. 6).

RANCHING

Livestock grazing has a long history in the San Pedro River Valley starting in the 1600s (Dobyns 1981, Bahre 1991). In the early 1800s, the Mexican government established land grants for ranching in the upper basin. These ranches were eventually abandoned due to Apache deprivations, but large feral herds remained behind. In fact, the only violent encounter of the Mormon Battalion during their 1848 sojourn through Arizona was with a band of rampaging feral bulls in the upper San Pedro River Valley!

European ranchers brought in large herds of cattle to the upper and lower basins in the late 1800s (Hastings 1959, Hastings and Turner 1965, Bahre 1991) (fig. 11.1). During decades of heavy rainfall, thousands of cattle were brought to the area, and numbers peaked at different times during the last quarter of the nineteenth century and early twentieth century. When drought years occurred, and forage became sparse, most of the cattle died from starvation, after having eaten everything edible. This in turn led to a search in the early 1900s and again in the 1930s for forage grasses to revegetate the area, with emphasis on a few species imported from Africa (Tellman 2002).

Until recently, most river and tributary banks were grazed and also used for large cattle drives (Krueper et al. 2003). The overgrazing of the past has been significantly reduced, especially since passage of the Taylor Grazing

Fig 11.1. (top; 11.1a): Cattle grazing in the San Pedro on the Boquillas Ranch. No date, twentieth century. Courtesy of Bisbee Mining and Historical Museum Accession 80.141.34. (bottom; 11.1b): Cattle drive north from Mexico in the vicinity of Hereford. No date, 1900–1910. Courtesy of the Arizona Historical Society, Tucson, Buehman Collection 200360.

Act (1934) and development of permit systems for federal and state lands (Rowley 1985). Almost all ranching today in the area is conducted on ranches made up of an assemblage of public land leases and private land. Along the river itself, grazing is excluded from the SPRNCA, The Nature Conservancy (TNC) preserves, and other preserves. Within the watershed, grazing is excluded from Fort Huachuca and urban lands.

AGRICULTURE

Agriculture was another significant source of change in the San Pedro River basin. Irrigated agriculture began in the area more than 2,000 years ago. These early farmers tapped surface water during the summer rainy period, using brush diversion dams that were frequently washed out during floods, but easily replaced, and also utilized terracing to capture surface flow for crops. Spaniards did little farming in the area, except near presidios, especially along the Rio Nutrias, a major San Pedro headwaters stream. Apaches had small farms, harvesting summer runoff.

Virtually all the good locations for farming—broad fertile floodplain with good access to water—were utilized at some time. Irrigation has been essential throughout the region, and has long been the primary water use in the Southwest. When major floods widened and deepened the river channel, it became more difficult to construct dams and diversion ditches through which the water could flow by gravity to the fields.

In contrast to much of the West, modern-day farming along the San Pedro has been conducted by small family farmers, rather than large corporations. The most prominent crops have been forage crops and pasturage. In the early days, Fort Huachuca's many horses required large amounts of hay, so the army contracted with people who gathered wild hay or grew hay for market (Fort Huachuca 1976). Fruits and vegetables were important crops in the nineteenth century, when mining was at its height and importation difficult. St. David, in the upper basin, has been the center of a family farming area since the 1870s. Orchard crops, a wide variety of vegetables, and forage have been, and are, grown. The residents of St. David, and later Pomerene to the north, built diversion dams to capture San Pedro water for agricultural use. Farther downstream, from Redington to the Gila confluence, small family farms similarly have prevailed along the river, again mostly growing forage crops and pasture (Muffey 1938, Larson 1999).

Many of these agricultural fields have been abandoned and lie fallow or have been sold for other uses. In the early twenty-first century, TNC began to acquire farms along the river in order to retire water rights and is making efforts to establish perennial native grasslands on the fields (see chap. 19). Within and adjoining the SPRNCA, more than 2,000 acres (810 ha) of agricultural land has been retired (Fredlake et al. 1993).

MINING

Gold, silver, and other ores. Prospectors found silver ore in the Tombstone area in the late 1870s, and soon hundreds of prospectors flocked to the area, and Tombstone quickly became the largest town in Arizona. Since little water was available at Tombstone, ore processing occurred along the San Pedro River in towns such as Millville and Charleston. As mining proceeded deeper and deeper, however, water was encountered and soon became a serious problem. Huge pumps operated 24 hours a day, moving water into Walnut Gulch, a San Pedro tributary. The ore-processing facilities were moved away from the river partly to utilize this excess water. In 1910, however, the pumps failed and most mining ceased. This deep water source is under consideration today as a way to augment water supplies for the San Pedro (Cook 1987, Shillingberg 1999).

The first gold mining claim in the lower basin was at Tiger in 1881. During World War I, molybdenum and vanadium were extracted. The mine reopened in 1936 to produce lead and zinc, and during World War II it produced vanadium. Tungsten mines and processing facilities operated in the Huachucas and Whetstones in the first half of the twentieth century (Dale and Stewart 1960).

Abandoned mines are a poorly documented source of water pollution in the area (see chap. 17). Use of toxic material such as cyanide and arsenic in processing is well documented, but the long-term impacts on water quality are less well known. Some abandoned mines have become important roosting and nest places for bats (Snow and Castner 1996).

Copper mines. The major copper mining areas were at Cananea, Bisbee, San Manuel, and Winkelman, part of a large copper belt that stretches from Sonora to central Arizona. Large-scale copper mining in Cananea, Sonora, began in the 1880s, and by 1900, the mines and processing facilities, smelter, and the town itself were in full operation. Water came from nearby springs and both surface water and groundwater in both the San Pedro and Rio Sonora watersheds. By 1980 the Cananea District had the largest copper pits in North America. Rather than spend money to renovate an old polluting smelter, the owner, Grupo Mexico, closed it in 1999. By 2000 most mining had ceased. Most of the water supply and water impacts from mining occurred on the Rio Sonora side of the watershed, although some were in the San Pedro watershed.

Prospectors first staked claims in the Bisbee area in 1877, and open-pit mining began in 1917. Entire hills were removed to extract ore, extensively changing the landscape (Newkirk 1966, Epler and Dillard 1981). Mining ceased when Phelps Dodge closed the mine in 1974, and the pit and underground mine are now tourist attractions. Because water was scarce, the old smelter was replaced by a large smelter in nearby Douglas in the Río Yaqui watershed, where water was somewhat more plentiful. Phelps Dodge closed the smelter in 1987 because of the cost of meeting new air quality regulations.

Farther downstream, Magma Copper Company in 1950 purchased lands in the Tiger/Mammoth/San Manuel area and tapped into artesian wells near the San Pedro River from which they piped water 8 km to the town and underground mine. Since the ore was low grade, the resulting tailings ponds grew to more than 11.5 km^2 (Knoerr 1956, Canty 1991). The smelter emitted about 75,000 tons of sulfur annually until replaced in the 1980s. BMP, the most recent owner, closed the mine in 1999, except for the in situ leaching section. The deep mine shafts were left to flood.

Open-pit copper mines and processing facilities are at Hayden and Winkelman near the Gila River and San Pedro confluence. In 1883 the Ray Copper Company installed its first mine and smelter in the lower basin. Over the years this mine continued under different owners and was a major copper producer and employer for nearly a century. The current owner, Grupo Mexico, has land and water rights in the San Pedro and Gila Rivers that affect TNC's San Pedro Preserve (see chap. 23).

FUELWOOD CUTTING

Associated with mining was tree harvest in the watershed and riparian zones to supply mines with fuelwood and timber and the populace with firewood (Dobyns 1981). Wood roads were abundant and fanned out from Tombstone "like the veins of a leaf" (Bahre and Hutchinson 1985). Direct disturbance of the watershed through acquisition and transport of wood to fuel the mines increased erosion and sediment movement into the stream channels (Bahre and Hutchinson 1985). The demand for wood was so great that entire hillsides were denuded of all useable timber, although many trees including oak and mesquite resprouted after harvest. In the Cananea and Bisbee areas, deforestation led to especially severe erosion and flooding problems. Hundreds of check dams were built in the 1920s and 1930s in the hills surrounding Bisbee to help control flooding. Fort Huachuca, too, had an active check dam program (Newkirk 1966, Merrill 1981, Johnson 1988).

Hundreds of people were employed in small-scale charcoal-making operations during the last quarter of the nineteenth century. Large smelting operations contracted with entrepreneurs to obtain much of their supply. Since it took about one cord of wood to produce 35–40 bushels of charcoal, areas around the burning operations were quickly depleted. The charcoal burner would then move elsewhere or bring wood from farther and farther away (Ramenofsky 1984).

From 1860 to 1900, commercial lumbering occurred in the Huachucas, where sawmills processed thousands of trees (mostly Ponderosa pine) annually. The arrival of the railroad led to importation of lumber from elsewhere. Small-scale operations continued, but the great period of lumbering was over by 1900, and the forests have re-grown.

FIRE MANAGEMENT

Fires in the San Pedro River watershed occur in response to lightning strikes, typically in association with early monsoonal thunderstorms. Tree-ring scar studies in five mountain ranges in the San Pedro watershed show that before 1900 small fires occurred at least once per decade (Swetnam and Betancourt 1990, Wohl and Pearthree 1991, Danzer et al. 1996). These small fires tended to reduce fuel load so that large fires were unlikely. Following active fire suppression on the U.S. side of the border, large Arizona wildfires became infrequent but more intense when they did occur (Swetnam et al. 2001). The U.S. Forest Service installed its first fire lookout towers in the Huachucas before 1920 and adopted policies of suppressing fires as quickly as possible. New firefighting techniques and equipment made firefighting relatively efficient. Without frequent fires, fuel loads built up, culminating in massive crown fires in the Huachucas and the Catalinas at the turn of the twenty-first century (Biggs et al. 1999, Swetnam 1999, Swetnam et al. 2001, Allen 2002, Parker 2002).

Historic grassland fires are more difficult to document than forest fires, but they were frequent in early historic times. Again, fire suppression became the dominant policy, especially where the fires threatened human structures. But many ranchers have long advocated natural and controlled burns. As ranches have been divided into smaller and smaller units, allowing fires to burn is more difficult because there are more human structures to protect (Biggs et al. 1999).

WILDLIFE MANAGEMENT AND CONTROL

Increased population, ranching, and farming led to demands for control of wildlife considered detrimental. By 1900 Cochise County was offering bounties for wildlife such as mountain lions, coyotes, and bears as well as "nuisance animals" such as badgers. Fifteen years later, the United States government had developed a program for control of certain predators, rodents, and other unwanted wildlife, including species such as skunks that may spread rabies. The program succeeded in extirpating wolves, grizzly bears, jaguars, and prairie dogs and reducing populations of some felines, but coyote and rodent numbers continually recovered in spite of repeated efforts. Personal hunting was common, especially for deer, bear, and mountain lions. Establishment of a state game and fish agency and hunting regulations starting in the 1920s has limited hunting of species such as bear, turkey, and deer to what is considered a sustainable level (Tellman 2006).

ROADS AND RAILROADS

The U.S. government sponsored road surveys throughout the West to facilitate communication and travel, including the Army of the West, led by Col. Stephen Watts Kearny, that traversed the San Pedro River Valley in 1846 (Jackson 1952). The arrival of animal-drawn wagons with steel-rimmed wheels in 1846 played a role in watershed erosion by cutting soil surface ruts, which further incised during surface water runoffs (Dobyns 1981). Roads were built in, along, and across channels that soon became rutted, capturing and concentrating runoff. In addition to heavily traveled roads that paralleled the San Pedro River, a network of roads that connected mines and mills, isolated communities, ranches, and watering points was constructed. Railroads were established during the last quarter of the nineteenth century and facilitated transport to and from the mines (Myrick 1975). During major floods, road and railway bridges often failed and were replaced by much-wider ones. An unintended consequence of bridges has been adoption of the expansion cracks by bats.

URBANIZATION

The population of the Cochise County portion of the upper San Pedro basin has changed considerably in the past 150 years. The area experienced two major periods of rapid urbanization, one during the nineteenth-century peak of gold and silver mining (fig. 11.2) and another during the twentieth century as subdivision development in the lower basin increased with Fort Huachuca expansion and the area became a desirable retirement and commercial region (fig. 11.3a). Population has steadily increased in the Sierra Vista region since 1955 in spite of mine closings and a decline in Fort Huachuca population since the heyday of World War II. Population of the lower basin has consistently been much less than the upper basin for the last 150 years, and its population today is growing at a much slower rate (fig. 11.3b).

The towns. In the late nineteenth and early twentieth century, towns such as Fairbank and Tiger thrived, but they later became ghost towns as mining declined. Cananea, Bisbee, Tombstone, San Manuel, Hayden, and Winkelman all began as mining towns, usually designed as company towns. Cananea, with a population of about 15,000, was the largest town in the watershed for more than 50 years until the growth of Sierra Vista. Bisbee, San Manuel, and Tombstone succeeded in making the transition from mining towns to towns based on tourism, retirement, or commuting. Of the twin border towns of Naco, Arizona, and Naco, Sonora, the latter grew larger than the former with the growth of maquiladora (twin industrial plant) construction starting in the 1980s.

For more than 50 years, small settlements were located near the entrance to Fort Huachuca. During the Fort population peak of World War II, a small community of mobile homes, bars, and whorehouses grew up there. During the Korean War, the army again expanded and Sierra Vista was incorporated. This area is experiencing the highest rate of population growth in the watershed. Benson began as a Southern Pacific Railroad station in the 1880s and was an important transportation hub that for a while served three railroads. Population rates remained steady until establishment of nearby Kartchner

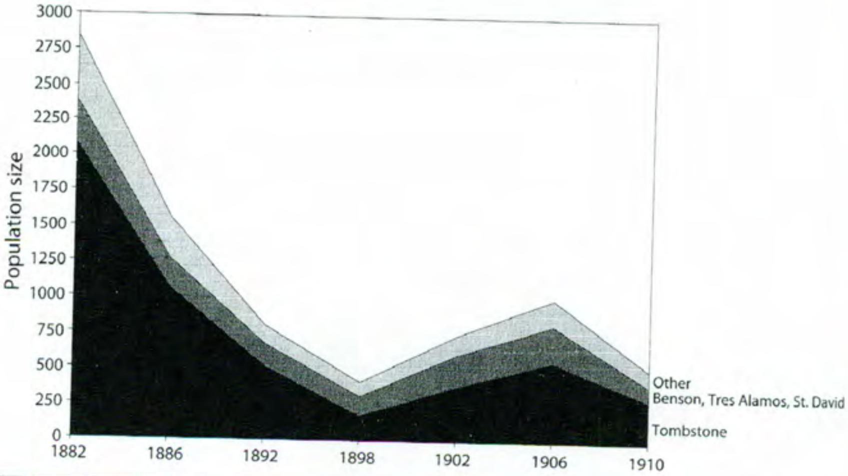

Fig. 11.2. Estimated adult male voting population of the U.S. portion of the San Pedro Valley in the late nineteenth and early twentieth centuries. Estimates derived from Great Registers of Voters. "Other" category includes Fort Huachuca, Huachuca Mountains, and miscellaneous mining towns and other towns.

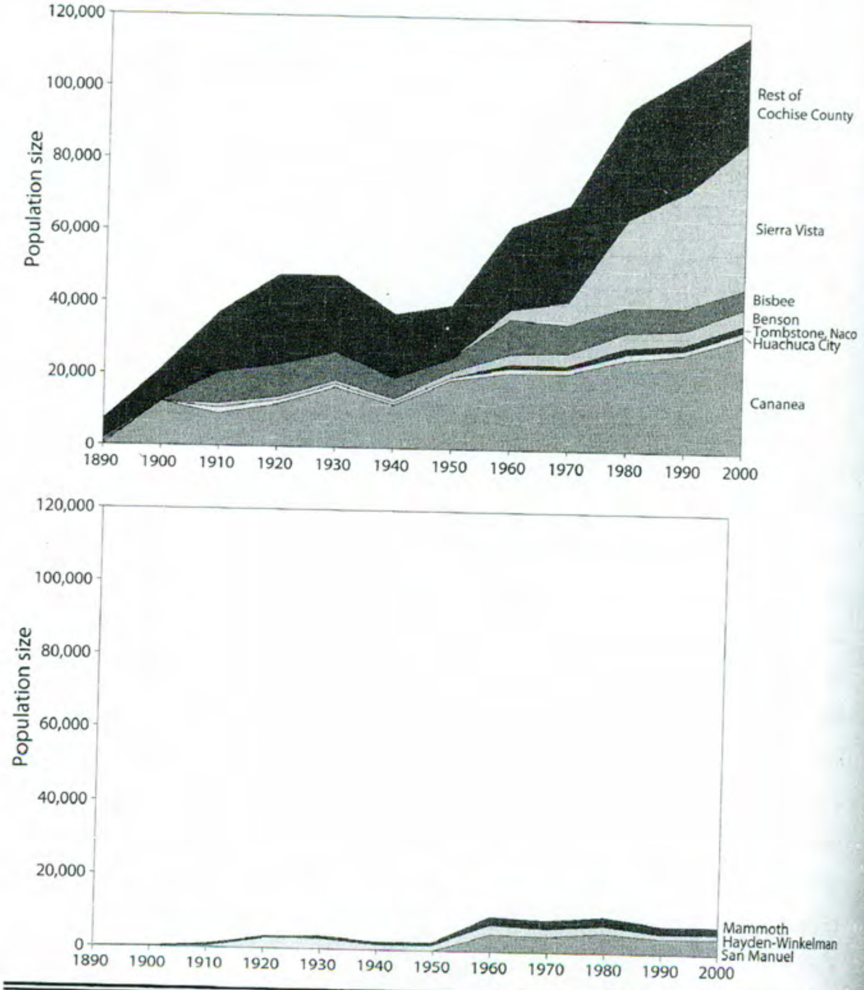

Fig. 11.3. Population of towns in the upper (top; 11.3a) and lower (bottom; 11.3b) San Pedro watershed in the twentieth century. Figures derived from U.S. Census.

Caverns State Park when the area was promoted for tourism and development. The nearby small town of Pomerene is an unincorporated farming community established in the early 1900s (Larson 1999); the Benson–Pomerene area currently is undergoing a population increase.

The region has several unincorporated communities, including Hereford and St. David, a family-oriented farming town founded in the 1880s as a Mormon settlement. Cascabel, the only community between Benson–Pomerene and San Manuel, is on an unpaved road that keeps this ranching area relatively isolated (Muffey 1938). Plans to build a railroad along the river in the 1870s were abandoned, as were subsequent plans for paved roads. In 2006, planners once again proposed a paved road from Benson to San Manuel, leading to concerns over the impacts the road and accompanying population growth would have on the river.

WATER USE AND MANAGEMENT

Conflicts over water rights in the San Pedro basin are documented as early as the 1880s when the first lawsuits were brought to court. The first big dam on the San Pedro was proposed in the 1880s, and a short-lived dam was actually built for mine processing. Demands for a dam increased in the 1920s and 1930s to increase water for agriculture, but the costs were too high (Griggs Engineering 1927, G. Smith 1942). In the 1950s, the U.S. Bureau of Reclamation investigated the feasibility of a dam at Charleston as part of the Central Arizona Project (CAP), a major water project that transports Colorado River water to central and southern Arizona (Johnson 1977) (fig. 11.4). The CAP was authorized in 1968, but the dam was never built.

Another plan for increasing water supply for human use involved phreatophyte removal. From the 1950s to the 1970s, saltcedar as well as native phreatophytes were cleared from several Arizona rivers, with the expectation of increased flow to the rivers and thus downstream for human use. The San Pedro River was studied, but large-scale projects were not implemented (Manes 1968).

Water supplies for towns. All of the mining towns have been dependent on groundwater both for mining and for domestic use. Cananea was unusual among all these towns in not having a central water supply system for all residents. Bisbee did not have adequate potable water supplies, so it developed a central water system dependent on wells in the Naco area. Tombstone's water comes from wells and a pipeline built in the 1880s that brings water from springs in the Huachuca Mountains 42 km across the San Pedro River Valley (Cook 1987).

In the greater Sierra Vista area, private water companies provide water from wells, and many residents have their own wells. The multiplicity of

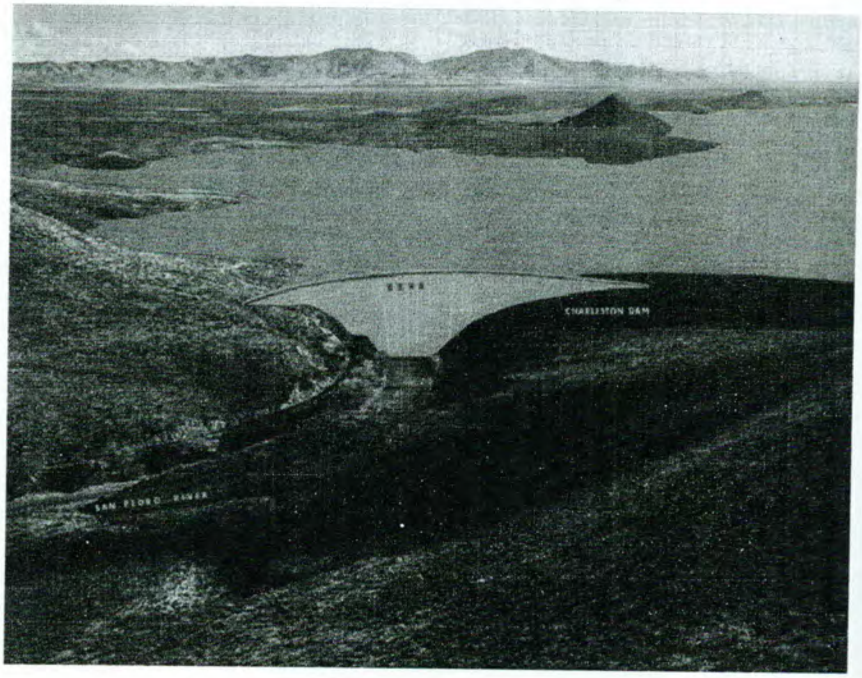

Fig. 11.4. 1960s artist's rendering of what Charleston Dam and the reservoir would look like if constructed. The "photo" looks south into much of what is now SPRNCA. Photo source: U.S. Bureau of Reclamation, available at University of Arizona Special Collections Library (AZ15).

water providers offers challenges to developing water conservation programs. Benson has had a municipal water company since the 1920s, also using groundwater. Private wells are the norm along the rest of the river, except for San Manuel, which has a municipal water utility.

WASTEWATER TREATMENT AND REUSE

All of the towns in the watershed, with the exception of Cananea, have a community wastewater treatment system. In 1980 Tombstone became the most recent Cochise County town to build a modern wastewater treatment plant. Many residents in sparsely populated areas have their own septic tanks. Inadequate sewage treatment has created water quality problems in Cananea, Naco, and Benson.

Fort Huachuca began to use wastewater on its golf course during World War II and has continued to promote reuse and recharge. Sierra Vista operates a regional wastewater treatment plant, with the water discharged into the regional aquifer. This concentration of wastewater offers potential for coordinated reuse and recharge projects that are underway with a goal of prolonging the supply to protect the river while allowing for population growth (ASL 1995). The Naco wastewater plant has a reuse component, but in the rest of the area, all treated wastewater is discharged to washes or evaporation ponds.

Present Land Ownership and Management

The current border between the United States and Mexico was established by the Gadsden Purchase in 1853. For the first 100 years, the border was relatively open, with people and their cattle, as well as wildlife moving relatively freely between the two nations. Over the past 50 years, the United States has attempted to secure the border and has increasingly attempted to restrict entry, with varied success.

SONORA

Land ownership in the Sonoran part of the watershed is mostly divided between ejidos (communally owned ranches) and private lands. Most of this area formerly was part of a land grant that was subsequently bought by American mining entrepreneur and rancher, Col. William Greene. The ejidos developed from the Greene lands (Longwell 1974).

The Sierra de los Ajos is a largely public preserve in Sonora, Mexico, a portion of which is in the San Pedro watershed. Non-profit groups own land for preservation purposes along Rio Nutrias (see chap. 23).

UNITED STATES

Federal land. Land ownership and management in the San Pedro basin is a complex mixture of federal, state, and private land. The national forests (U.S. Department of Agriculture) operate under a multiple-use mandate to protect the watershed and forest resources and provide for appropriate human uses, including grazing, timber cutting, mining, and recreation. The Coronado National Forest is spread over 12 mountain ranges in southeastern Arizona, including portions of the San Pedro watershed in the Catalina, Huachuca, Rincon, Muleshoe, Galiuro, Winchester, and Dragoon Mountains. Most Bureau of Land Management (BLM—U.S. Department of Interior) property is mandated as multiple-use land. Grazing is the main land use of the BLM land in the watershed (J. Williams et al. 2003)

There are many riparian preserves along the San Pedro and its tributaries, ranging from public to private. Congress designated a portion of land along the river as the San Pedro Riparian Conservation Area (SPRNCA) in 1988, giving it protected status (see chap. 20). The area had been a Spanish land grant and subsequently an American ranch and was about to be rezoned for a large planned development. BLM also manages a riparian preserve in Aravaipa Canyon. The U.S. Bureau of Reclamation oversees Cook's Lake and is a partner in preserving the lower San Pedro River flows (see chap. 19).

Fort Huachuca (U.S. Department of Defense) occupies 30,000 ha in the Huachuca Mountains and on the uplands to the east. This land is used for military purposes and is not open for grazing, but some areas are available to the public for hiking and bird-watching. Portions of the area are managed to protect threatened and endangered species and their habitat.

The Coronado National Memorial (U.S. National Park Service) occupies 1,922 ha of grassland and oak woodland on the south end of the Hua-

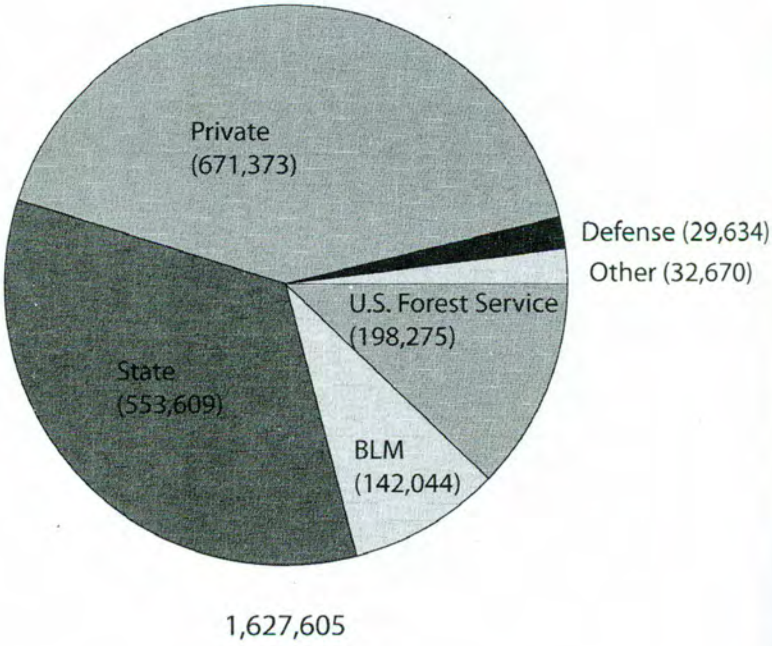

Fig. 11.5. Land ownership in Cochise County (in hectares) in 2000.

chucas. It is managed primarily for its historic value but also for habitat conservation.

State of Arizona. Approximately one-third of the land in Cochise County is held in trust by the Arizona State Land Department, which also holds lands downstream (fig. 11.5). Because state trust lands are constitutionally mandated to be managed for the economic benefit of public schools and other purposes, they may be leased or sold under certain conditions. Most leasing is for livestock grazing, although leases are available for such purposes as sand and gravel operations and mining. Nearly all state trust land is by law subject to sale to the highest bidder (Varady 1991). Over the past decade voters have rejected initiatives to allow for conservation uses. State property also includes Kartchner Caverns State Park, a large, wet cave in the Whetstone Mountains about 11 km south of Benson that hosts a breeding colony of some 1,000 cave myotis bats (*Myotis velifer*).

Natural Resource Conservation Districts (NRCDs) are legal state entities within the Arizona State Land Department whose mission is to "provide for the restoration and conservation of lands and soil resources of the state, the preservation of water rights and the control and prevention of soil erosion, and thereby to conserve natural resources, conserve wildlife, protect the tax base, protect public lands and protect and restore this state's rivers and streams and associated riparian habitats." NRCDs also receive assistance from the U.S. Natural Resources Conservation Service. The San Pedro River Valley includes parts of four NRCDs.

Private land. While the mountainous areas of the watershed are mostly under federal jurisdiction, nearly half of the land at the lower elevations is privately owned. Permissible private land uses are under the jurisdiction of the county boards of supervisors and, within cities, the appropriate city council, operating under state enabling legislation. A countywide comprehensive plan outlines permissible land uses, but rezonings and plan amendments are common in the county and the cities (Cochise County 2002). The lower basin with very little population pressure has less detailed planning efforts but operates under similar laws.

TNC and its partners have been pioneers in preserving land and water, starting with the Ramsey Canyon Preserve in 1974 and continuing to this day along the river and its tributaries from Sonora to the Gila River confluence (see chap. 19). Although the river flows through only a small remote part of Pima County, the county bought Bingham Ciénega along the lower San Pedro, which is managed by TNC.

Summary

Boom and bust cycles were common in the American West, and the San Pedro region was no exception. The silver mining boom of the late nineteenth century that made Tombstone the largest town in Arizona Territory lasted only about twenty years. Cutting of lumber and firewood left many hillsides bare. Grazing cycles prevailed with thousands of cattle thriving on the range, followed by droughts when thousands perished, leading to loss of ground cover, erosion, and introduction of non-native grasses for forage, but since the 1930s cattle numbers have remained relatively stable. The copper boom lasted nearly a century, but copper mining has declined in most of the region, although most mining towns survived supported by new economies. The most recent boom, rapid population growth in the upper basin, has led to decline of the aquifer and water supply for the river.

Some of the impacts on the river were short-lived, while others continue to this day and will continue long into the future. Mining pollution had major impacts for short periods, but the long-term impacts are mostly minimal. Hillsides have largely recovered from deforestation and overgrazing. Channel change from several sources has been long-lasting. The long-term impacts of the twentieth century population boom and large-scale groundwater pumping are unknown.

Attempts to conserve and restore the area began with National Forest formation in the early twentieth century. In the 1980s SPRNCA's creation occurred along with non-profit organization land acquisition and preservation efforts from the Sonoran region to the Gila confluence. Recovery of the river as a result of these efforts along with land use change has been dramatic in parts of the lower and upper basins.

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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

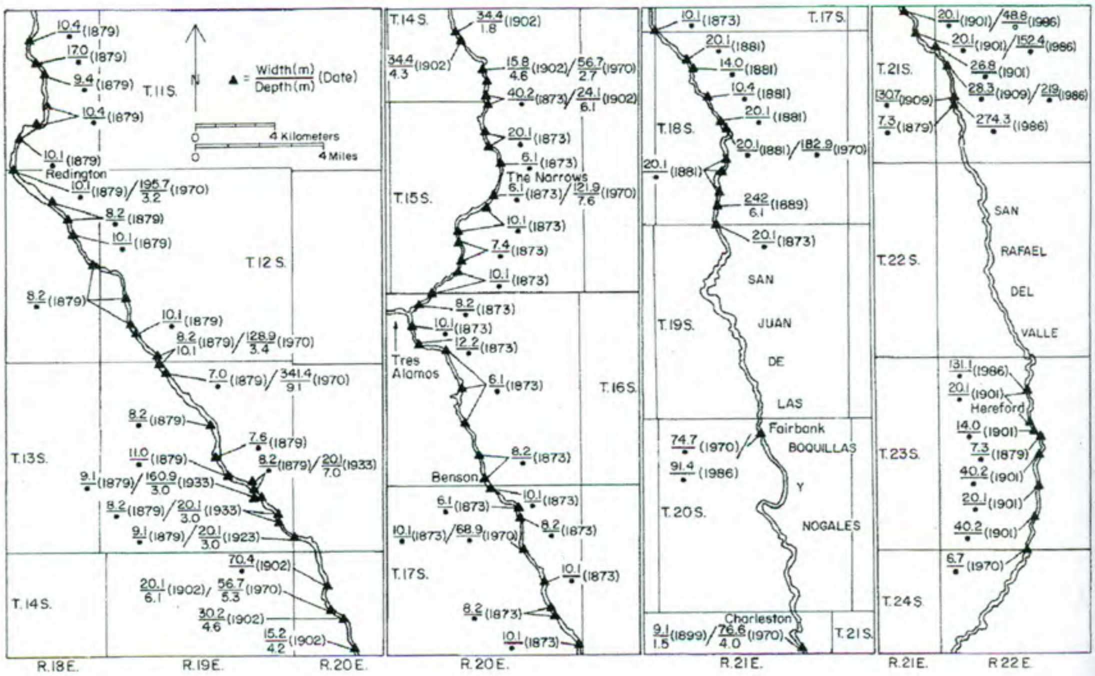

Fig. 12.1. Maps showing width and depth observations from cadastral surveys 1873–1933, amended from Cooke and Reeves (1976).

1959, Betancourt 1990). The degree of detail given in the accounts correlates 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 observations can be bridged by stratigraphic records from critical localities.

These records can help resolve two questions about pre-entrenchment

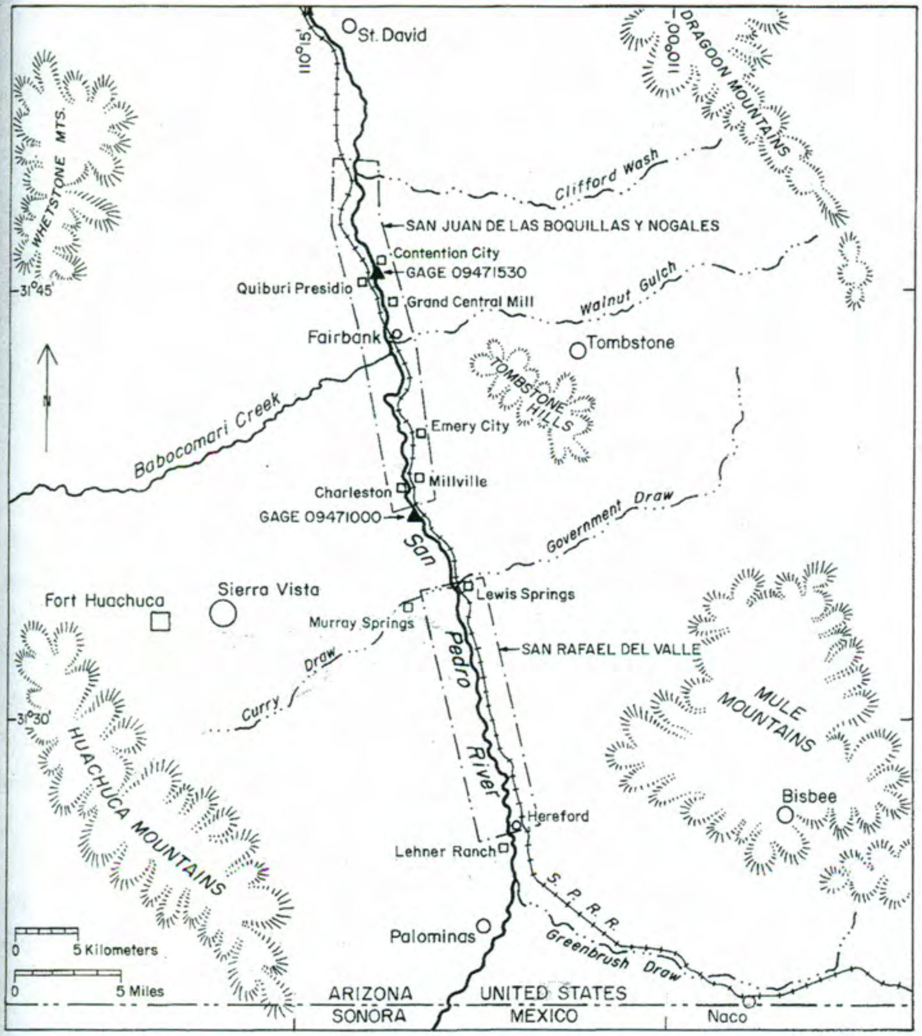

Fig. 12.2. Map of upper San Pedro River Valley showing locations of current and historical features. Illustration credit: Chuck Sternberg.

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,

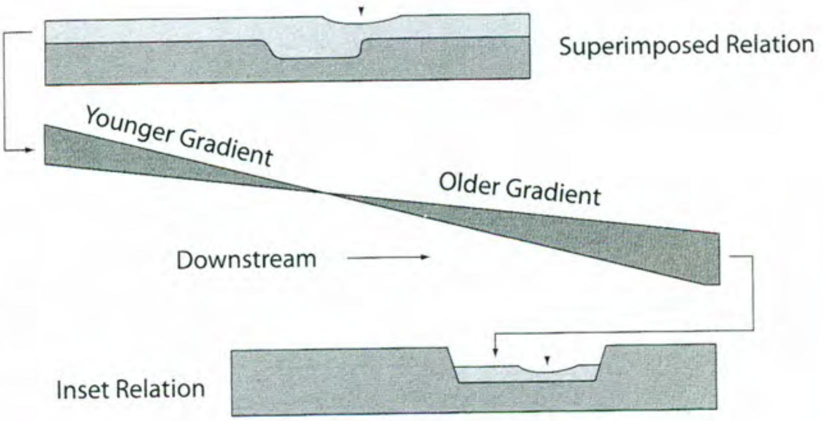

Fig. 12.3. Superimposed and inset stratigraphic relations and their geomorphic expression.

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 1983). 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

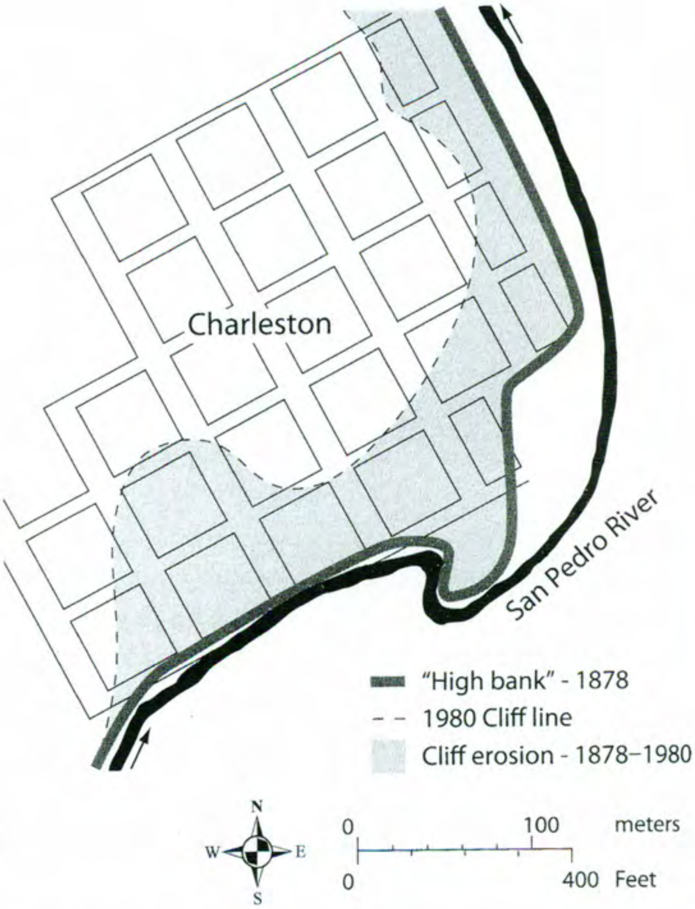

Fig. 12.4. Plat of Charleston in 1879 by A. J. Mitchell. Adapted from K. Tiller (1982).

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

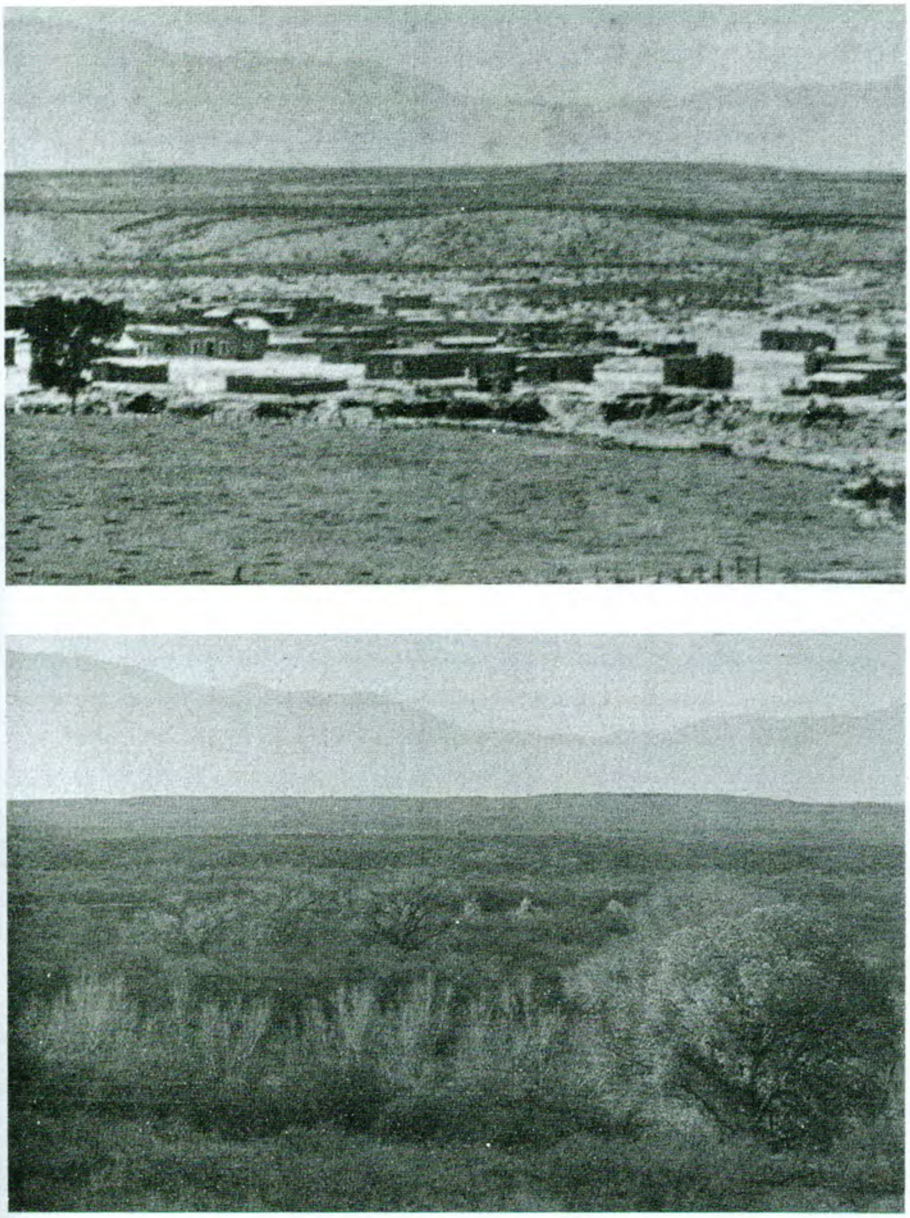

Fig. 12.5. (top; 12.5a): Photograph of Charleston taken by Carleton Watkins in 1883 looking southwest toward Huachuca Mountains. The San Pedro River runs from left to right through well-defined channel. (bottom; 12.5b): Same view in 1960. Photo credit: Rod Hastings, U.S. Geological Survey Desert Laboratory 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^{3}s^{-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

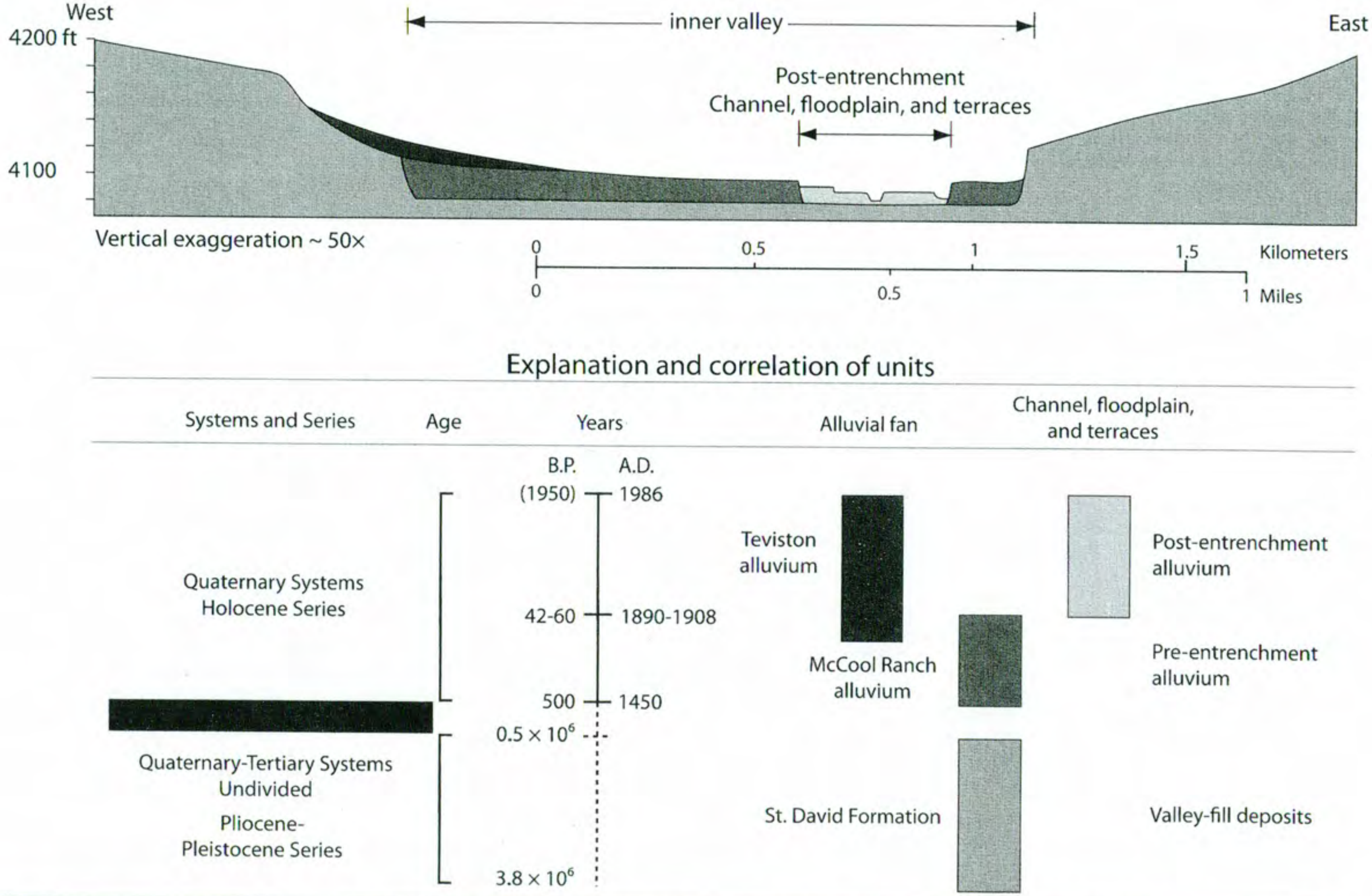

Fig. 12.6. Geologic cross section showing correlation of surficial deposits and geomorphology of the inner valley of the San Pedro River in the vicinity of Lewis Springs. The geologic relations, geomorphology, and deposits are typical of the upper San Pedro.

"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

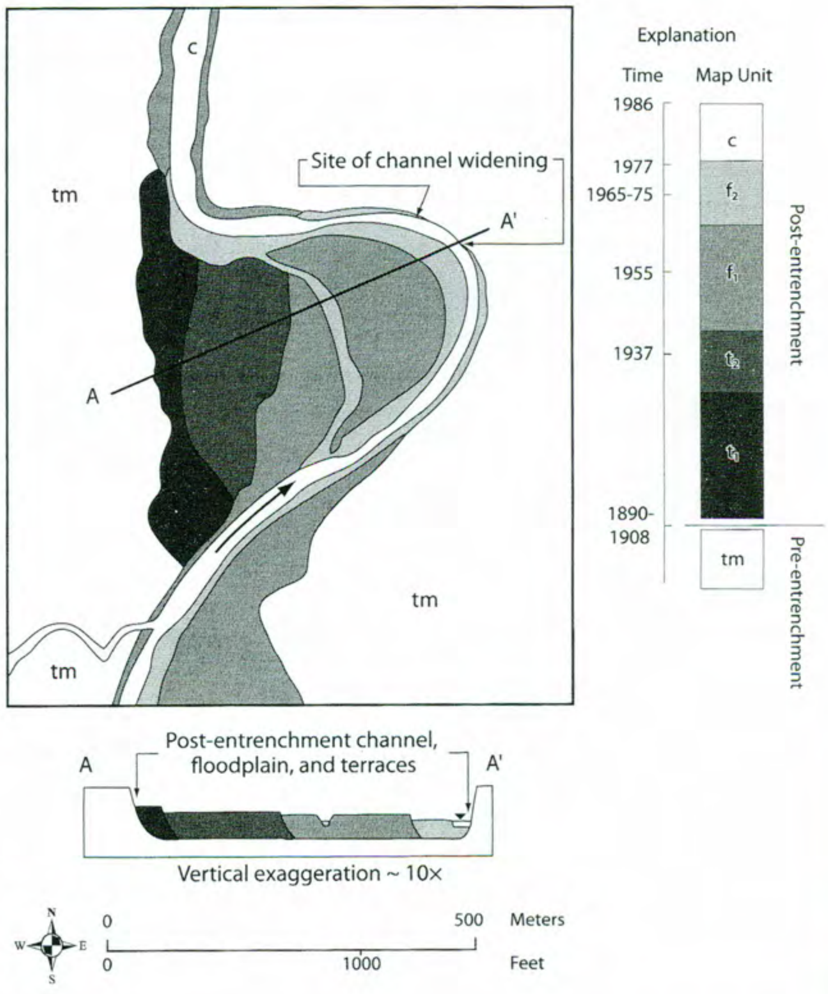

Fig. 12.7. Geologic map and cross-section of the post-entrenchment alluvium exposed on a point bar north of Hereford.

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

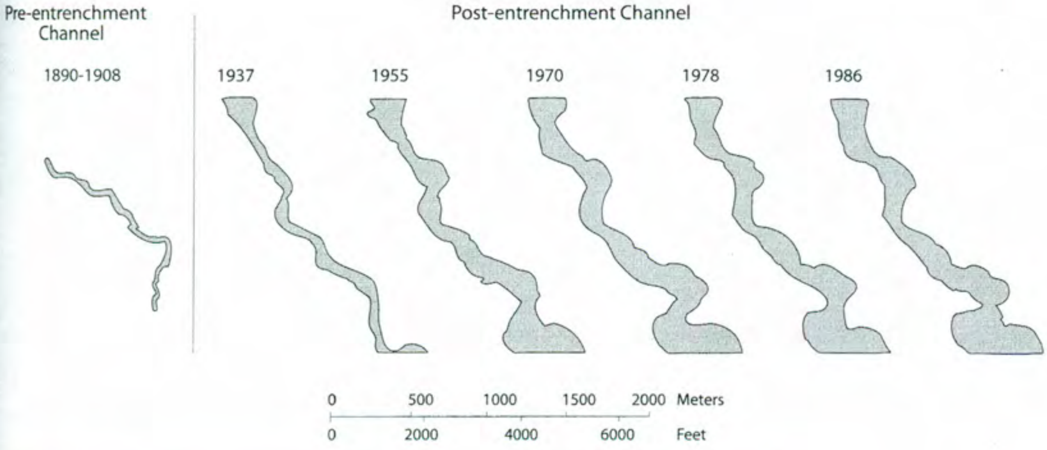

Fig. 12.8. Maps showing the pre-entrenchment channel and expansion of the post-entrenchment channel as compiled from sequential aerial photography since 1937, and from cadastral survey notes and plats at the turn of the century.

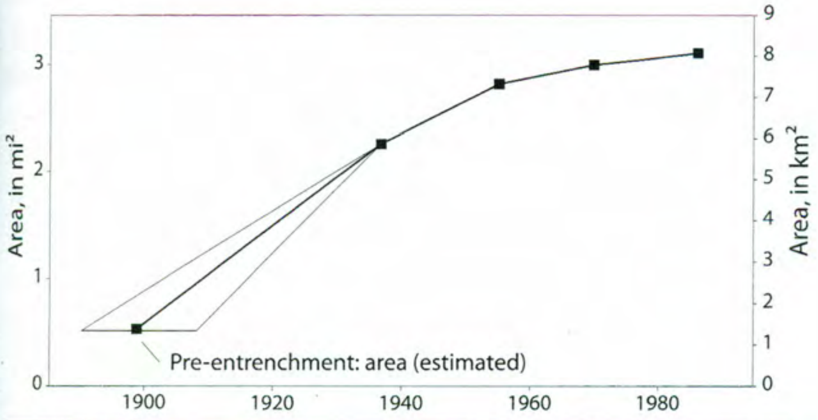

Fig. 12.9. Time series showing cumulative area of the entrenched channel. Channel expansion slowed appreciably by at least 1955.

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-

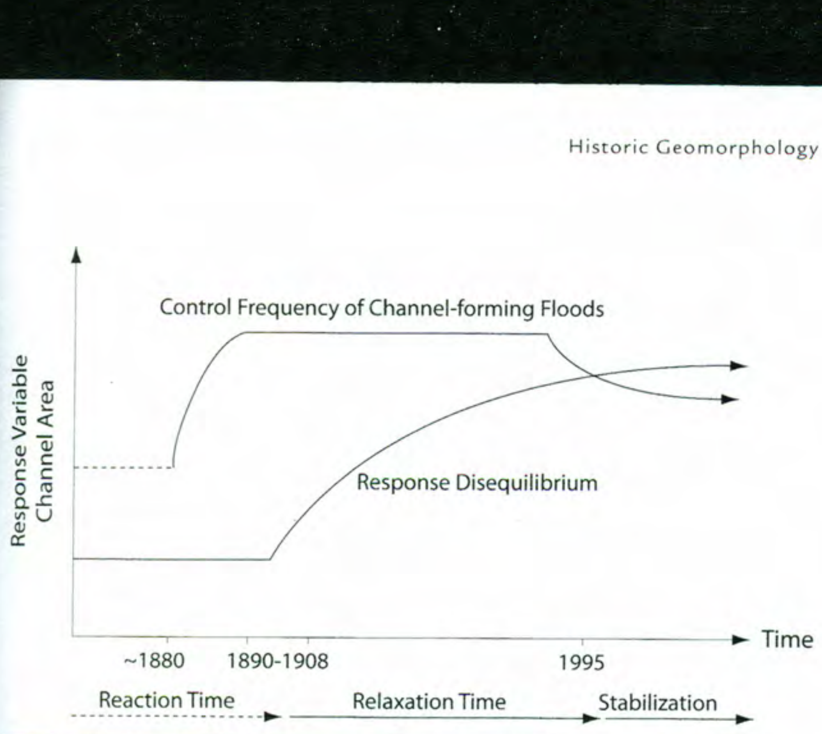

Fig. 12.10. Conceptualization of channel equilibrium in terms of control and response variables, based on Graf (1988a) and Knighton (1984).

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 ciénegas 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.

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Fluvial Geomorphology

THIRTEEN

Introduction

Grounded in the disciplines of geography and geology, geomorphology seeks to understand the active processes and history responsible for the configuration of planetary surfaces. Fluvial geomorphology is a subdiscipline that focuses on flowing water as a surficial process. Geomorphologists pay considerable attention to flowing water because in most places of the world, and particularly in deserts, it is the primary agency by which landscapes are shaped. Whereas many physical and chemical processes act to break down rock, for most of earth's surface it is water that removes the weathered material and transports it away.

Given that most geomorphic changes are accomplished by flowing water, some of the most dynamic components of the landscape are streams, rivers, and floodplains. Fluvial systems gather water from a broad area and concentrate it along streams and rivers, producing extensive erosion and sediment transport along channels and adjacent floodplains. Floodplains are a very small part of the terrestrial landscape but are where much of the geomorphic work is accomplished. Stream networks are a primary means by which landscapes are sculpted, and they are constantly adjusting to changes in the environment to transport geological materials effectively.

Climate change and human changes to the watershed have affected the geomorphology of the San Pedro River in the past and continue to do so today. Dramatic climate changes may occur at timescales of 10^3–10^4 years in association with glacial-interglacial oscillations, whereas smaller changes in temperature and moisture occur at timescales of 10^1–10^2 years due to solar variation, volcanic eruptions, and ocean-atmosphere dynamics such as El Niño–Southern Oscillation and Pacific Decadal Oscillation. As long as there is climatic variability, there is an inherent tendency for rivers to downcut, backfill, and shift their channels; human disturbances may augment or dampen these climate-driven transformations. Regardless of cause, fluvial changes represent recurrent disturbances that affect the structure of riparian communities (Malanson 1993, Hughes 1997). Because geomorphic processes influence biotic components in floodplain ecosystems, effective management of riparian resources requires a consideration of geomorphic history and process.

This chapter places the San Pedro River in a geomorphic context with the aim of providing readers with a sense of the dynamic and nonlinear aspects of hydrologic processes and their impact on stream geomorphology and riparian resources. The emphasis is on both natural and human-caused processes. Following an overview of fluvial processes, we describe physical characteristics of the San Pedro River and its floodplain and discuss mechanisms by which river channels change in time and space, and the ecological implications. This is followed by a review of agents of change affecting San Pedro River geomorphology.

Fluvial Fundamentals

Despite an abundance of quantitative studies in fluvial geomorphology, a universal equation (or set of equations) defining the full mechanics of streamflow and sediment transport has yet to be defined, and may never be defined, given the complexity. Nonetheless, basic processes involved in streamflow, sediment transport, and channel formation are relatively well understood (Leliavsky 1955, Leopold et al. 1964, Morisawa 1968, Schumm 1977, Knighton 1998). One conceptual approach to understanding rivers and sediment transport is to view them as open systems whereby a balance is approached between the sediment to be transported and the water available to accomplish the task. Sediment is provided to the system by physical and chemical breakdown of rock that is then available for transport by gravity or some fluid agent (wind or water) from hillslopes to stream channels. Once in motion, sediment continues to move until gravitational forces exceed the tractive forces acting on its motion. If more grains settle than are translocated, then a sedimentary deposit is created. These sedimentary deposits accumulate through time and underlie floodplain surfaces.

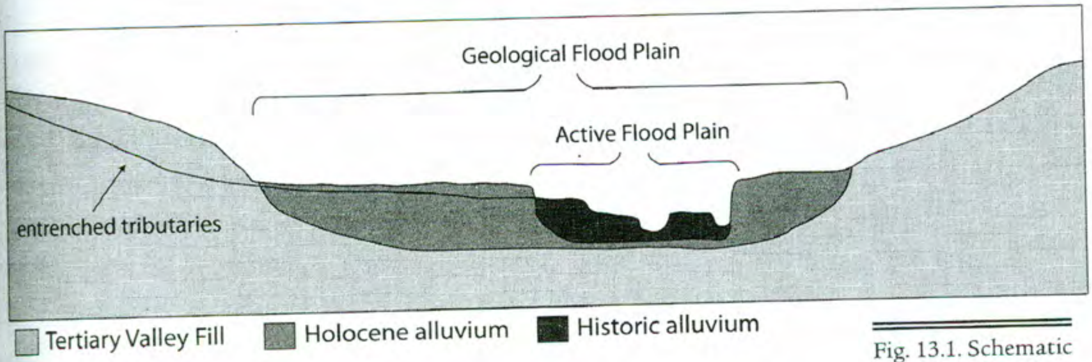

Fig. 13.1. Schematic cross section of San Pedro River floodplain and the post-entrenchment channel.

FLOODPLAINS AND TERRACES

Definitions. The concept of a floodplain is intuitively obvious: an area that periodically is inundated with floodwater. However, geomorphologists, hydrologists, and others often disagree with the boundaries of such areas (Graf 1988b) and the precise definition of "periodically." Many consider the floodplain to be surfaces adjacent to the active channel that are inundated when streamflow exceeds bank-full conditions. Others include surfaces adjacent to the channel composed of alluvium deposited during the current interglacial period, i.e., the last 11,000 years.

Surfaces that are currently too high above the modern channel to experience flooding given current channel conditions are not part of the floodplain but instead are stream terraces (Wolman and Leopold 1957). If the floodplain is deeply entrenched, such as much of the San Pedro River, the largest flows may be contained entirely within the inset channel (or series of channels). Given a definition of floodplain as geomorphic surfaces prone to frequent inundation, the San Pedro floodplain is limited to the entrenched zone (figs. 13.1, 13.2).

Prior to historic arroyo cutting (see chap. 12), the San Pedro River contained a relatively broad floodplain. Following arroyo cutting, surfaces that were once part of the floodplain became terraces. We include the pre-entrenchment floodplain surface with the entrenched zone to represent the geological floodplain and refer to the entrenched zone that contains the modern channel and adjacent surfaces prone to frequent inundation as the active floodplain.

Floodplain construction. Sediment is constantly added and removed from floodplains by moving water. Periods of net sediment storage are associated with floodplain construction. Given the complexity of streamflow and sediment transport, deposition is spatially and temporally variable, and there are many ways a floodplain can be constructed; these can be grouped into the two general processes of lateral and vertical accretion (Wolman and Leopold 1957, Morisawa 1968, Brakenridge 1988). Lateral accretion is characterized by the horizontal shifting of the main channel such that the outer edge of a bend migrates into

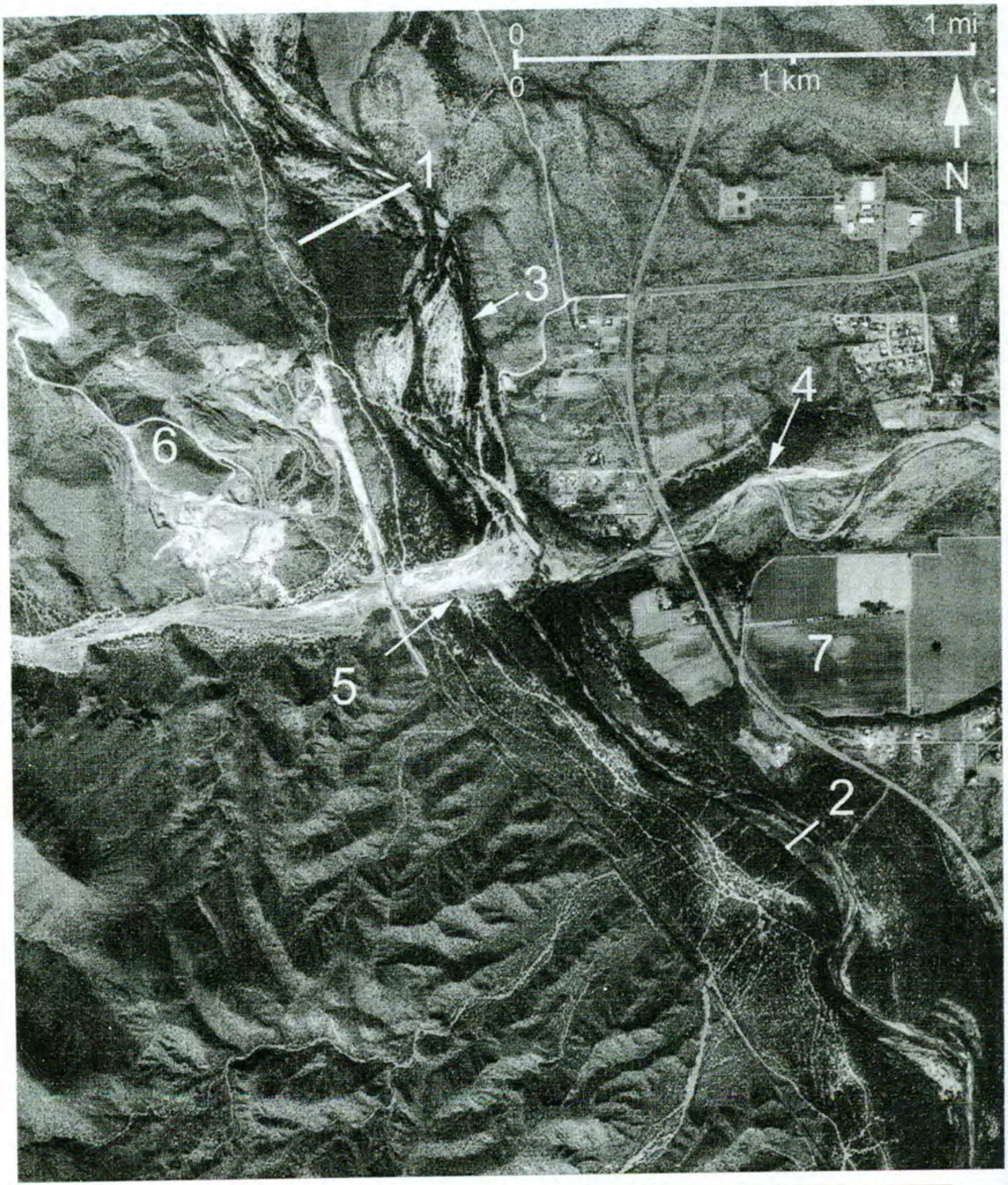

Fig. 13.2. Aerial photograph of San Pedro River floodplain at its junction with Aravaipa Creek. Highlighted features include 1. San Pedro River geological floodplain; 2. active (post-entrenchment) channel; 3. secondary flood channel; 4. Aravaipa Creek; 5. Putnam Wash; 6. mining on hillslopes; and 7. agriculture. Photo source: Arizona Regional Image Archive, University of Arizona.

existing alluvium while deposition occurs on the inside of the bend, often forming a gravel lag or point bar. Vertical accretion occurs as sediment-laden streamflow exceeds channel capacity and spreads onto adjacent floodplains.

In humid environments, channel flow is exceeded (resulting in overbank flow) on average every 1 to 2 years (Leopold and Wolman 1957). In arid environments, overbank flooding occurs more irregularly (see chap. 16) but nonetheless produces a vertical sequence of alluvial deposits, usually composed of fine sand, silt, and clay (see chap. 14). Through time, the height of the overbank deposits increases, resulting in a progressive increase in the size of discharge required to inundate adjacent surfaces. Eventually, the channel swings laterally and cuts into the stack of vertical accretion deposits, replacing them with channel sands and gravels. Alternatively, a large, erosive flood will strip the entire depositional sequence and leave a layer of gravels in its place (Nanson 1986). Both processes result in a mosaic of different-aged and -textured floodplain deposits that influence the age, structure, and composition of riparian plant communities (see chap. 1).

CHANNELS

Channel geometry is controlled by multiple factors including valley slope, discharge, sediment load, and floodplain vegetation. These factors influence how rivers erode and deposit sediment and thus influence the shape, size, and overall geometry of a river channel and its floodplain. Viewed from above, rivers generally fall into one of three plan-view shape categories: straight, meandering, and braided (Leopold and Wolman 1957). Straight channels are rare and generally occur where confined by bedrock or human structures.

Meandering channels. Meandering channels are frequently associated with low-gradient valleys, fine-grained alluvial sediment, and heavily vegetated banks (Schumm 1977). During relatively low to moderate flows, sediment accumulates on the inside of a meander, forming point bars, while erosion occurs on the outside of the meander; this causes the meander to shift horizontally across the floodplain transverse to valley slope, reducing the overall gradient of the channel. Meander loops also travel downvalley as the zone of maximum erosion is slightly offset downstream from the apex of the meander (Wolman and Leopold 1957). Meander cutoffs, semicircular abandoned segments of a stream channel, develop as meander loops become too large and unstable. If the meander cutoff retains water, it creates an oxbow lake.

Braided rivers. Braided rivers are characterized by multiple shallow, interconnecting channels passing among shallow sand and gravel bars. During high streamflow, bars are inundated and channels shift laterally. During periods of extended low flow, the sand and gravel bars can become covered with pioneer vegetation and eventually form islands within the braided floodplain. The channels are constantly filling with sediment forming sand/gravel bars that act to divert flow laterally creating new channels, driving rapid change in channel position and the number of channels (or anabranches).

Braided rivers are common where valley gradients are relatively steep and there is an ample supply of coarse sediment for transport. An abundance of sediment is yielded from floodplains that have a paucity of bank-stabilizing vegetation, and from arid or devegetated watersheds, perhaps through fire, deforestation, overgrazing, or mining. A highly variable discharge also appears important, given that braided rivers are most commonly found in dry environments where changes in streamflow can be rapid and dramatic (Graf 1988a).

Compound channels. Arid-region stream and river channels may have a combination of straight, meandering, and braided forms. Indeed, a common feature of floodplains in the desert Southwest is the compound channel (Graf 1988a), whereby a low-flow meandering channel is nested within a larger braided channel. Such forms are associated with fluvial systems that have frequent low flow contained within a single, meandering channel but also commonly experience larger floods whereby excess discharge is channeled through adjacent secondary and tertiary channels. As in braided channel forms, a highly variable discharge regime plays a critical role in creating and maintaining compound channels, but so does a smaller, semi-regular discharge.

CHANNEL PATTERNS IN TIME AND SPACE

Streamflow variance and channel change. Rivers may be uniformly meandering or braided, they may contain reaches that alternate between meanders and braids, or they may contain elements of both along a single reach. A river segment may also change its size and shape through time, particularly in response to large floods. Rivers in arid environments are particularly susceptible to radical changes in width and depth (Knighton and Nanson 1997), given their high variance in seasonal discharge (Graf 1988a; and see chap. 16). During large, high-energy floods, channels may downcut, widen, and shift laterally, often creating a channel much larger than what is needed to convey most flows. Changes in the form and course of the stream, such as in a meander cutoff, are referred to as avulsions.

Floods, vegetation, and channel change. The degree to which floodplains are altered through erosion depends on the magnitude and duration of a flood as well as the resistance of bank sediments to surface flow (Wolman and Miller 1960, Wolman and Gerson 1978, Costa and O'Connor 1995). If the interval between large floods is fairly long, the stream channel returns to a form more suited for smaller discharges, aided by vegetation that colonizes floodplains and sand/gravel bars (J. Friedman and Lee 2002). Along perennial stream reaches, the flood-widened channels soon re-narrow in association with vegetation establishment (J. Friedman et al. 1996a, 1996b). The recovery time in dryland streams is slower than for humid streams (Wolman and Gerson 1978).

Where the vegetation colonizes within a recently disturbed floodplain (e.g., within or outside the channel) can influence how the channel geometry will recover. Dense bank vegetation can result in narrower channels, while the presence of abundant channel-bed vegetation may result in channel widening (Huang and Nanson 1997). Regardless of the specific channel response, highly irregular streamflow and slow recovery times often preclude the formation of any equilibrium channel in dryland fluvial systems (Stevens et al. 1975, Graf 1988a).

Sediment yield and channel change. Vegetation type and precipitation pattern within the watershed both influence sediment yield. Arid-region catchments have low biomass and plant cover. Plant cover reduces runoff and erosion by minimizing raindrop splash energy on bare soil and slowing sheetwash so that more water infiltrates into the subsurface, while plant roots hold sediment in place. Shifts in precipitation and in plant cover both can have a significant effect on sediment yield in desert and grassland biomes (Langbein and Schumm 1958, Bull 1991) and can lead to significant changes in channel geometry.

San Pedro River Geomorphology

ENVIRONMENTAL SETTING

Geologic context. Most of the mountains in the San Pedro basin contain volcanic and metamorphic rock created during the Mid-Tertiary Orogeny 30–20 million years ago, whereas the mountains were formed by extensional forces during the Basin and Range Physiographic Province disturbance 15 to 8 million years ago (Shafiqullah et al. 1980, Menges and Pearthree 1989). Originally, the valleys were internally drained, as evidenced by alluvial fan deposits grading into extensive playa and lake deposits exposed along the valley margin, but eventually the basins filled and the San Pedro and Gila Rivers became integrated. Once this occurred, alluvial fans became the dominant depositional landform extending from mountains to floodplain. However, with drainage integration came episodes of valley entrenchment whereby the San Pedro River and its tributaries incised into basin fill, cutting a series of erosional fan terraces and pediments into margins of the valley, each veneered with stream gravels (Tuan 1962, Haynes 1987, Cochran and Richardson 2003). These alluvial fan and pediment surfaces extending upslope from the San Pedro River are collectively referred to as the valley piedmont.

Since the height of the last glaciation approximately 20,000 years ago, the river has cut a trench into the Tertiary basin fill along the axis of the valley (fig. 13.1). The trench is filled with post-glacial alluvium that underlies the geological floodplain of the San Pedro River. This includes deposits introduced by piedmont streams, commonly forming tributary alluvial fans at the margin of the geologic floodplain where rapid sedimentation occurs. The geologic floodplain and tributary fans have been periodically entrenched by the San Pedro River, most recently during the mid- to late 1800s and early 1900s, forming an inset, entrenched zone, i.e., the active floodplain (see chap. 12). In places, historic alluvium is beginning to fill the entrenched zone (Hereford 1993).

Upper and lower basins. The piedmont in the upper basin of the San Pedro is broad and only moderately dissected by tributary streams and slopes gently above the axial valley trench. In the lower basin, the axial trench increases in slope and is bounded by steeper and more dissected piedmont surfaces (Heindl 1952a, 1952b, Tuan 1962). This results in a higher drainage density (length of stream channel per unit land area) in the watershed.

The higher drainage density and slope of the bounding piedmont affects baseflow and the flood regime of the lower San Pedro River. Basins with high drainage densities display high drainage network efficiency and more rapid hydrograph response (Patton 1988). Runoff is more quickly conveyed through the network of tributary channels to the main trunk stream, increasing peak flows and also reducing infiltration on the piedmont, an important source of baseflow for the river. Increasing urbanization in the upper basin is likely to mimic the effect of increased drainage density through replacement of vegetated surfaces with impervious ones (Kepner et al. 2004).

Floodplain width. Overall, the width of the San Pedro River active floodplain increases downstream, except where locally constrained by geologic features. This downstream increase in width reflects the effects of large floods on bank cutting. The lower basin with its larger catchment area and greater drainage density has greater maximum flood size potential. Moreover, hydraulic measurements indicate that the middle and lower reaches of the San Pedro River channel have higher values of stream power per unit length of channel compared to the upper basin, thus increasing the river's ability to strip vegetation and erode sediment (Lite 2003). Whereas the width of the active floodplain is greater in the lower basin, the size of the main flow channel decreases downstream. Unlike the active floodplain, the main flow channel is formed by more seasonal runoff and baseflow, and regular streamflow decreases downstream due to infiltration.

Aquifer conditions. With the exception of a few short segments where bedrock emerges at the surface, the San Pedro River flows over Holocene alluvium inset within the axial trench. Both basin fill and Holocene alluvium serve as aquifers for the valley, with the Holocene alluvium very permeable but prone to seasonal fluctuations of the water table. In most places, the San Pedro River is influent, i.e., surface flow infiltrates down to the water table below the channel, resulting in reduced downstream discharge. However, there are perennial reaches where local water tables intersect the surface, usually near bedrock outcrops. The longest perennial reach is approximately 30 km long between Hereford and Fairbank in the upper basin (D. Brown et al. 1981; and see Introduction).

HISTORIC CHANGES

The San Pedro River and its tributaries have done their part in shaping the landscape in southeastern Arizona and northern Sonora: they have cut canyons, filled basins, and created terraced landforms for at least the last five million years (K. Bryan 1926, Tuan 1962, Lindsay et al. 1990). During this time, the region overall has been tectonically stable, and changes in deposition and erosion by the river and its tributaries are attributable mainly to climate change. Numerous glacial-interglacial cycles during the Quaternary altered the hydrology of the river and repeatedly reshuffled plant and animal communities in the valley and adjacent mountains. The river responded to these long-term changes in climate, and consequent effects on vegetation, fire frequency, and flood regime, by cycles of downcutting and backfilling, resulting in a dissected landscape in the basin and terraced landforms along the river.

In addition to long-term changes, there have been short-term stream dynamics occurring at timescales of decades to centuries. For example, incision of the San Pedro River channel in the mid-1800s and early 1900s radically altered floodplain geometry and vegetation (see chap. 12). These changes may be linked to smaller variations in climate—such as El Niño frequency, strength of the southwestern monsoon, and drought—that control flood regime, as well as human activities within the hydrologic basin.

The probability that incision along the San Pedro was caused by a combination of natural climate variability and human alterations of the landscape creates a problem for resource managers. Given the San Pedro River's history of change due to climatic variability, how does one separate natural from anthropogenic changes? Arroyos and gullies that formed throughout the San Pedro River Valley by the late 1800s were attributed by many to overgrazing; yet the San Pedro River and many other streams in southeastern Arizona had downcut and backfilled at least five times prior (Waters and Haynes 2001). Rivers like the San Pedro are complex, open systems that adjust channel size, shape, and configuration in response to changes in runoff and sediment yield from drainage basins. Such changes can have multiple causes, and it may not be possible to determine to what degree river metamorphosis is human induced.

Channel geometry. Dramatic changes in channel geometry during the last 150 years are well documented for the San Pedro and other rivers in the American Southwest (Burkham 1972, Cooke and Reeves 1976, Graf 1983, Hereford 1984, Huckleberry 1994a, Hooke 1996; and see chap. 12). These include

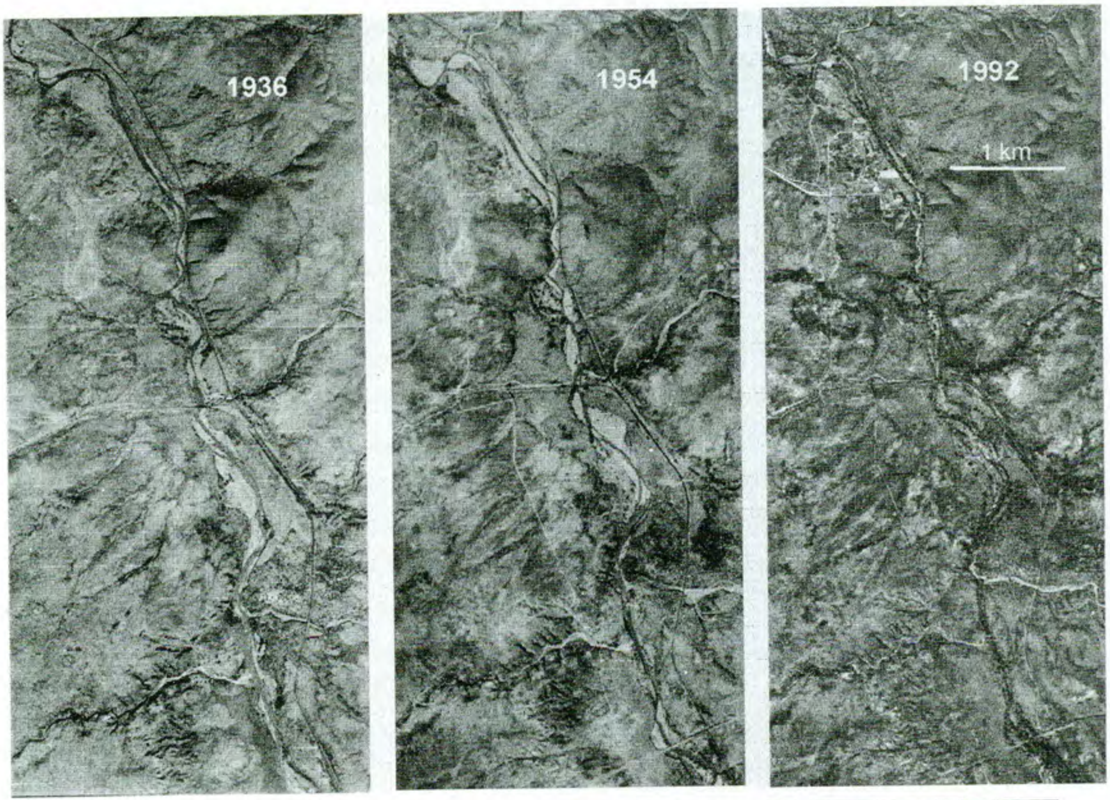

Fig. 13.3. Repeat aerial photography (1936, 1954, 1992) for the upper San Pedro River at Lewis Springs. Extensive areas of the active floodplain that were unvegetated in 1936 and 1954 were subsequently occupied by large stands of woody vegetation. Photos courtesy of Robert Webb.

floodplain transformations caused by vertical downcutting of the channel (i.e., arroyo formation) and fluctuations between meandering and braided patterns. These transformations affected riparian vegetation through erosion and consequent changes to water tables.

Prior to the mid-1800s, the San Pedro River flowed over an unincised surface and had a larger area prone to flooding. It contained a single meandering channel, and marshes were common (Hastings 1959, Hereford 1993, Huckleberry 1994b, Wood 1997; and see chap. 12). Following historic floodplain entrenchment, water tables lowered and marsh habitat declined (Hendrickson and Minckley 1984), but the subsequent channel widening also created the wide, braided channel conditions that facilitated the establishment of riparian forests of cottonwood (*Populus fremontii*) and willow (*Salix gooddingii*) (figs. 13.3, 13.4).

The incised channel of the San Pedro River has widened since initial arroyo development, especially during the largest recorded flood, that of September 1926. The result is an inset floodplain consisting of a post-entrenchment channel with numerous secondary flood channels and low gravel surfaces that in places is several hundred meters wide (fig. 13.3). The low-flow channel

Fig. 13.4. Repeat photography of San Pedro River near the U.S.-Mexico border at Palominas, looking downstream. (top; 13.4a): Photo taken 4/17/1930 by W. E. Dickinson (#1456, courtesy of U.S. Geological Survey Arizona District) reveals relatively unvegetated channel with exposed sand and gravel bars. (bottom; 13.4b): Photo taken 11/28/2000 by Dominic Oldershaw (survey stake 1954, courtesy of the U.S. Geological Survey Desert Laboratory Repeat Photography Collection) reveals a narrower channel with increased riparian vegetation.

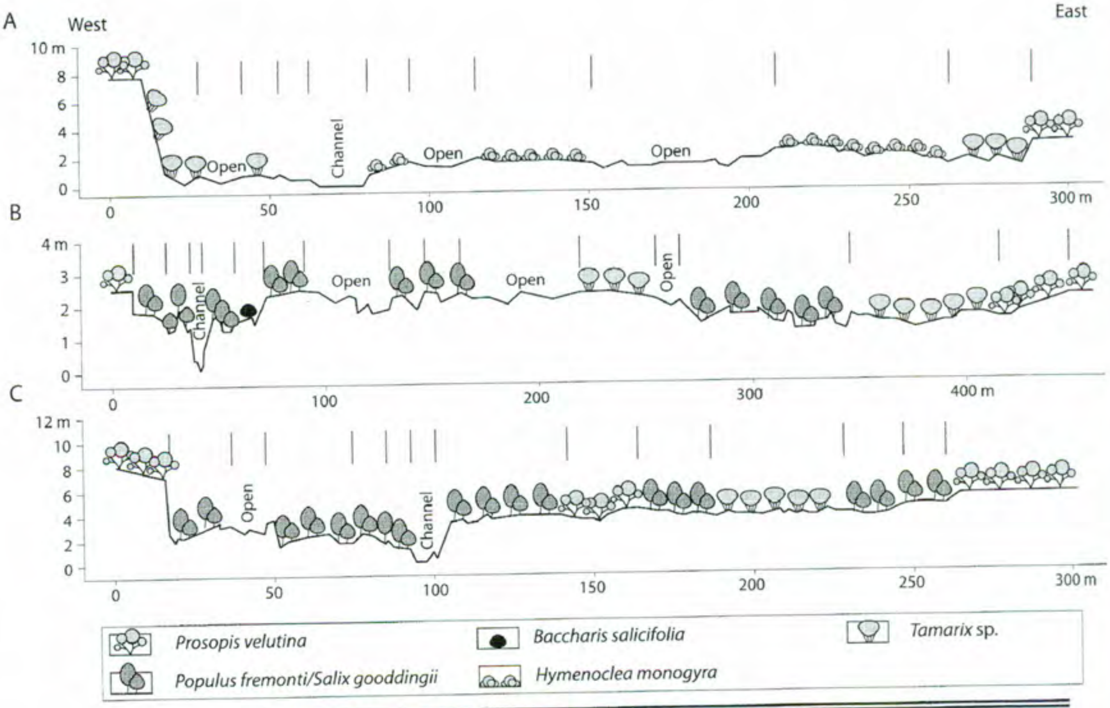

Fig. 13.5. Cross sections of the San Pedro River active floodplain with vegetation patch types (adapted from Lite 2003) at a reach in lower basin with highly intermittent flow (A), reach in lower basin with moderately intermittent flow (B), and reach in upper basin with perennial flow (C). The short vertical lines represent divisions between vegetation types and vegetation age classes. Illustration credit: Mike Buffington.

meanders but also has several braided sections and, in most reaches, forms a compound plan-view form. The low-flow channel has changed position due to meander migration and cutoffs (Wood 1997), as well as braided channel shifts. The result is an active floodplain with surfaces of different ages including gravel bars, swales (elliptical depressions formed by scour of sediment), and active and abandoned channels that contain different-textured alluvial soils and support a patchwork of riparian plant communities (fig. 13.5).

Floodplain development. As pioneer seedlings become established after floods on new bare sand and gravel surfaces, the new plant growth increases the hydraulic roughness of the floodplain and decreases flow velocities during floods. During the first half of the twentieth century, the channel was wide and braided and sparsely vegetated (Hereford 1993) (figs. 13.4, 13.5). Today, the active floodplain contains dense vegetation that acts as an impediment to the swift movement of large floods (Phillips et al. 1998).

By increasing hydraulic roughness and reducing peak discharge, dense floodplain vegetation facilitates the deposition of sediment, causing the floodplain to aggrade. Hence, there exists an alluvial cycle on the San Pedro River marked by channel downcutting followed by channel widening through lateral channel swings and bank collapse. As the channel widens, new alluvial surfaces are created for vegetation growth that help to trap sediment and facilitate the backfilling of the incised channel (Meyer 1989). This process can be accelerated if hillslopes are disturbed (e.g., see open-pit mining in fig. 13.2). As riparian vegetation colonizes and covers much of the active floodplain, the San Pedro River may eventually backfill much like it has several times during the Holocene. To what degree human activities will modify this cycle remains to be seen.

Agents of Change

Rivers are naturally prone to change. For the San Pedro River, we highlight four primary agents of geomorphic change, variously influenced by anthropogenic actions and often interrelated, that affect the form and behavior of the channel: changes in dominant streamflow, floods, fire, and animal populations (including cattle and beavers).

CHANGES IN STREAMFLOW

Today, portions of the San Pedro River Valley are experiencing unprecedented demands on water, while other reaches are being rewatered for conservation purposes. Changes in streamflow rates can have geomorphic consequences, but the degree to which a river channel responds may not be commensurate with the magnitude of the disturbance. For example, streams may be close to a threshold of change in channel geometry and will respond dramatically to small disturbances, while streams farther from such thresholds can withstand large disturbances and retain a stable configuration. Determining the proximity of a fluvial system to an internal threshold is difficult, and this precludes easy predictions of channel behavior for rivers like the San Pedro.

In general, stream banks are less stable, and streams have greater width/depth ratios, in areas where streamflow is ephemeral or intermittent (vs. perennial) and where the channel is composed of more easily erodable materials (Gordon et al. 1992). The reduction in cover of densely rooted wetland plants that occurs as streams become increasingly intermittent (see chap. 1) further contributes to bank instability. The reduction in bank vegetation by drought ultimately can lead to changes in channel pattern, such as a shift from a meandering to a braided form (Millar 2000).

Changes in streamflow also influence stream geomorphology by driving shifts in floodplain vegetation. As rivers such as the San Pedro become drier, cottonwood/willow forests shift to saltcedar shrublands and then to sparsely vegetated xeroriparian shrublands (see chap. 1); the associated changes in stem density and stem size lead to geomorphic changes. Stands with high density of large-stemmed shrubs such as saltcedar may result in increased hydraulic roughness and greater dissipation of energy and sedimentation in comparison to the more widely spaced, but larger, cottonwoods and willow stems (Hadley 1961, Graf 1980, Hupp 1992, Phillips et al. 1998). High density of woody stems can cause geomorphic adjustments including bank stabilization, channel downcutting, decreased channel migration, and channel narrowing (Graf 1978, Graf 1982, Birkeland 1996, Allred and Schmidt 1999, Tickner et al. 2001, Cooper et al. 2003). The resulting restricted and stabilized channel may not be able to adjust to changes in discharge or convey large floods, and flows that would previously have been contained within the channel will inundate portions of the floodplain (Blackburn et al. 1982). Greater study is needed to assess the full geomorphic effects of saltcedar presence on actively scoured rivers such as the San Pedro, and to determine if flood energy dissipation processes vary substantially along hydrologic gradients.

FLOOD REGIME CHANGES

Flood magnitude and frequency may increase in the future in response to intensification of the hydrological cycle associated with global warming (see chap. 3) and perhaps also to urbanization of the watershed. The size of a flood is important with respect to the amount of erosion that occurs: larger floods have greater stream power, and most sediment movement in dryland fluvial systems is accomplished by large floods (Baker 1977). Equally important to size is duration of flooding. Floods of medium to long duration with large peak stream power per unit area are considered to be most effective in altering floodplain geometry (Costa and O'Connor 1995) and can result in dramatic erosion and channel widening (Huckleberry 1994a).

In addition to direct effects, floods indirectly produce geomorphic changes by altering the density, age, and species composition of riparian vegetation (Auble and Scott 1998, Rood et al. 1998; and see chap. 1). Over time, as the pioneer trees grow and as new plant species colonize their understory, geomorphically significant characteristics such as stem density, stem size, rooting depth, and vegetation height change in tandem.

FIRE REGIME CHANGES

Wildfires influence fluvial geomorphic processes by altering vegetation, soil, and rock characteristics. When upland hillslopes burn, this can increase the amount of sediment supplied to river channels (Benda et al. 2003). Post-fire sediment is delivered from tributaries to higher-order channels in debris flows or in sediment-laden streamflows following storms (Wohl and Pearthree 1991). This punctuated sediment delivery can lead to channel aggradation, altered substrate particle size, and alluvial fan growth at tributary junctions and can create heterogeneous habitat and landforms in river and floodplain ecosystems (Miller et al. 2003). Fire-induced sediment pulses can also alter channel gradient. Because arid-region rivers such as the San Pedro transport most of their sediment load during infrequent large flows, sediment from tributary streams may remain in place for years, forming alluvial fans within the axial floodplain and altering slope-energy relationships within the channel until discharge is competent to remove it.

Fire in the riparian zone, in the short term, is similar to floods in destroying vegetation and thus decreasing flow resistance, bank strength, and nucleation of bar sedimentation and in increasing the supply of woody debris for overbank deposits (Hicken 1984, Huang and Nanson 1997). Reduced flow resistance in the floodplain could lead to higher flow velocities and to enhanced sediment transport and channel erosion. The longer-term effects of floodplain fires will depend upon the fire tolerance of riparian plants and their rate and style of post-fire revegetation (see chap. 1). The net effect may be reduced flow resistance in parts of the floodplain with high tree mortality and little resprouting, but heightened flow resistance and sedimentation in areas with dense stands of resprouted trees.

ANIMAL ABUNDANCE

Livestock. Livestock grazing has a long history in the San Pedro River Valley, stemming back to the 1600s (see chap. 11). Livestock grazing can affect floodplain geomorphology by inducing changes in riparian vegetation abundance and composition, but cause-and-effect relationships between grazing and geomorphic processes are complex. Dense herbaceous cover increases hydraulic roughness, slows water velocity, and facilitates sedimentation, and its removal through grazing can increase the erosion potential of floodplain surfaces. However, selective browsing by cattle can drive shifts from pioneer trees to pioneer shrubs (see chap. 1), potentially resulting in channel narrowing. Grazing on surrounding hillslopes influences geomorphic processes by compacting soils and modifying runoff. Reduced infiltration leads to increased surface runoff; cattle trails then foster rill and gully formation by concentrating this runoff (Cooke and Reeves 1976). Erosion on hillslopes translates to increased sediment loads in streams and washes, leading to sedimentation which can favor disturbance-dependent vegetation. Other possible geomorphic effects include changes to stream width and depth; bank angle, height, and stability; and pool depth (Myers and Swanson 1995, Sidle and Sharma 1996, Belsky et al. 1999).

Beaver. North American beaver (*Castor canadensis*) are semiaquatic rodents that construct lodges and dams out of logs, branches, mud, and stone (see chap. 6). One primary geomorphic effect of beaver is enhancement of sedimentation, which follows from the reduction of water velocity due to dam construction (Butler 1995). As beaver ponds fill with silt, and water tables are raised, the areas become wet meadows (Ives 1942). During large floods, beaver dams are damaged or destroyed, but they do reduce conveyance and attenuate flood waves, thus reducing the erosive potential of large floods. In addition to dams, beavers construct canals and other diversions to flow either to assist the transport of logs or to maintain pond depth (Butler 1995). These features can divert water within the floodplain and ostensibly play a role in channel shifts and meander abandonment.

Some argue that the removal of beaver in the late 1800s played an important role in the entrenchment of floodplains throughout the Gila River watershed (Dobyns 1981, McNamee 1994). However, the effectiveness of beaver dams to slow the largest floods that have tremendous erosive power is questionable. Unfortunately, quantitative data demonstrating the hydraulic effects of beaver dams along arid streams are lacking, and thus it is difficult to determine the geomorphic response to beaver removal. Today, beavers are present along portions of the upper and lower San Pedro River, providing opportunities to measure the geomorphic significance of this species.

Conclusions

Rivers like the San Pedro are dynamic components of the landscape that constantly adjust channel size, shape, and gradient in response to changes in runoff and sediment. Vegetation plays an important role in this process by influencing patterns of runoff, surface stability, and sediment movement both within and outside of floodplains. As channels make adjustments, floodplains experience erosion and deposition: the former process destroying previously established vegetation and the latter process commonly creating new planting surfaces. During plant succession, differences in plant type, age, and structure alter the hydraulic conditions of the floodplain, thus affecting channel behavior. It is a two-way relationship between plants and rivers, and the dynamic between the two can be quite complex and difficult to predict.

One certainty, however, is change. Stratigraphic evidence indicates that the San Pedro River has altered its channel geometry several times over the last several thousand years. Over the last 150 years, the river channel has downcut, shifted laterally, changed between braided and meandering forms, and deposited sediment in the floodplain. Arroyo cutting removed numerous marshes within the floodplain but eventually created fresh disturbed surfaces for establishment of the large willow and cottonwood galleries that are the hallmark of the San Pedro and provide key habitat for migratory birds and other species.

Because fluvial systems are naturally prone to change due to climate variability and intrinsic geomorphic processes, it is difficult to quantify the degree to which humans have caused past and present transformations of the San Pedro River. Many of the geomorphic changes experienced by the San Pedro River during the last 150 years are undoubtedly linked in part to water depletion, overgrazing, deforestation, and introduction of plant species. Human actions continue to impact fluvial geomorphic processes in the river today through improved grazing management but also increased urbanization in the uplands; intentional burning and increased accidental fire ignitions; introduction of beaver and exclusion of livestock from some river reaches; and, depending on reach, reduced or increased groundwater pumping. More research is needed to monitor current geomorphic processes in rivers like the San Pedro to provide greater insight into current conditions and help forecast future changes in floodplain behavior under a variety of climate, land use, and population growth scenarios.