# WHERE THE RIVER MEETS THE DITCH:
# HUMAN AND NATURAL IMPACTS ON THE GILA RIVER, NEW MEXICO, 1880–2000

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## ABSTRACT

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In the late 1800's the Gila River in southwestern New Mexico occupied a single deep channel with thickly vegetated banks. In the Gila Valley, just downstream of a National Forest boundary, the river today is wide, shallow, and braided among cobble floodplains largely devoid of vegetation. The Gila River's current condition could be the result of natural events, a series of major floods on the river between 1971 and 1997. Or it could reflect the river's response to human efforts that include diversions for irrigation and the construction of check dams and levees beginning about 1950. A number of data sources were employed to examine temporal correspondence among these factors. Flood histories, anecdotal accounts of change in the riparian corridor, and surveys of floodplain morphology conducted during site visits in 1999 and 2000 were evaluated to reconstruct probable depositional and erosive phases during the past century. Changes in the extent of vegetated bar and floodplain surfaces were quantified from six sets of historic aerial photographs (airphotos) dating from 1935 through 1996. The airphotos also provided documentation of leveed reaches and relative frequency of channel avulsion along vegetated and unvegetated banks. To predict potential patterns of riparian regeneration on floodplains, eight piezometers were installed near the river channel to obtain bi-weekly data on relative elevations of ground- and Gila River surface water during the study period. Variance between the river's natural base flow regime and base flow remaining after irrigation diversions was examined for the period 1969 through 2001. Morphological and flood data indicate that the current condition in the Gila Valley is due in part to levee construction and repair, and they suggest that major modifications to channel form for restoration purposes may have unpredictable consequences. Evaluation of relative groundwater levels in conjunction with the historic airphotos reveals complex interactions between the anthropogenic and natural hydrologic systems within the valley. Vegetation regrowth on the active channel upstream of the diversions has occurred more rapidly than downstream of them, where riparian regeneration generally occurs earliest in abandoned channels and backwaters removed from the currently active channel.

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## PREFACE

The Gila River in southwestern New Mexico flows out of the Gila Wilderness and into one of the first of the small valleys where its waters are diverted for irrigation. Anglo settlers who reached the area in the 1870s built some of the irrigation ditches that are still in use today. In the 1950s, local farmers, assisted by federal funds, began work to channelize and control the river. In the early 1960s, check dams were constructed across most of the tributary drainages that join the river in the Gila Valley.

The Gila River experienced a series of large flood events during the 1980s and 1990s after decades in which moderate floods were the rule. Within the valley, tall cutbanks and broad, barren floodplains of cobble now line long stretches of the river. The river and its riparian corridor appear very different from their condition in 1950, when the river generally occupied a single channel between sandy floodplains vegetated with cottonwood, sycamore, and willow. The Nature Conservancy manages a preserve just upstream of the valley, and acquired a second preserve there during the course of this study. The organization's mission is to preserve or return endangered ecosystems to their natural functioning condition, prompting this study's initial question: Is the river's current state in the Gila Valley a result of natural flood processes, or a response to human impacts, including levee construction and diversion of its waters for irrigation?

My first visit to the Gila Valley was in October, 1998, and over the six months that followed, a general theory emerged that eventually culminated in this thesis. It seemed likely that the river's current condition was the result of a combination of flood effects and channelization efforts, and much of the research I conducted was aimed at clearly defining the river's flood history, and the history of human impacts within the valley, since about 1880. Additionally, no study had previously identified the nature and chronology of changes in the river and its floodplains over time, and this formed a second component of the study. Lastly, return of vegetation to the riparian corridor, and the importance of its role in shaping the river's future condition, suggested another critical thesis component, an examination of the impact of diversions on availability of water to floodplain areas.

The conclusions I reached in the study regarding causes for the river's current condition and its likely influence on future condition synthesized data from a variety of quantitative and anecdotal sources, in addition to observations made during field work between March, 1999 and April, 2001. Evaluation of this study approach and its implications form a final component of the thesis.

## INTRODUCTION

Ecologists working within the southwestern U.S. recognize the essential role of riparian areas within the region. Typically occupying only a small percentage of the land area within semi-arid regions (less than 1%, according to Apple, 1985), riparian zones include disproportionate amounts of total forage production, cover, and, of course, water available in desert or semi-arid areas. Thus they provide habitat essential for hundreds of species that occupy them year-round or use them as migratory stopover points. Complex biologic, geomorphic, and hydrologic interactions are created and sustained by these systems and their consequent diversity is well recognized (Auble, Friedman, & Scott, 1994; Brady, Patton, & Paxson, 1985; Bren, 1993; Lamb & Lord, 1992).

A dramatic overall net loss in riparian area in the southwest has occurred during the past two centuries and more is in danger of being lost (Kauffman et al., 1997; Rojo et al., 1998; Stromberg, Patten, & Richter, 1991). Recognized threats to riparian zones can be grouped into seven categories; all but one of which are generally perceived as anthropogenic in cause. The first may be the most controversial; it includes a host of potential impacts attributed to livestock, such as overgrazing or bank trampling.[1] Other threats include 2) modification of the natural flow regime by dam construction and operation; 3) introduction of exotic riparian species, particularly salt cedar (*Tamarix chinensis*); 4) high rates of groundwater withdrawal that result in declining groundwater levels; 5) surface water diversions, generally for agricultural irrigation; and 6) structures and control devices (e.g., levees) that may interfere with normal interaction between a river and its floodplain. The seventh recognized threat can no longer be classified as strictly anthropogenic or natural. Long-term climate change prior to this century was a natural event that may have caused profound modification of riparian zones. Ongoing climate change—which may be the result of natural or human forces—will continue to affect riparian areas. As yet no one has

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[1] I have no wish to enter the "ungulate debate," but it would be wrong to avoid mention of it. Grazing impacts of nondomesticated herbivores—especially elk—are also recognized (Medina & Rinne, 1999). Nonetheless, one might argue that even these may be essentially anthropogenic in cause. Humans extirpated Merriam's elk, the subspecies endemic to the region, by 1900 (Anderson & Barlow, 1978; Mearns, 1907). The now possibly overabundant Rocky Mountain elk was introduced to Arizona and New Mexico in 1913 (Eldridge, 1955), and humans have "managed" populations of these elk since that time.

devised a means to definitively identify the relative magnitude of climatic and human-caused impacts on riparian systems (Brookes, 1996; Lewin, 1996), but it is undisputed that anthropogenic effects pose a serious threat to many riparian zones in the southwestern U.S.

This study examines one 12-mile reach of the Gila River within the Gila Valley of southwestern New Mexico (Figure 1). The Köppen Climate Classification system defines the area's climate as dry semi-arid (Genootschap voor Geofictie, 1998). The region's climate, vegetation, and history are fairly typical of many that lie within the larger southwestern U.S. In 1846, when Colonel Emory reached this vicinity of the upper Gila during his military survey, he described the river as “narrow, covered with large round pebbles. The growth of trees and weeds was very luxuriant…” Native riparian tree species were typical of such areas in the southwest; Emory described them as “cottonwood, a new sycamore, mezquite.” (Emory, 1848).

Along most of the study reach in 2000, the river channel was wide. Except for an intermittent, narrow band of riparian growth hugging the active channel, its cobble and gravel floodplain for a hundred feet or more on either side of the stream was frequently devoid of all but sparse upland vegetation like catclaw and broom snakeweed (Figures 2 and 3). While a few younger stands of cottonwood were evident, most obvious were enormous and isolated older trees on terraces above the active floodplain. In some reach segments, the channel was composed of large cobbles, slippery with algae; in other segments, sand and silt covered the channel bed to a depth of a foot or more. Active cutbanks of unconsolidated silt and gravel, sometimes ten feet high, lined long stretches of the river. Gordon (1997) documented high rates of both bank erosion and sediment deposition within the Gila Valley, perhaps leading to additional aggradation and widening of the channel in some areas (Hupp, 1992).

The river corridor in the Gila Valley, in other words, appears less than "healthy." But is it? Is the current condition of this reach of the Gila River a function of natural processes operating over the past century, of human perturbations to the system, or of some combination of the two? A series of large floods came through the Gila Valley between 1972 and 1997. The river here has been leveed and bulldozed, and cattle still graze along its banks in some areas. Irrigation diversions have been moved upstream where the river has incised its channel or downstream to accommodate shifts in the channel’s location (Gordon, 1997). Does the river's appearance reflect only one phase of an ongoing transition in response to a natural cycle of moderate and extreme flood events? Or is it a reaction to human impacts that should be corrected through active

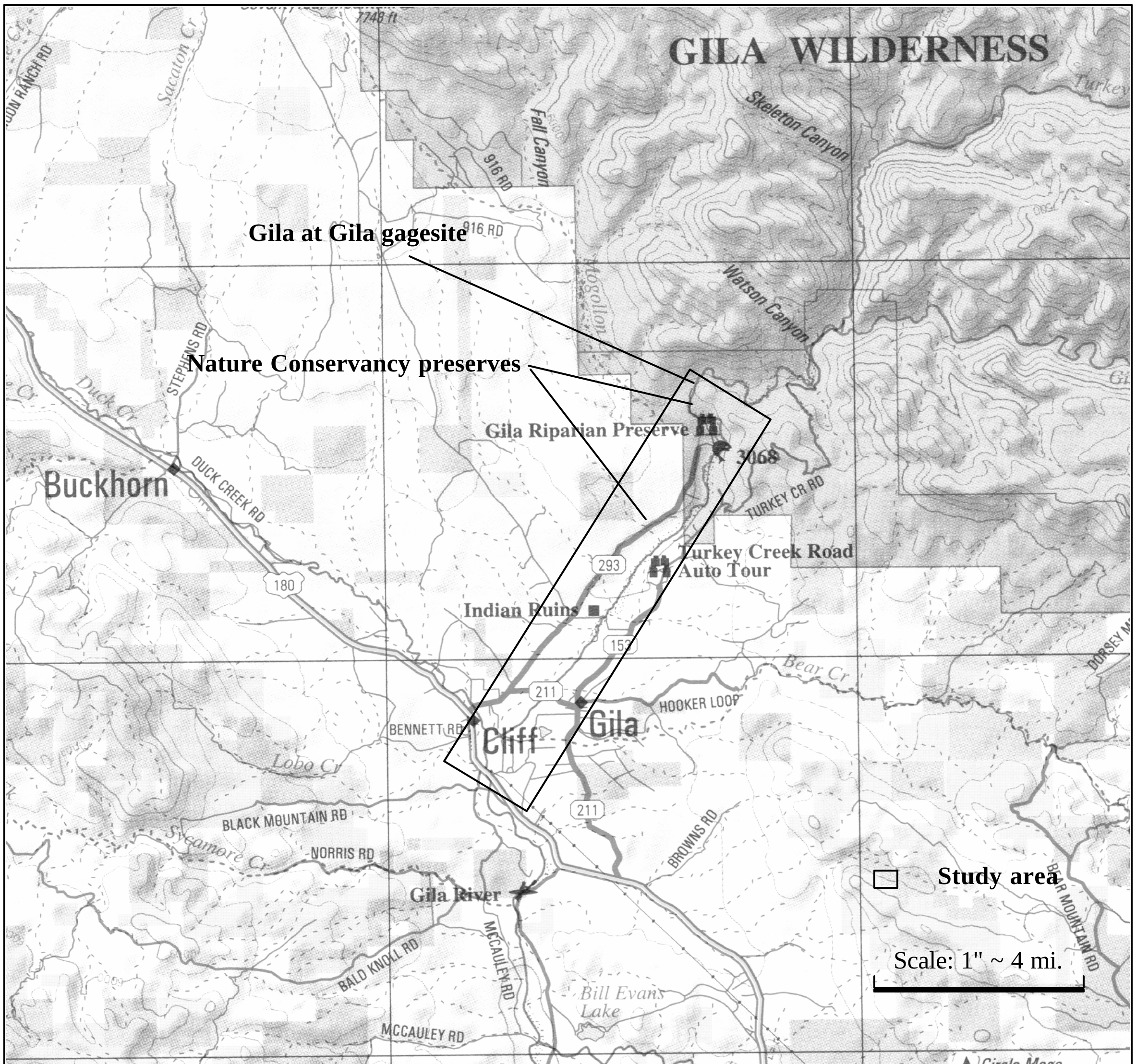



**Figure 1. Location map and general map of study area. Adapted from DeLorme's (1998)** ***New Mexico Atlas.***

**Figure 2. First view of the Gila River near Gila, New Mexico, October 1998.**

**Figure 3. Cutbank at Bear Creek confluence near downstream end of study reach, May 1999.**

"restoration" efforts? If so, what should the river look like after restoration? This last question raises basic issues in the field of environmental restoration, particularly in relation to riparian environments, and some of those are examined below.

**Environmental restoration**

One definition of environmental restoration is to return an area to its pre-disturbance condition. This is problematic along riparian strips within the southwestern U.S. for two reasons: one perceptual, the other temporal. The perceptual difficulty masks the fact that "pre-disturbance" and "desirable" are not necessarily synonymous. "Desirable" condition may be defined by some perceived combination of human aesthetic appeal and habitat availability for riparian-dependent species; in other words, as a clear-flowing stream within a "stable" stream corridor lined by lush riparian vegetation. Turbid water, shifting or downcutting channels, and barren bars or banks become "undesirable." Equating "undesirable" with "disturbed" is only a tempting, but dangerous, step away.

The temporal fallacy is closely related. When current condition—a "snapshot" of the river at a particular moment in time—is misconstrued as a permanent one, our response is often to assume that we must *act* in order to fix a problem. Recognizing the potential fallacy in this line of reasoning, however, only spawns more questions. Over what time frame can one determine the natural *functioning* of such a river system? What *range* of conditions will the system demonstrate over that time frame? Studies of rivers in the Southwest (e.g., Kondolf, 1998) indicate that they are anything but static—even in the absence of major anthropogenic interference. Distinguishing between anthropogenic and climatic influences on river systems in semi-arid regions is difficult, to say the least (Hereford, 1984; Hirsch et al., 1990; Webb and Betancourt, 1992). Baker (2000), discussing ephemeral streams in southwestern alluvial basins, notes that they "have long histories of channel change, incision, and aggradation, operating on time scales of several decades to centuries" (291). Restoration efforts on these rivers sometimes misinterpret "how the river actually behaved… [Understanding their natural functioning condition requires] the use of historical/interpretive sciences to discover the actual operations of natural resource phenomena" (Baker: 2000: 292). Moreover, recognizing pre-Anglo variability in southwestern river systems provides no guarantee that contemporary change occurs within a system's natural limits. Flournoy (2000) elaborates:

> [If] there is no single moment of origin, or at least not one on which we have information, what then? (189). We cannot…recreate some single mythic ideal state of a given natural system. [Rather] we must judge what attributes of the ecosystem to restore and then identify the processes and functions that would enable the ecosystem to continue to *evolve* with those attributes (195). [emphasis mine]

And this brings us back to the problem of correctly defining which "attributes of the ecosystem" are in need of "restoration." This is a nearly chimerical business, as the statements above indicate. The situation is frustrating. The need to protect or restore habitat for threatened species whose survival may depend on our efforts imposes stern time limits on such efforts. Yet realistic evaluation of "success" will occur only over time. Evaluation must take into account three different factors: 1) what is recognized as known, 2) what is recognized as unknown, and 3) what is *unrecognized* as unknown. Only a combination of intensive study, careful experimentation, and rigorous monitoring of results will enlighten us on the last factor and provide a reliable assessment of a river system's natural variability or the impact of restoration efforts imposed on it (Richards et al., 1996). Flournoy (2000) may understate the situation when she says that "the problem of evaluating 'success' in restoration remains a major theoretical and practical challenge" (193).

For the Gila River, two more complications in attempting to evaluate the necessity of restoration efforts must be taken into account as well.

1) Human-caused effects on current condition in any watershed vary in scale. The impacts may be watershed-wide, like grazing and logging intensities, or more localized, as in the case of channelization works. The restoration strategy applicable to a given situation will vary depending on the impact(s) deemed responsible. For example, channel scour can result from increased flood intensities due to highly concentrated surface runoff from a watershed whose vegetative cover has been lost. Efforts aimed at restoring vegetation within the watershed would be more likely called for in this situation than in-channel modifications (Gillilan, 1996). Conversely, in-channel restoration may be appropriate to localized impacts such as dikes or levees. Major in-channel restoration is typically aimed at dissipating stream energy and reconnecting the channel to its floodplains. Such work often requires massive earth-moving efforts to modify the channel's shape and planform and to reduce the height of vertical banks relative to the active channel. Channel restoration efforts for the Gila River have been proposed (Wittler, 1997). Results from the current study's examination of the potential effects of

modifications to the river corridor within the Gila Valley may shed some light on their advisability, but evaluation of watershed-wide effects was beyond the scope of this study.

2) Another complication in evaluating the need for restoration on the Gila River lies in the valley's use for agriculture. The Gila Valley is not a protected area in which functioning of natural ecosystem can be observed (Arcese & Sinclair, 1997). Or, more aptly perhaps, the valley's ecosystem is one in which humans do and will continue to play a very direct role. Since this is generally true for more ecosystems than not, work that attempts to incorporate the human element into ecosystem management or restoration is common (e.g., Johnson, 1998; Propst & Culp, 2000.) The reality of such situations is summarized by Baker's (2000) observation on "environmental pragmatism," which requires that

> one not perceive the natural community as an objective system, isolated from humanity, and specified in advance in terms of its temporal and spatial scales. The attributes of nature are to be discovered for each specific circumstance. People are to be involved in the natural community, and the interpretative science of that community should influence the thought of its human members…This is actually a much broader notion of "experiment" than that applied in mathematical/predictive physical sciences (294-295).

**Interest groups**

Baker (2000) might have been describing the Gila Valley, where the natural community—although very much in evidence—is anything but isolated from humanity. This study was initially prompted by a desire expressed by The Nature Conservancy (TNC)—and other organizations or agencies (e.g., Natural Resources Conservation Service [NRCS], 1998; Upper Gila Watershed Alliance, 1998; USDA Forest Service, 1996)—to understand the effects of human activities on the Gila River. As the study progressed, however, it became more useful to consider the humans who share the river's valley, and the changes they have imposed on it, along a sort of continuum. The spectrum of interest groups associated with the Gila River ranges from what might be called *conservers* to those who could be labeled *users*. In such a deliberately oversimplified version of reality, conservers, occupying one extremity of the continuum, can be identified as those who believe that:

- Channelization efforts and irrigation diversions are "bad." Levees isolate the river from its floodplain and promote channel incision; the diversions rob the river channel of water needed to support the riparian ecosystem.
- Riparian vegetation is not only "good," but essential, as habitat for other species.
- Users don't care about the river or riparian habitat but only about their own needs.

At the other extreme, users might be said to believe that:

- Channelization efforts and diversions are "good." Levees protect their fields from erosion during floods; diversions are essential to their livelihood and provide barely enough water for irrigation as it is.
- Riparian vegetation is "bad"; it utilizes water that could otherwise be applied to fields, and field erosion during floods is exacerbated when floodwaters are "pinned" between fields and vegetation on floodplains.
- Conservers don't care about humans but only about other species.

Of course, in reality, Gila Valley residents and others interested in the river range all over the spectrum. For example, some users who may bristle at the idea of using irrigation water to maintain flow in the river also think that returning riparian vegetation to the floodplains is a good idea. But this sort of “us versus them” model is useful because it helps to illuminate some of the preconceived notions that those at the far ends of the conserver–user continuum tend to have about the river. These notions delineated some of the questions that were addressed during the course of this project. For instance, is it true that the diversions actually inhibit riparian reestablishment? Would rebuilding the levees really protect fields from additional erosion? Does vegetation actually exacerbate field erosion during big floods?

This work sets out to construct a framework for understanding both the effects of previous impacts and their likely implications for future condition on the Gila River, and this forced me to confront two significant issues in the project and its design. The first stems from the dilemmas inherent to the definition of environmental restoration, as described earlier. The second, related issue concerns the difficulty of extracting meaningful information from a study that attempts to grapple with anything so intricate as the river/riparian complex, much less to differentiate between its natural and anthropogenic components. The approach adopted for the study resulted from my attitudes about these issues, and their influence on the general objectives for this research is set forth next. More detailed examination of their implications appears in the Discussion section.

**Study approach and objectives**

This study sought to discriminate between the results of selected anthropogenic and natural factors operating within the Gila Valley riparian corridor during the past century. Both factors functioned simultaneously, and each was capable of creating a feedback mechanism that would serve to magnify the effects of the other. Flood effects on unvegetated levee surfaces, for example, will probably differ from those on vegetated floodplains. Furthermore, watershed-wide impacts—grazing or logging intensities, for instance—also acted as confounding variables. Such interactions make it difficult to even identify every significant variable influencing current and historic conditions on the Gila River; measuring them all was clearly impossible. Therefore, while selected variables were identified and measured for the study, these data formed only part of the larger study design, which also incorporated subjective anecdotal information, archival research, and personal observation.

The interpretation of combined quantitative and qualitative data in the present research suggested a study design based on what Jacob (1989) calls an "orienting theory," an approach that begins less with a specific hypothesis than with a general concept to be tested against all the data available. The theory behind this study is bifaceted: one section focuses on current condition of the river, and the second on probable future condition. The first half proposes that current condition on the Gila results from some combination of anthropogenic modification and natural processes and can therefore be understood only in light of the river's geologic and geomorphic context, and its known hydrologic and social history over the past 100 years or so. Three study objectives are aimed at distinguishing between the results of natural and anthropogenic factors on current river condition:

- Evaluate valley geomorphology, change in the river corridor, and the river's historic flood regime prior to channelization efforts (ca. 1880 to 1950) for evidence of riparian and stream channel response to floods during the period.
- For selected periods after channelization (ca. 1950), document channelization efforts, construct flood hydrographs, map channel planform shifts, and quantify changes in unvegetated bar and floodplain area.

- Evaluate changes in planform and vegetation with respect to channelization work and flooding, particularly similar-magnitude floods occurring before and after channelization.

The second half of the theory proposes that probable future condition will largely depend on patterns of riparian regeneration. Regeneration patterns are influenced by current condition, including constructed modifications to the river channel. Their future development will depend on flood regime, an unpredictable variable, and subsurface water availability, a (somewhat) more quantifiable one—yet one still subject to future human modification. Predictions of future condition in the riparian corridor are the focus of three study objectives:

- Examine diversion impacts on river base flow regime by comparing historic streamflow data from a point immediately upstream of the valley with data representative of a point immediately downstream of irrigation diversions.
- Identify relationships between surface water and groundwater elevations at various locations within the undiverted portion of the study reach.
- Evaluate these relationships for causes of variance in groundwater gradient and flow rates that may significantly affect spatial distribution of future vegetation.

Descriptions of the study methods follow the next two sections, which summarize selected work conducted by previous researchers in the Gila Valley and place the current research within the region's geographic and historical context. Earlier studies provided background information useful for the current research. However, none has documented temporal correspondence between impacts imposed on the river corridor, both natural and anthropogenic, and condition of the river and riparian area.

**Previous studies in the Gila Valley**

Federal agencies have conducted extensive work in the valley. The US Forest Service (USFS) included the valley in an early report on *Forest Conditions in the Gila River Forest Reserve, New Mexico* (Rixon, 1905). The Soil Conservation Service, concerned over loss of farmland and silting of San Carlos Reservoir, conducted detailed research on the Gila River in the Gila Valley (USDA Soil Conservation Service [SCS] 1936; 1954). The Hooker Dam project generated a topographic survey of the river valley (US Geological Survey [USGS], 1948: 70) and innumerable reports (e.g., Hoppe, 1981; Peterson, 1986; USDI Bureau of Reclamation, 1930, 1982, 1984, 1987). The USFS produced a *Multiple Use Impact Survey Report* on the proposed Hooker reservoir (1968). In 1979 the US Army Corps of Engineers (COE) examined the economic benefit and environmental impact of repair work on Gila Valley levees that were originally constructed around the early 1950s (US Army COE, March 1979; April 1979). Donegon (1997) reviewed the status of the same leveed areas after flooding in 1983–1984. The US Fish and Wildlife Service (USFWS) conducted numerous reviews related to proposed levee construction and rehabilitation (e.g., Pacific/Souder, 1979; Silver City Daily Press, 1979; Spiller, 1992).

More recently, Gordon (1997) examined options for irrigation diversion after a series of major flood events in the valley caused repeated failure of a major irrigation diversion berm. NRCS (1998) conducted a "Rosgen-based" river morphology study in the Gila Valley and briefly reported its findings based on surveys of 19 cross-sections of the river channel. A study of riparian vegetation communities throughout New Mexico, conducted by the University of New Mexico (Durkin et al., 1996) inventoried and classified vegetation and channel condition at the Hooker damsite, Gila/Mogollon confluence, and within the Gila Valley. Brock (1985) evaluated riparian soil characteristics near Mogollon Creek. The Bureau of Reclamation returned to the valley in 1997 to study the feasibility of bank stabilization efforts to protect farmland (Wittler, 1997). The Gila Valley supports a large population of the endangered southwestern willow flycatcher, prompting a number of ongoing studies (e.g., Parker, 1997; cited in Stoleson, 1998). The New Mexico State Engineer's Office has conducted annual hydrographic surveys of the Gila Valley since 1964 in order to calculate water use in the area (e.g. Wilson, 1998). Land ownership, crop production, and water rights are documented as part of each year's survey.

## GEOGRAPHIC AND HISTORIC CONTEXT

### The Gila River

In western New Mexico, the Gila River gathers itself from springs that trickle through the high elevations of the Mogollon and Black mountains, around 10,000 feet. Water from the springs and melted snow meets in mountain streams with names like Turkeyfeather, Iron, Snow, Diamond, Clear, and Willow, which in turn coalesce at lower elevations—around 6000 to 7000 feet—into the three forks of the Gila River (USGS, 1923). An opened left palm placed over a map of the area will outline the forks' paths: the West and Middle Forks, stemming from the Mogollon Mountains, flow respectively beneath the little and ring fingers. Beneath the thumb, the East Fork winds its way from the Black Mountains in the northeast. The three join at the thumb's base, just south of the Catron/Grant counties boundary and the Gila Cliff Dwellings National Monument. The river runs southwest another 12 miles, or so, before turning abruptly west at its confluence with Sapillo Creek. Flowing mostly within steep canyon walls, the Gila reaches its confluence with Turkey Creek about ten miles downstream (Figure 1).

For most of a century the human presence has been relatively benign on these upper stretches of the Gila. The landscape through which it flows was designated a Forest Reserve in 1899, and became the country's first National Wilderness area in 1930 (Tellman, Yarde, & Wallace, 1997). In spite of grazing allotments and recreational use, the river is generally clear and an abundance of riparian vegetation inhabits its floodplains in the Gila Wilderness (Figure 4); (Durkin et al.,1996: 118).

Designated wilderness ends about a mile upstream of Turkey Creek, but the river remains on National Forest land for another four miles or so. Still contained between high canyon walls, the Gila leaves the Forest Reserve at a tortuous, nearly 90° turn to the south, nine miles upstream of the town of Gila. Bolted to the canyon wall at the turn is a USGS water-stage recorder gaging station, designated the "Gila" gagesite, No. 09430500 (Figure 5). A nearly continuous record of discharge has been collected at or near this gagesite since 1928. Elevation at the gagesite is 4655 feet above sea level, and its watershed at this point encompasses 1864 mile$^2$ (USGS, 2003). The US Forest Service (1968) characterized the watershed vegetation as roughly 1/3 pinyon, 1/3 pinyon–juniper, and 1/3 grass and brush lands, with blue grama the most common range grass.

**Figure 4. Gila River in Gila National Forest upstream of the study reach, April 2000.**

The river is perennial at the gagesite, where low flow during the drier months is generally around 40 to 50 cubic feet per second (cfs).

Leaving its canyon, the river's next 14 miles carry it through a slightly wider alluvial valley. Just below the gagesite, the river enters the Gila Riparian Preserve, a property managed by TNC of New Mexico that extends along this "box" of the river for more than a mile. Downstream the river crosses another mile of National Forest land before entering a hodgepodge of private and TNC-owned lands in the Gila Valley proper, and flowing past the tiny towns of Gila, Cliff, and Riverside. The Gila Valley is relatively small: less than two miles across at its widest point, and about 14 miles long. Large-scale agriculture has never been practiced here. But the small irrigation diversions that supply its farmers and ranchers with water for their fields are among the upstream-most on the mainstem Gila River.

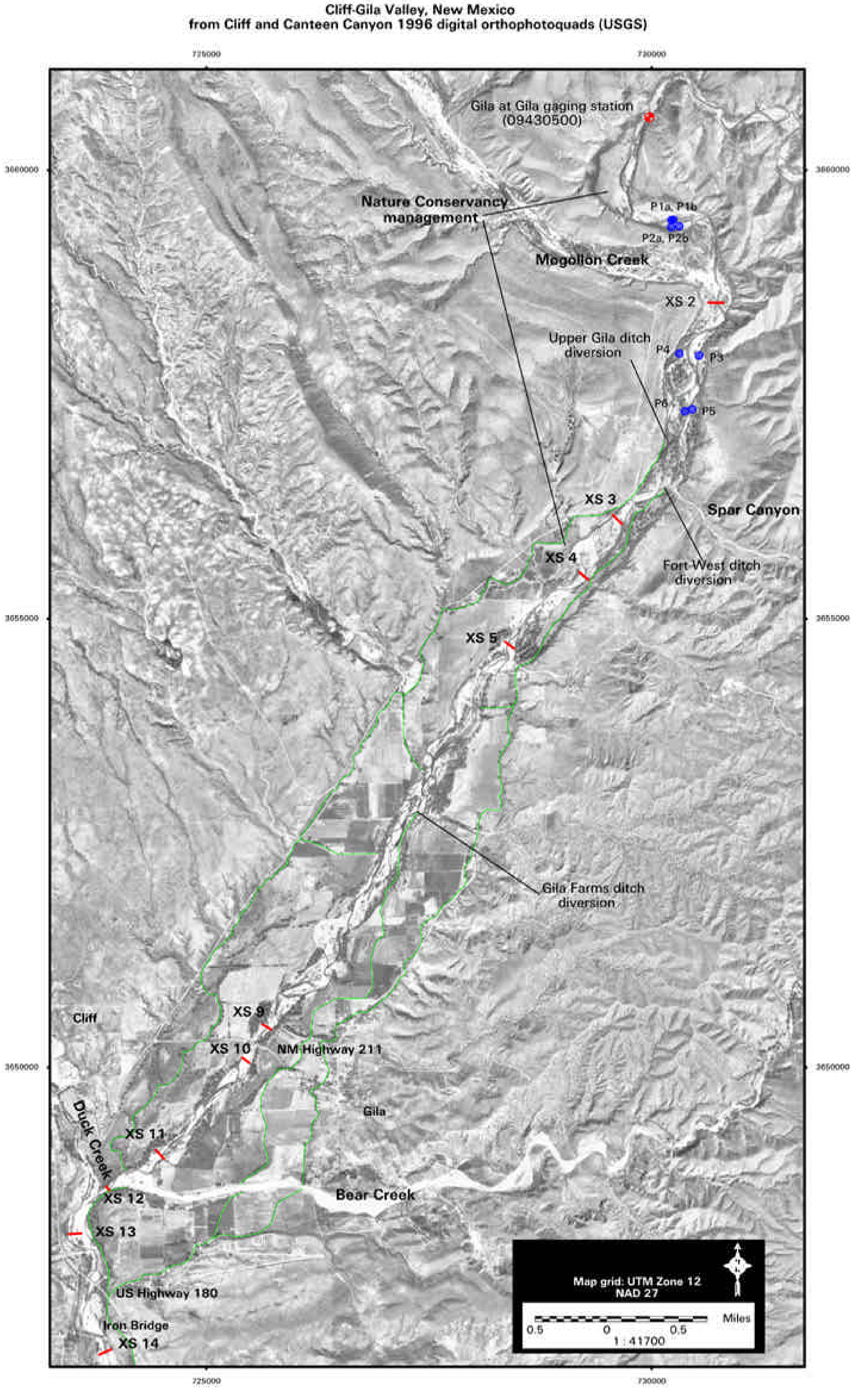


Figure 5. Map of study reach, major tributaries and diversions, and data collection sites.

**The Gila Valley**

Cliff, Gila, and Riverside appeared at a relatively late date, even in the short Anglo history of the American southwest. They owe their existence to the river and its valley—and to the silver and copper mining industries that this region of New Mexico supports. Silver City lies 30 miles to the east, and the open pit of the Santa Rita copper mine, mined sporadically through the early 19th century and in earnest thereafter, gapes among the hills a few miles farther away. Mogollon, a silver mining town high in the mountains of the same name, is about 50 miles to the north.

One of the earlier descriptions of the Gila Valley comes from Conner's (1956) account of his 1863 travels across New Mexico and Arizona. Conner makes note of both the river's small floodplain in the valley and of a very dry year:

> …all [the landscape around Fort West was] covered with a fair growth of grama grass... A few scattering clumps of scrubby oaks marked the ravines and hillsides while perhaps enough cottonwood trees to indicate the direction of Gila grew upon its banks, for there was but little bottom land on this river so high up. I will venture to assert that the Gila is the longest river of its size in the world and that it drains more country than any other stream of its width and depth and yet it has time to go dry in places (45).

In 1868, a group of Missouri immigrants tried to establish a farm in the Gila Valley, near what would become Cliff, but "Apaches had run off every hoof of stock and left [them] hopeless and on the border of destitution" within six months (Calvin, 1946: 79). Mormon settlers brought farming to the valley again a few years later, and the Fort West ditch, one of three major ditches in the valley, was built in 1875 (Stailey, personal communication, March 18, 2000). Infamous figure Tom Lyons established an enormous ranch, the L-C, sometime during the 1880s, pioneering a number of other irrigation efforts in the process (Calvin, 1946). Still, the Cliff post office was not established until 1894 (*Silver City Enterprise*, 1894) and construction of a Town Hall took another 16 years (*Silver City Enterprise*, 1910). Around 1890, it was a local farmer who opened the first grocery in Cliff, to serve the supply wagons that traveled between Mogollon and Silver City (Calvin, 1946: 114). The grocer also ran the only ferry across the Gila River in the region. No local bridge spanned the river in the area until 1915 (*Mogollon Mines*, 1916) when Iron Bridge, just south of Cliff, was constructed (Figure 6).

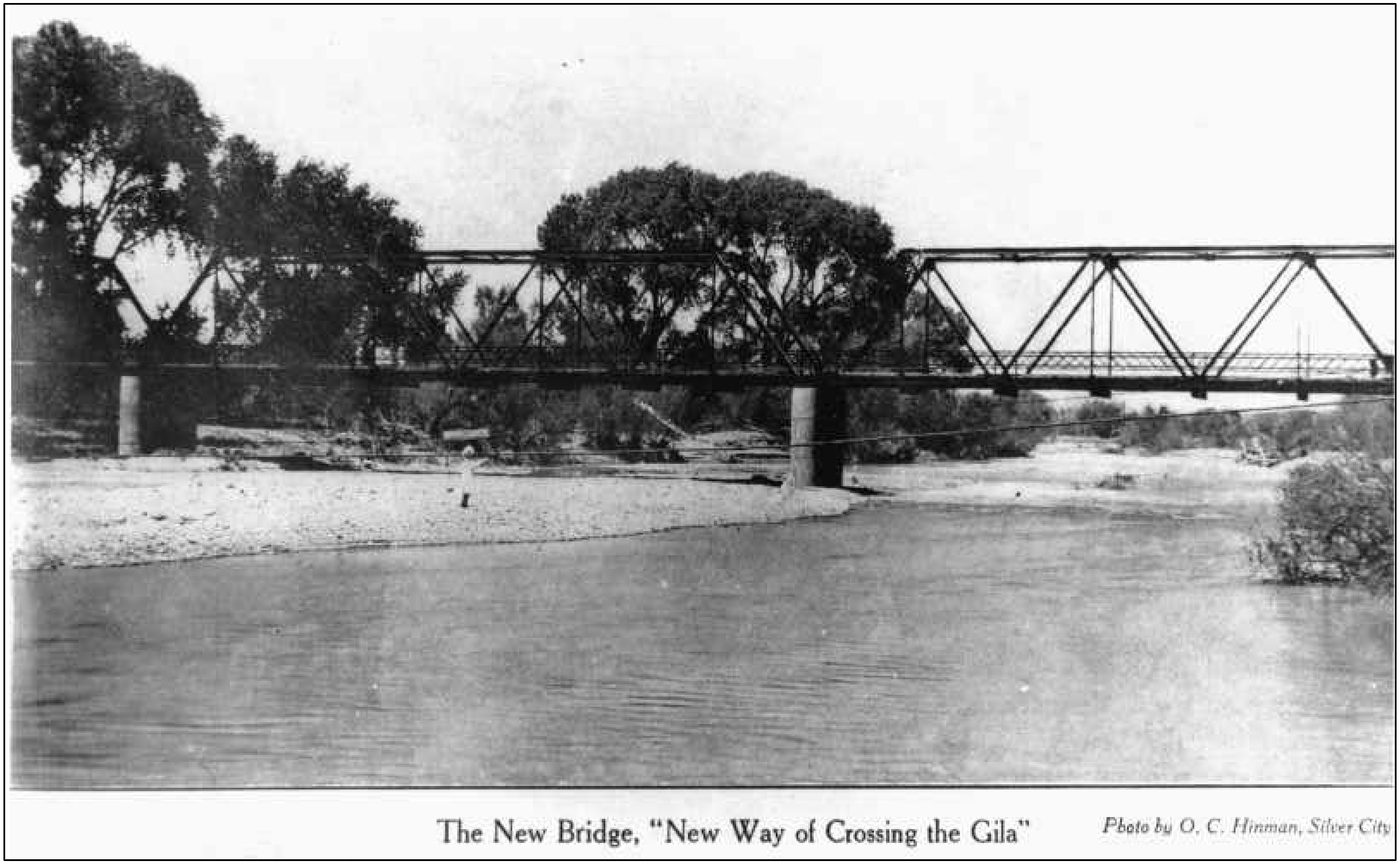


**Figure 6. Iron Bridge near Cliff, shortly after construction in 1915. Courtesy Silver City Museum.**

In 1905, the USFS (Rixon, 1905) noted that "grazing [is] the most important of the industries of the region" and that a few farming settlements existed along Gila River, "where the "main crops raised are alfalfa and corn" (13). Livestock grazing peaked in the Gila watershed in the 1880s (USDA SCS, 1954). Black (1927), investigating irrigation possibilities in the valley, noted that 2900 acres were already being irrigated to produce "corn, alfalfa, garden truck, melons, and deciduous fruits" (9). He concluded that another 12,000 acres on terraces above the river could be brought under irrigation through construction of a reservoir and pumping stations, but nothing came of this proposal. A few years later, USDI Bureau of Reclamation (BOR; 1930) reported that

> approximately 3,500 acres of the bottom lands of this valley which can be irrigated by direct diversion without expensive headworks or canals, are under cultivation, largely in the upper part of the valley. The lower end of the valley is unfavorably affected by the meandering river channel which makes maintenance of diversions difficult and the contracted valley outlet [at the Duck Creek confluence] which causes frequent flooding of the lower lands (6).

In 1954, the SCS investigated erosion in the Gila River watershed and estimated that 73 percent of the total watershed was affected by moderate to severe erosion. They concluded that "before accelerated erosion became widespread…a grass cover supported by runoff from higher areas protected the surface soils and created optimum infiltration conditions" (4). In the Gila valley, irrigated acreage had increased to about 4300 acres, mostly in small farms of 30 to 60 acres producing corn, alfalfa, and grain (Figure 5). By 1959, the Grant Soil Conservation District reported that about 88 percent of the Gila Valley watershed was rangeland and that "range and hydrologic conditions are poor" (4). Irrigated crops occupied about 3200 acres: about 60 percent alfalfa or irrigated pasture, and about 40 percent in small grains, corn, and grain sorghums.

## **Levees and check dams**

Complicating the geomorphic picture in the Gila Valley is a history of channelization projects probably dating back 50 years. Channelizing a river corridor typically creates an increase in the stream's local gradient, increasing sediment transport capacity within the channelized reach. As a consequence, upstream reaches progressively degrade, while aggradation occurs downstream where transport capacity is less (Hirsch et al., 1990; Leopold & Maddock, 1953; Schumm, 1999).

In the late 1940s, the Soil Conservation Service engaged in straightening and diking a few reaches of the Gila River within the Gila Valley (interview, April 2000). The US Army COE rebuilt old levees and added new ones throughout the Gila Valley in 1979, after a major flood in December 1978 (Donegon, 1997). Donegon's review of the project notes that "it is generally believed that the [original] levees were constructed in the late 1930s…to protect privately owned property" (2). The COE was required to provide cost-benefit analyses to justify expenditures for the levee replacements. Donegon (1997) states that "it is apparent that much effort was expended to arrive at cost-benefit ratios," and suggests that the imposed financial constraints, plus the requirement of *repairing* "in kind," rather than *improving* the structures, resulted in "less than adequate design" (3). The levees, in Donegon's phrase, were "effectively destroyed" by floods in 1983 and 1984 (4). Yet significant remnants still exist. They continue to focus the energy of moderate floods (< 5000 cfs) within the channel, to isolate parts of the floodplain from the river, and perhaps to enhance aggradation in downstream reaches. There are those in the Gila Valley, nonetheless, who would like to see the levees rebuilt and channelization efforts reinstated. The levees, they believe, protect pastures, fields, and bridges from moderate flood events. A commonly held belief in the valley is that rechannelizing the river "would move the water on through the valley," rather than allowing it to overtop floodplains and damage cultivated fields and pastures (interviews, April 2000).

Damage to cultivated fields from flooding in tributary drainages also convinced the Grant Soil Conservation District (1959) to design and provide funding assistance for the construction of 12 sediment control dams in the valley. The check dams were completed by 1965 and prevent sediment from all but one of the major drainages in the farmed valley areas from reaching the river or its floodplains.

**Land ownership and water rights**

Since the late 1950s, Phelps Dodge Corporation (PD) has been by far the largest land and water rights owner in the Gila Valley. Phelps Dodge owns a copper mine at Tyrone, New Mexico, about 30 miles southeast of Gila. Operating as Pacific Western Land Company, the corporation bought land—and the attached water rights, many of which hold priority dates as early as any in the valley—from many, if not most, of the small landowners there (interview, April 2000).

Opinion in the valley about the company's purchases of water rights varies, but at least one resident recalled that locals had their "suspicions" about the buyouts, long before it became known that Phelps Dodge was behind the purchases (interview, February 2001). Some valley residents believe that they were a godsend for cash-strapped farmers. This may well be true; one person (interview, February 2001) remembered that PD paid about $700–$900 per acre for their land and water rights purchases in the 1950s-1960s, and Reisner (1990) notes that water rights in the Gila-San Francisco basin were selling for $3000 per acre-foot by the 1970s. Phelps Dodge built a diversion and pumping station on the river downstream of the valley. On the top of a hill nearby, they built Bill Evans Lake. Water was pumped to the reservoir for storage and eventually piped downhill to Tyrone for mining operations.

Land use patterns within the valley apparently changed after the PD acquisitions. Nine of the residents interviewed for this study recall that before the PD buyouts, fields of corn and beans far outnumbered those of alfalfa in the valley (interviews April 2000 and February 2001). Major land owners frequently leased parts of their land to tenant farmers or sharecroppers who grew corn during the 1930s and 1940s (interview, February 2001). Corn and bean fields are said to have gone fallow or into pasturage during the 1960s and 1970s (interview, April 2000). Phelps Dodge, however, no longer uses the water it acquired here to operate the Tyrone mine (interview, April 2000). In order to retain water rights, it has leased many of its Gila Valley holdings to a local rancher for grazing and pasturage. The water irrigates his pastures and alfalfa fields (interview, July 1999).

Somewhat ironically, one of the greatest threats to the Gila River could turn out to be water use in Silver City, about 30 miles away from the Gila Valley and just outside the river's watershed. (Silver City is in the Mimbres River watershed.) Export of water beyond its watershed of origin is a murky and unsettled issue in New Mexico. Exxon Corporation owns about 1150 acres of water rights in the Gila River basin and contracted to sell them to Silver City in 1998 (Fridinger, 2002; Runyan 2002). The State Engineer's office of New Mexico oversees water rights and calculates the rights per acre based on the amount of water required to irrigate each acre in an "average" year. In the Gila Valley, an acre of water is currently calculated as 2.9 acre-feet per year. Therefore, Exxon's rights amount to over 3300 acre-feet annually: nearly 144,000,000 cubic feet per year, equivalent to about 4.5 cfs of streamflow. Although surface flow in the river is fully apportioned—Exxon would not be allowed to divert water directly from the river—withdrawal of this amount of water from the regional aquifer could impact streamflow in the river. No complete study of the connections between the aquifer and surface flow in the Gila River exists. USDI Bureau of Reclamation (1987) estimated that the "available groundwater supply" of the towns of central Grant County—mainly Silver City—would be insufficient to meet their needs by sometime between 2010 and 2018. For the time being, the State Engineer's office has ruled that Exxon be allowed to transfer 102 acres of its water right to Silver City. The fate of the remaining water right is unsettled due to complexities in the corporation's historic use of its water (Fridinger, 2003).

**Hooker Damsite**

The Gila Valley is no stranger to controversy over the river and its use. Political and legal wrangling among the southwestern states over the waters of the Colorado River are legend (Clark, 1987; Fradkin, 1968). As the Colorado's most downstream tributary, the Gila, too, has been the object of jealous scrutiny. In addition to the gage on the mainstem Gila north of the Gila Valley, USGS also maintains gages on two of the major irrigation ditches within the valley. These gages, more than 500 miles upstream of the Gila's confluence with the Colorado River, are legacies of the awkward lengths to which humans will go to fit the river's nature to political boundaries. They were installed in the 1960s as part of a monitoring system designed to confirm usage of the river supply within New Mexico. Like other western states, Arizona and New Mexico adhere to the law of prior appropriation in distributing water rights (Gillilan & Brown, 1997; Nelson, Horak, & Solomon, 1978). The "Rifkind Decree" of 1960 aimed to establish, once and for all, the amount of Gila River water to which New Mexico is historically entitled. Confirming usage was an effort to resolve dispute between Arizona and New Mexico over rights to Gila River water. The infamous Hooker Dam proposal was another.

Hooker Dam was slated for a site immediately upstream of the Gila's confluence with Mogollon Creek, at the current gagesite (Figure 1). It was named for a current resident's grandfather, Frank Hooker, who farmed the terraces near the damsite (D. Hooker, personal communication, February 9, 2001). The damsite was originally considered as a power production site as early as 1916, and as a major storage area for irrigation in 1927 (Black, 1927). Dam construction at the site was reproposed after a COE irrigation and flood control study of the Gila River in 1938 (Clark, 1987), and officially authorized as part of the Colorado River Basin Project

Act in 1968 (Reisner, 1986). Hooker Dam would have created an impoundment reservoir to store up to 18,000 acre-feet of water for New Mexico; downstream users in Arizona would have been "reimbursed" with Central Arizona Project water (USDI Bureau of Reclamation, 1987). Water impounded by Hooker Dam, however, would have backed up into the Gila Wilderness. It was essentially this fact that led to the eventual demise of the proposal (Fradkin, 1968). The dam's defeat—and the later defeat of a proposal to store the Gila's waters farther downstream at the Connor damsite, near Red Rock, New Mexico—meant that New Mexico has been allowed to use no greater share of the Gila's waters than it could prove had traditionally been used within the state. The remainder must be passed on to Arizona (Resource Technology, Inc., 1991). In the Cliff/Gila area, residents must continue to rely on the river's sometimes small flows (typically around 40 cfs during dry months) to supply irrigation water, supplemented by shallow groundwater wells (Wilson, 1998). More importantly, for some, the death of the dam proposal seemed to seal the valley's fate as a small agricultural and ranching area. Larger-scale development is impossible without greater water supply.

**The Gila Valley and the river: 1999**

In 1999, the Gila Valley was still sparsely settled, dotted with farmhouses and adobe barns. The valley's population was less than 200 (U.S. Census Bureau, 2003). There are local schools, a grocery store, one gas station, and two restaurants among the three towns of Cliff, Gila, and Riverside. Iron Bridge is closed to vehicular traffic, and a newer bridge on Highway 180, the only paved road between the towns to the north and Silver City, now spans the river.

From the gagesite downstream through the valley and past Iron Bridge, the river flows through wide cobble floodplains or between six-to-eight foot cutbanks of silt and sand. Levee remnants are sometimes evident, forming five-foot high cobble and gravel berms next to the active channel. In many reaches, virtually nothing except clover grows next to the active channel, while broomweed, rabbit brush, and ragweed provide sparse vegetation on higher floodplain surfaces and terraces. Enormous, isolated cottonwoods perch on high sandy terraces eight to ten feet above the active channel. Discharge at the time of initial site visits was less than 100 cfs, and typically occupied only one channel. However, swales and depressions marking the courses of abandoned or overflow channels created an extensive mosaic across floodplains, and "stringers" of younger riparian trees, especially cottonwoods of up to about 5 inches in diameter, had colonized some of these. Ten cross-sections were surveyed as part of the study (see Methods, below), and photographs of selected cross-sections taken in 1999 appear in Figures 7 through 14. For reference, cross-section locations appear in Figure 5.

**Figure 7. Looking upstream at cross-section 2 location, May 1999.**

**Figure 8. Looking upstream at cross-section 3 location, March 1999. Upper Gila ditch is approximately 10 feet above water surface upstream of large cottonwoods on left side of photo.**

**Figure 9. Looking upstream and across channel at cross-section 4 location, May 1999.**

**Figure 10. Looking upstream at cross-section 5 location, May 1999. Remnant levee visible in front of large cottonwoods on left side of photo.**

**Figure 11. Looking downstream toward cross-section 10 from Highway 211 bridge, March 1999.**

**Figure 12. Looking downstream at cross-section 12 location toward Duck Creek confluence, May 1999.**

**Figure 13. Looking downstream toward cross-section 13 and remnant levee, March 1999.**

**Figure 14. Looking upstream toward eastern end of Iron Bridge at cross-section 14 location, May 1999.**

## METHODS

Data for the study, covering the period from about 1880 through 2000, were collected from a number of sources. Anecdotal and archival accounts provided evidence of early flooding; gaging station records available for part of the study period were also obtained. Archival information and interviews with local residents provided descriptions of varying conditions on the Gila River throughout the period studied. Changing conditions within the riparian corridor for the period 1935 to 1997 were also evaluated by photogrammetric and topographic survey methods. Field observation during site visits generated a substantial amount of information ultimately used in the evaluation of current condition. Effects of current condition on potential future condition were assessed by analysis of diversion effects on stream baseflow and by evaluation of existing topography and relative ground- and surface water elevations. Data collection and analysis methods are detailed below.

### Archival research and interviews

Evidence of flood impacts on resulting Gila River condition prior to construction of levees and check dams may indicate whether or not flooding alone is capable of creating conditions similar to those currently in evidence on the river. Historic records dating to about 1880 are available. Accordingly, the methods adopted for understanding the effects of previous impacts on current river condition can be roughly divided into those aimed at characterizing floods and the riparian corridor prior to channelization and flood control efforts (ca. 1880 to 1950) and after (ca. 1950 to 1997). Archival documents and interviews with valley residents supplied most of the data available for the earlier period.

***Flood evidence.*** The period between 1880 and 1950 can be subdivided further, based on the availability of streamgage records for reconstructing the river's local flood history. The Gila gage site near Mogollon Creek began operation in 1928, and only scattered gage records from other nearby sites are available prior to this date. Therefore, archival and anecdotal data provide most of the evidence for floods for the period ca. 1880 to 1930; records held by some Gila Valley residents were especially useful.

***Condition of river corridor.*** Archival research for historic maps, photographs, and studies pertaining to the Gila Valley located a number of documents that were useful in deciphering the river's history during the past 100 years. Of special interest were documents providing evidence of floodplain scour or lateral channel erosion and removal of riparian vegetation. Most of these were found at the State Engineer's office in Santa Fe, New Mexico, Special Collections at the University of New Mexico, Western New Mexico University Library, or the Silver City Museum. Selected issues of the New Mexico State Engineer's Office annual hydrographic surveys of the Gila Valley, published since 1964, and the original 1964 base maps on which later reports were based, were collected (e.g., Wilson, 1998). Updated 1998 maps prepared by the State Engineer's office were also obtained, along with related reports (e.g., Brown et al., 1992). Public land surveys from around 1890 were located at the Grant County courthouse in Silver City. Each archive possessed scattered historical accounts of landscape condition, regional mining and ranching activities, and flooding, and these were also collected.

Change in the Gila Valley river corridor during the past century is partly the story of the interaction between its residents and their environment. Valley residents therefore seemed to be likely sources of information about the river. Lindsay (1997: 35) observes that "individuals are among the most important sources of information available to human geographers," and the value of anecdotal description has been long established in hydrologic research (e.g., Aldridge, 1970; Melis et al., 1996; Rowlands et al., 1995). Therefore, interviews with sixteen Gila Valley residents were conducted in 2000 and 2001. Interview data provided details of the interaction between the valley's residents and their environment that were available nowhere else, substantiating Lamb and Lord's (1992) claim that effective research into the riparian–human interface must incorporate some understanding of public perception of the river system. Interviews conducted for this work sought descriptive accounts of the river and floodplain during the past century, dates and details of levee or checkdam construction, and changes in land use.

Interviewees included landowners on whose property field work was conducted during the 15 months of site visits, and valley residents identified as particularly knowledgeable on river issues, including officials of the three major ditch groups in the valley. Frequently individuals who participated in early interviews suggested the names of others they thought might have particular information, eventually resulting in a "tree" of potential interviewees. In general, I sought interviews with older residents, in order to obtain data related to the era prior to levee construction, and with those residents who seemed to support channelization and erosion control efforts. As a general rule, these residents tend to be those most likely to depend directly on the river for their livelihoods. The deliberately biased selection was aimed at gathering evidence from those who have the greatest investment—both psychological and financial—in channelization work. I reasoned that they would be most likely, for instance, to inspect the levees for damage subsequent to flooding; as a consequence they might be able to offer evidence of situations in which the levees did serve to protect fields. I also sought to understand the basis for the belief held by many irrigators that riparian vegetation exacerbates lateral erosion beyond the floodplain into fields. In addition, irrigators were the best source of information for understanding the pattern of diversions, ditches, and tailwater points (where irrigation water is returned to the river channel) within the Gila Valley. This information provided insight into the complex interaction between the anthropogenic and natural hydrologic regimes within the valley. It provided a valuable framework for organizing subsequent analysis of the aerial photo series, and significantly shaped the eventual conclusions drawn in the study. The information received in interviews also helped to fill gaps in the aerial photography series. For example, information about the effects of a major flood in 1978 helped in reconstructing events between the two sets of aerial photographs taken in 1974 and 1980.

The interviews were relatively unstructured. Those interviewed were asked questions from a prepared list (see Appendix A), but if their responses tended to "wander" toward some other aspect of river or valley change they were generally not hard pressed to return to the original query. This approach helped to elicit any information the respondent might perceive as most important about changes in the river and valley—including details that I would not have had the knowledge to ask about. They were unrecorded to encourage a relaxed and conversational atmosphere. Brief notes were taken during the interview and then completed immediately thereafter. Those interviewed signed an acknowledgment and release form for the information given in his or her interview.

Statements made by a number of those interviewed were validated by information received from others or found in historical archives. Temporal and spatial agreement among respondents regarding significant changes in the river planform or profile were identified; some residents were reinterviewed after new questions emerged from other interviews or examination of archival documents. Every statement made by interviewees about change along the Gila River corridor was incorporated into the evaluation of floods and changes in river planform, channel morphology, and riparian extent that appears in the Results. Persons interviewed and the dates of interviews are listed in the References. For anonymity, only the month in which an interview occurred is cited in the text.

**Flood hydrographs**

Reconstructing the Gila River's flood history included the search for historical records of floods prior to 1929 described above, and collection of peak flood data for the period of record at USGS stream gaging station 09430500 (Gila River at Gila; hereafter referred to as the Gila gage). In addition, peak flood data were obtained from USGS gaging station 09430600 on Mogollon Creek, a large tributary just upstream of the Gila Valley (Figure 5). Peak flow data from the Gila gagesite are available for the period August 1928–August 1999, and from the Mogollon Creek gagesite for the period August 1967–August 1999. All daily means from the two gagesites were also obtained: for water years (WYs) 1929–2001 at the Gila gagesite, and WYs 1969–2001 at the Mogollon gagesite (all data from USGS, 2003).

To assess potential differences between the series of major floods that occurred after 1970 and the more moderate floods that preceded them, daily mean streamflow data from the Gila gagesite were evaluated using Indicators of Hydrologic Alteration software (IHA; Smythe Scientific Software, 2001). Flood magnitudes and durations during two periods, 1929–1969 and 1970–2001, were compared. The IHA statistically characterizes streamflow variation based on 32 "ecologically significant" parameters such as flow magnitudes, low and high flow duration and frequency, timing of extreme events, and rate of change. Each parameter's value is calculated for the defined period. Differences in central tendency or variance between the two conditions are calculated, and confidence limits for these differences are established.

**Historic map and aerial photography interpretation**

***Channel planform map.*** Two public land surveys and five sets of aerial photographs were used to map changes in river flow pattern and riparian area during the past 100 years. The first known surveys of the Gila Valley, conducted for the Surveyor General's Office in Santa Fe, date from 1882, 1884, and 1904. Copies of these surveys (hereafter referred to as the SGO surveys) were obtained from the county courthouse in Silver City.

In 1917, squabbling over irrigation rights in the valley had intensified to such a degree that local ditch groups—including the Fort West ditch group, which had a clear water right dating back to 1875—agreed to settle on a common priority date of 1897 for all ditches then operating in the valley. The ditch groups hired county surveyor C.E. Johnson to provide a definitive cadastral survey of ditches, fallow areas, and farmed fields in the valley. The survey was filed with the New Mexico State Engineer's office in 1918 as official documentation of valley water rights and use (French, 1918a, 1918b; interviews, March 2000 and April 2000). As it turned out, the original survey (13 pages, approximately 24 x 30 inches, hand-colored on waxed linen) is now in the keeping of a local resident, George Jackson, who graciously entrusted it to me for reproduction.

The 1980 *Cliff* and *Canteen Canyon* 7.5' orthophotoquad sheets (USGS, 1980), were scanned and georeferenced to UTM grid zone 12S in *Imagine* (v. 8.5, ERDAS, 2001). These served as the base layer to which other maps and photo sets were georeferenced to create the map of channel planform change. To construct the map, however, no attempt was made to georeference the historic surveys to UTM coordinates due to obvious survey imprecision. Scaling and overlays for the map utilized US Public Land System (USPLS) township/range lines and section corners. The early (SGO 1882/1884/1904) and Johnson (1918) survey maps were rescaled to 1:24000 and overlaid on the orthophotoquads.

Channel patterns mapped on the 1959 *Cliff* 15' quad (USGS) were also referenced by USPLS and added to the map of channel planform change. A set of 1995 vertical airphotos was originally georeferenced by the procedure described in the section below on Photogrammetric analyses. Channel pattern was digitized from this photo set and then overlaid on the historic map using the Gila gagesite, bridges, and other features as control points. Channel plan forms, acequias or ditches, and other features appearing on the surveys and orthophotoquads were mapped onto Mylar overlays and digitized in Adobe Illustrator (v. 10, 2001). Resulting layers were superimposed on a mosaic created from parts of the *Canteen Canyon* (USGS, 1965) and *Cliff* (USGS, 1986) 7.5' topographic quadrangles at 1:24000 scale. The resulting map is reproduced at 1:60000 scale in Figure 15. The map depicts large-scale change in the active channel pattern from 1882 through 1995 with a precision of +/-200 feet.

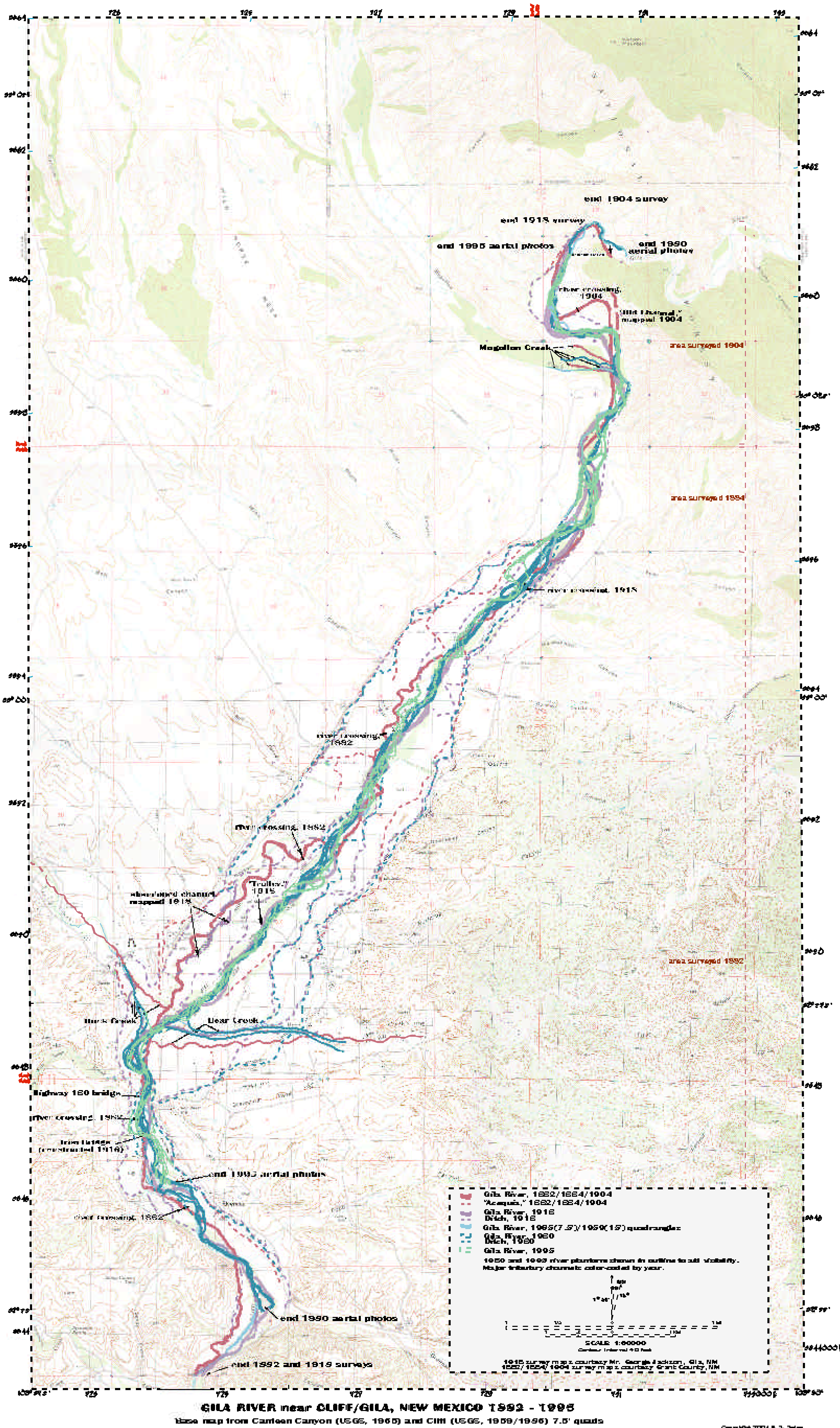


Figure 15. Historic Gila River channels, Gila Valley, ca. 1882 to 1995, and irrigation ditches. Map scale 1:60,000.

***Photogrammetric analyses***. Digitized, georeferenced orthophotoquads [DOQs] of 1996 imagery became available through USGS in November 2000. These were used to check georeferencing, by UTM, of the previously scanned 1980 orthophotoquads and also formed the base layer for 1996 mapping. For this work, the 1996 DOQs replaced the 1995 airphoto layer used to construct the historic channel planform map. Four sets of black-and-white vertical airphotos of the Gila Valley region spanning the period from 1935 through 1974 were also obtained (see Table 1). Photo scales ranged from 1:18000 to 1:40000. Six to nine airphotos per set provided physical coverage of the study reach. Budgetary constraints precluded obtaining stereoscopic coverage for all but a few subreaches. All airphotos were scanned at 600 dots per inch (dpi). Georeferencing utilized a linear rubber sheeting procedure. On each airphoto, 150 to 350 ground control points, predominantly in the region of the river corridor, were identified and marked for the georeferencing procedure. Root mean square error was less than 8 meters (about 26 feet) for all control points. Once georeferenced, the airphotos comprising each year's coverage were joined to provide a semi-controlled mosaic of the study reach. All mosaics were retained as raster layers.

The digitized airphoto imagery from all years (1935, 1950, 1965, 1974, 1980, and 1996) was then used to create vector layers. Vector layers were generated to define change in river planform at a finer level of detail than for the historic map, and to allow quantification of change in the areal extent of riparian vegetation along the Gila River. Levees, irrigation ditches and diversions, and locations of cross-section and piezometer sites for this study were mapped onto one vector layer. Three vector layers were also created from each of the six airphoto mosaics. From each raster mosaic, active river channel and evident overflow channels were digitized onto one of these layers. Unvegetated bar and floodplain surfaces were digitized onto a separate layer with a minimum mapping unit of 5 meters (about 16 feet). Finally, vegetation growing beyond the active floodplain was roughly digitized from each raster layer. This layer was used only for visual comparison of vegetated areas and not for quantitative calculations.

As used in this analysis, the term *unvegetated* refers to surfaces that meet two of three criteria: 1) *Uncanopied:* This criterion applies to all areas classified as "unvegetated." Canopy cover obviously precludes examination of the ground surface beneath a large cottonwood tree, for example. Therefore, canopied areas were of necessity classified as vegetated; uncanopied areas were classified as unvegetated if they met one of the two remaining criteria: 2) *Bare*: cobble, gravel, and/or sand are obviously visible on the aerial photograph. 3) *Sparsely vegetated*: grass, upland vegetation, or sparse forbs are apparent, but no evidence of significant riparian regeneration (e.g., willow, baccharis, cottonwood) is detectable in the airphoto.

Unvegetated bar and floodplain areas were mapped by subreach: from the gagesite to the uppermost cross-section; from cross-section 2 to cross-section 3, and so forth (cross-section locations are shown in Figure 5). Within each subreach, all polygons outlining vegetation within the active floodplain area are completely enclosed within *unvegetated* polygons. Total *vegetated* area was then subtracted from *unvegetated* area to calculate net unvegetated area by subreach.

For continuity, I established a system of rules by which surfaces were judged as floodplain or terrace based on elevational adjacency to the active channel; in other words, at a level relative to the channel thalweg that seems likely to allow riparian regeneration under moderate flood and low flow conditions ("floodplain"), or above it ("terrace"). Active water surface area visible in each photo set was classified as unvegetated floodplain in order to avoid misquantification due to varying river stage on the various photo dates. High terraces were identified during field work in 1999–2001. Terraces were excluded from the *vegetated* or *unvegetated* classification on all photo sets, except on any sets prior to 1974 in which they were clearly occupied by the active channel. (For this reason, the large area immediately south of the S-curve between cross-section 3 and cross-section 4 [Figure 5], although obviously inundated during floods between 1978 and 1996, was excluded from unvegetated floodplain area in the 1980 and 1996 vector sets.) Any unvegetated area within the floodplain but shoreward of a solid riparian band was also excluded from unvegetated floodplain area unless it occupied more than 100 $ft^2$. There were few such small patches, and shadow effects within them frequently made accurate assessment of their vegetated status difficult. Floodplain areas shoreward of levees or dikes were also excluded except where clear evidence of a levee breach or flooding past the upstream end of a levee existed on the aerial photo.

**Table 1. Gila River floods, public land survey, and aerial photography summary.**

| Flood event date | Discharge (cfs)[1] | Survey or photo mo/year[2] | Agency | Survey or photo scale, type[3] |
|---|---|---|---|---|
| | | 1884 | SGO | ~1:31,680 |
| 1891 | unknown | | | |
| 1897 | unknown | | | |
| 10/1904 | unknown | | | |
| 11/1905 | unknown | | | |
| 12/1906 | unknown | | | |
| 10/1914 | unknown | | | |
| 1/1916 | unknown | | | |
| | | 1918 | Johnson | ~1: 12100 |
| | | 1935 | NARA, EDAC | Unknown, vertical |
| 9/1941 | 25,400 | | | |
| 1/1949 | 12,000 | | | |
| | | 9/1950 | EDAC | 1:40000, vertical |
| | | 2/1965 | BLM | 1:18000, vertical |
| 12/1965 | 6,240 | | | |
| 10/1972 | 12,500 | | | |
| | | 4/1974 | SCS | 1:40000, vertical |
| 12/1978 | 32,400 | | | |
| | | 9/1980 | USGS | 1:24000 Orthophotoquad |
| 10/1983 | 15,000 | | | |
| 12/1984 | 35,200 | | | |
| 9/1988 | 14,400 | | | |
| 2/1993 | 14,200 | | | |
| 11/1994 | 16,700 | | | |
| | | 5/1995 | NMED | 1:18000 |
| | | 10/1996 | USGS | 1:24000 D. orthophotoquad |
| 9/1997 | 18,200 | | | |

Agency: SGO = Surveyor General's Office, Santa Fe, NM; Johnson = C.E. Johnson; NARA = National Archives, Washington, DC; EDAC = Earth Data Analysis Center, Albuquerque, NM; BLM = Bureau of Land Management; SCS = Soil Conservation Service; USGS = US Geological Survey; NMED = New Mexico Environmental Department. [1] per USGS, 2003. [2] 1884 = combined 1882, 1884, 1904 SGO surveys. [3] Unknown = unknown photo scale; D. orthophotoquad = digital orthophotoquad. Months in which 1918 survey and 1935 airphotos were compiled are unknown.

Accurate interpretation of floodplain vegetated status was complicated by shadow effects and ambiguous vegetation types on some airphotos. Fine adjustments of photo contrast by manipulation of the histogram associated with each photo's pixel values were made continually as digitizing proceeded. The adjustments sharpened the variance between shadows and the canopy cover that produced it, and improved the texture and tone contrasts that aid in distinguishing among vegetation types (e.g., between riparian willow and more xeric shrub species). In some cases, inspection of a later airphoto helped to clarify the possible presence of emergent vegetation. For example, areas of dense vegetation on the 1974 photo helped to confirm the presence of what appeared to be emergent vegetation on the 1965 airphoto. This technique was used sparingly, however, due to uncertainty inherent in the time gaps between the photo series. Approximately 600 to 950 polygons were digitized for each vegetated–unvegetated vector layer, except for the 1980 layer, in which large contiguous areas were barren of vegetation. Slightly more than 300 polygons were digitized for this layer.

**Field observation and data collection**

***Field data collection***. NRCS staff members surveyed 19 cross-sections of the Gila River in the 14-mile reach downstream from the "Gila at Gila" gagesite in the summer of 1998 (NRCS, 1998). The sites were selected to represent typical morphologies of the river channel in this region. Ten of these cross-sections were selected for resurvey and located during a site visit with NRCS personnel in January 1999. For this study, each cross-section is identified by the number assigned it in the original NRCS survey (NRCS cross-section 1 was at the gagesite; cross-section 19 at the farthest downstream location.) Cross-section locations are shown in Figure 5. For this study, I extended most of the NRCS cross-section widths by 200 to 500 feet in order to include all floodplain and abandoned channel surfaces within each survey. The extended survey data provide baseline geomorphic data against which changes to not only the current active channel, but floodplains, overflow channels, and existing vegetation that may result from future floods can be measured. Surveys were conducted after spring snowmelt in 1999, after the 1999 summer monsoon season, and again in the spring of 2000 in order to document channel geometry and position changes. The only major flow event during the study period, a 2800 cfs flood, occurred on August 6, 1999.

Local and extended channel and valley slopes were also surveyed. Median and 84th-percentile bed material sizes were calculated from samples collected via Wolman's (1954) pebble count procedure at each cross-section. Changes in channel morphology and vegetation at these locations were documented over the 15-month period with photographs/slides of the river channel, floodplains, and terraces. Extensive field notes accompany the photographs. Survey data were collected using standard rod and level methods. A tape recorder and laser level allowed me to work unassisted when necessary. The upper left and right extents of the active channel cross-sections were staked with ½-inch rebar to allow rectification of cross-section elevation and width data from each set of measurements. Data points representing locations of vegetation and changes in bank or bed material were also collected. Data collected from each cross-section survey were overlaid and graphed in SigmaPlot software (SPSS, Inc., v. 5.00, 1999).

All field data were used in evaluating channel morphology changes and potential vegetation reestablishment, and in constructing stage/discharge relationships for some cross-sections. A preliminary report that included evaluation of changes in bed material size and cross-section morphology after the August 1999 flood was supplied to The Nature Conservancy in February 2000 (Soles, 2000). For the thesis, results from the cross-section surveys are confined to tracking the lateral and downward movement of the river channel over time and developing a more thorough understanding of the interactions between complex floodplain components—especially the role of abandoned channels and ditches in reestablishment of vegetation.

In addition to the cross-section surveys, extensive reconnaissance of the entire river corridor from upstream of the gagesite to Iron Bridge was conducted. Many hours were spent visiting and revisiting the river, its floodplains, irrigation tailwater and diversion points, and tributary drainages. Photographs and field notes documented change in these areas. Familiarity with the river system and the changes I observed in it over time formed a substantial study component, and observations that seem significant to understanding the river are incorporated here.

***Cross-section rating curves.*** Survey data were analyzed in WIN XSPro v. 2.0 (US Forest Service, 1998). Rating curves for the three cross-sections nearest the gagesite were developed. The curves relate streamflow to mean water depth, allowing development of estimates of the discharge necessary to overtop banks and floodplains. Rating curves were also applied at selected cross-sections across abandoned channels that were mapped during the surveys. These provide a rough estimate of discharge levels required to overtop those channels.

To create the rating curves, elevation and distance data from each cross-section survey were entered into WinXSPro spreadsheets. One "stable point"—typically, the left or right pin (rebar) location—was identified and labeled within each cross-section spreadsheet. WinXSPro generates cross-section drawings from this information. Applying Arcement and Schneider's (1984) methods to Cowan's (1956) equation for estimating Manning's "n" values, separate roughness coefficients were calculated for the active channel, adjacent floodplains, and terrace/overflow channel areas at each cross-section. Cross-section drawings aided in selecting elevations and widths at which Manning's "n" was determined to change at increasing water stage; for example, at locations where vegetation density on floodplains changed substantially. Field notes and photographs assisted in estimating roughness values for each segment of the equation.

WinXSPro (1998) produces regressions showing the fit of discharge to hydraulic radius and of discharge to stage height for each stage requested. In this case, stage was calculated at intervals ranging from 0.10 foot to 0.25 foot Not surprisingly, regressions generally demonstrated the best fits at low (less than 300 cfs) to moderate (around 3000 cfs) discharge levels. Calculated discharge and mean depths were checked against measured discharge and stage at some locations in order to refine the rating curves for low discharge conditions. Calculated stage heights for 2800-cfs flows were checked against surveyed flood debris elevations left by the August 1999 flood for analysis of moderate flood effects.

**Groundwater data collection and analysis**

***Low flow variation.*** Comparison of the river's natural flow regime at the USGS Gila gagesite (09430500) with its flow immediately below the first two major irrigation diversions in the Gila Valley was conducted by IHA analysis (Smythe Scientific Software, 2001). IHA analyses of natural and diverted streamflow were conducted for the years 1969 to 2001 to detect any significant variation in flow regime under diversion conditions.

Data for the analysis were obtained from four sources: two ditch gages and two streamflow gages. USGS has operated gages on the Upper Gila and Fort West irrigation diversions (ditches) since WY 1969. These are the two upstream-most diversions in the Gila Valley (Figure 5). The ditch gages operate only during the irrigation season, generally April–October each year. Daily mean discharge values from 1969 through 2001 were obtained for both ditches. Daily mean discharge records were also obtained from the USGS gage on Mogollon Creek (09430600) for WYs 1969–2001. All daily means from the USGS Gila at Gila stream gage 09430500 were collected for its period of record, 1928–2001. The shortest period covered by the relevant gage records is therefore 33 years, and this serves as the limiting time frame for reconstructing the river's hydrologic regime in the study area (Richter et al., 1997).

For this study, four hydrologic parameters affected by the diversions—mean duration of low flow pulses, annual means of 30- or 90-day low flows, and base flow discharge—were identified. All four parameters are considered potentially “ecologically significant” for riparian seedling survival (Poff et al., 1997; Richter, 1999; Richter & Richter, 2000). Each parameter's value was calculated for natural regime conditions and altered conditions. IHA (2001) calculated differences in central tendency or variance between the two conditions, established confidence limits for these differences, and reported significance values for each.

For the IHA analysis, the altered regime immediately below the first diversions in the Gila Valley was calculated in a series of steps. Mean daily discharges of greater than 15 cfs that were measured at the Mogollon Creek gage were added to mean daily values from the Gila gage. The Mogollon gagesite is located 12 miles upstream of the creek's ephemeral confluence with the Gila River (Figure 16). During the two-year study period, surface flow in Mogollon Creek was observed at the confluence only once, during heavy monsoon rains in July 1999. Mogollon Creek flows through a relatively wide canyon for more than three miles above its Gila River confluence, where it meanders across a wide sand and gravel floodplain. Surface flow easily infiltrates the floodplain. Interviews and archival data confirm intermittent Mogollon surface flow near the Gila. The selection of 15 cfs as a cutoff point for adding Mogollon discharge to discharge at the Gila gagesite was arbitrary, and its validity for extended periods of low flow was checked against actual discharge in the Gila channel downstream of its confluence with Mogollon Creek as described below.

During site visits, I took discharge measurements at one or two locations downstream of the Mogollon Creek confluence. The upstream location (referred to as "xs2") is at the cross-section 2 site, about ¼ mile downstream of the Mogollon Creek confluence and near two piezometers installed for groundwater elevation measurements (see Piezometers, below). Approximately ½ mile farther downstream, a long midchannel bar separates river flow into two channels. The upstream end of the bar is periodically "rebermed" by bulldozer. Each channel formed by the bar meets a ditch diversion point a short distance downstream, and so I refer to this spot as the "diversion split." Two piezometers were also installed near this location.

**Figure 16. The Gila River (right) and Mogollon Creek (left) at confluence, May 1999. Cross-section 2 is at extreme lower left corner. Flow in Gila is from right to left.**

Discharge measurements were taken in order to correlate actual discharge at each location to flows measured at the Gila gage upstream. Measurements were made with a wading rod and Price AA meter according to techniques detailed in Buchanan and Somers (1969). Streamflow lag time at each measurement site was roughly estimated from average low flow velocities of 0.8 feet/sec and distances downstream of the gagesite. At xs2, lag time was estimated as 2 hours; at the diversion split, as 6 hours. USGS, Albuquerque provided provisional 15-minute discharge data from the Gila gagesite. Mean discharge for a 2-hour period was calculated; each period ended at the time estimated as the lag time. Calculated mean discharge at the Gila gagesite and measured discharge at each site are shown in Table 2.

**Table 2. Gila River discharge at three sites during study period.**

| Date | Gage Q (cfs) | xs2 Q (cfs) | Diversion split Q (cfs) |
|---|---|---|---|
| 3/12/99 | 63.3 | 54.4 | |
| 5/13/99 | 44.0 | 33.9 | |
| 5/18/99 | 40.0 | | 30.1 |
| 6/27/99 | 30.3[1] | 27.6 | 25.1 |
| 7/21/99 | 59.3 | 45.2 | |
| 7/22/99 | 174.4 | | 126.1 |
| 9/29/99 | 105.5[1] | 105.3 | 97.9 |
| 12/24/99 | 60.0 | | 60.3 |
| 4/4/00 | 57.3 | 54.3 | |
| 4/6/00 | 51.5 | | 51.8 |
| 5/21/00 | 29.0 | | 25.4 |
| 7/31/00 | 45.0 | 40.5 | 39.5 |

Gage Q = 2-h mean discharge at Gila gagesite beginning 4 h (for comparison with cross-section 2 Q) or 8 h (for comparison with diversion split Q) before time of discharge measurement. xs2 Q = measured at cross-section 2 by wading rod. Diversion split Q = measured at split by wading rod. [1]Gage Q same for both xsec2 and diversion split estimates.

As noted previously, Mogollon Creek appears to contribute little to Gila base flow during seasonally dry conditions. Comparison of low flow discharge values at the Gila gage with measurements taken downstream of the confluence tends to support this conclusion (Table 2), which was also checked in a preliminary analysis.

Regressions were fit in JMP (SAS, v. 3.2.1, 1997) from mean 2-h gagesite discharge to discharge measured at the two sites described above. Fits were good ($r^2$ of 0.97 and 0.95, respectively). Both showed decreasing downstream discharge—in other words, streamflow losses to floodplain areas—under extended low flow conditions. However, a "crossover" point often occurs during monsoonal seasons when discharge begins to *increase* in a downstream direction, as subsurface or surface flow from Mogollon Creek and/or from steep tributaries east of the river becomes greater than floodplain losses. This crossover is evident in the gagesite–xs2 relation, but is not captured in the gagesite–diversion split regression. Study of the 15-minute USGS gagesite data shows why. Timing of the initial monsoon-season measurements coincided with the beginning of an extended, slow rise in discharge levels, when Gila water surface levels near Mogollon Creek, at the upstream measurement location, had already begun to rise. Floodplain losses downstream still created a net discharge loss at the diversion split. Local incoming flows of sufficient magnitude *must* eventually increase channel flow downstream, but this will never be reflected by the diversion split regression. Therefore, the xs2 regression was used to check the validity of excluding all Mogollon flows of <15 cfs from consideration for IHA analysis. In the equation below, *Qxs2* = discharge at the upstream measurement site; *gage Q* = discharge at Gila gagesite:

$$Qxs2 = (1.04953 \text{ gage Q}) - 9.0922;\ r^2 = 0.97;\ F < 0.0001$$

This equation was applied to all Gila gagesite daily means for the months of April through October (designated as "summer" months for the IHA study) for the IHA period, 1969–2001. Results were compared against daily sums of mean discharge from the Gila gage and discharge >15 cfs from the Mogollon gage (*Qgm*). *Qgm* was greater than that calculated by regression for more than 99% of approximately 7060 summer days during the 1969–2001 period. Only *Qgm* greater than 250 cfs did not exceed discharge as calculated by the regression. Variance between summed and calculated estimates ranged from 1% to 3%. In other words, for flow conditions of less than 200 cfs—those most pertinent to seedling survival—*Qgm* generally overstates total discharge downstream of the Gila-Mogollon confluence. Even surface flows greater than 15 cfs at the Mogollon gage frequently fail to reach the Gila confluence. Including all Mogollon flows of at least 15 cfs in summed *Qgm*, however, helps to ensure that the IHA analysis avoids overstating possible groundwater depletion effects on riparian communities below the diversions.

Diversions are gaged only from April through October each year. Daily outflows to the two diversions as measured at the ditch gage sites over the 33-year period were subtracted from *Qgm* in order to arrive at estimated daily mean discharge values (*Qnet*) for the river below the diversions. As a result, *Qnet* most accurately represents net river flow regime immediately below the diversions, between Spar Canyon and Winn Canyon. Ditch and field seep and irrigation tailwater returns downstream of the diversions increase the volume of water in the river channel before other diversions farther downstream decrease it again. IHA (2001) analysis then compared *Qgm* and *Qnet* for significant variation in flow regime.

***Piezometers***. Given the limited scope of the study, it was impossible to incorporate groundwater flow modeling into the flow regime analysis. However, in order to monitor groundwater elevation shifts relative to water surface levels in the active Gila River channel, a total of eight 1 ¼-inch piezometers were installed at three sites in July 1999, using techniques and materials outlined in The Nature Conservancy, 1996. A GPS coordinate file was obtained with a Trimble Explorer II unit in April 2000 for each piezometer. Files were differentially corrected using base station files from Albuquerque. Coordinates for each piezometer appear in Table 3 and locations are shown in Figure 5. At each site, piezometers bracket the active channel. Odd-numbered piezometers are on river left. Piezometers 1a/1b – 2a/2b are upstream of the Gila River and Mogollon Creek confluence; piezometers 3 through 6 are downstream of it. Piezometers 5 and 6 are located farthest downstream, about 100 yards upstream of the diversion split.

**Table 3. Piezometer locations.**

| Piezometer no. | Approximate UTM coordinates | Approx. distance DS of gagesite (mi) | Active channel distance (ft.) |
|---|---|---|---|
| 1a,<br>1b | 3659400 N, 730300 E | 1.07 | 57<br>136 |
| 2a,<br>2b | 3659370 N, 730350 E | 1.08 | 252<br>252 |
| 3 | 3658240 N, 730460 E | 2.3 | 420 |
| 4 | 3658160 N, 730610 E | 2.3 | 325 |
| 5 | 3657470 N, 730380 E | 2.85 | 95 |
| 6 | 3657500 N, 730350 E | 2.85 | 134 |

DS = downstream; active channel distance = distance from piezometer to edge of water at low flow.

Final piezometer depths ranged from 12–18 feet below ground surface. Locations were selected for proximity to the active Gila River channel, downstream spacing, and substrate: cutbank areas or abandoned channels composed mostly of sand and fine gravel identified promising piezometer sites. (One site was relocated after all efforts to drive the well point through coarse subsurface gravel failed.) Permission to install piezometers and staff gages was obtained from appropriate parties. All piezometers are located upstream of irrigation diversions in the Gila Valley; property ownership considerations precluded the installation of additional piezometers downstream of the irrigation diversion split in the river channel.

A set of two staff gages was installed in and above the active channel at each piezometer site in order to monitor river stage from approximately 0.5 foot to 6.6 feet. During installation, the lip of each piezometer, ground surface, initial piezometer water levels, staff gages, and reference points were surveyed by transit. One reference point at each location was assigned an arbitrary elevation of 100.00 feet and all surveyed points were rectified to this elevation. Local TNC/Upper Gila Watershed Alliance (UGWA) staff were provided with detailed instructions on obtaining water surface levels in the channel and within the piezometers. They obtained most of the semi-monthly measurements gathered over the following 15-month period; I took measurements during scheduled site visits. Piezometers were bailed or purged to remove accumulated sediment about once every four months. No readings were taken within five days of each bailing treatment. Two staff gages were lost to flood and one to vandals, resulting in a few missing data points for river water surface elevations. The gages were replaced and all sites were resurveyed to ensure continued accuracy in calculations of relative elevation.

**Groundwater elevations analysis**

Data collected were used to examine the relationship between change in Gila River stage and groundwater levels, and to identify variation among sites in this relationship. Variance in groundwater elevation changes relative to river stage could suggest variability in substrate density between sites, or the existence of subsurface groundwater flow paths, i.e., abandoned river channels currently buried beneath the floodplain. To relate channel discharge to groundwater elevations at piezometer sites, the variance between each river stage and piezometer depth reading ($n$ = 31 to 33) was calculated. Variances were graphed against 1) time and 2) distance from channel edge.

Third-degree polynomial regressions were used to relate lagged Gila gagesite discharge to measured water elevations for piezometer 2b. Third-degree equations were also used to relate calculated *Qxs2* to measured water elevations for piezometers 4 and 6. A time series utilizing the regressions predicted groundwater elevations based on *Qnet* discharges calculated for the same days as those on which measurements had been taken, to evaluate their utility for estimating groundwater levels under diverted flow conditions.

**RESULTS**

Results from the study are examined chronologically. During the decades for which maps and airphotos are available, the river's planform underwent major changes twice, first between 1882 and 1918, and then about 70 years later, between 1980 and 1996. Nearly all of the evidence available prior to about 1930 of flooding and its effects within the Gila Valley is anecdotal or archival, and I examine this period first. The Gila gagesite was established in 1928 and the earliest available aerial photographic series is from 1935.

Evaluation of flooding after 1930 is based on data available from the Gila gagesite. Photogrammetric analysis and interpretation of the airphotos from 1935, 1950, 1965, 1974, 1980, and 1996 provides evidence of flood impacts and the effects of channelization work that began in the late 1940s. Evidence of changes in channel morphology and pattern were also identified through field observation and cross-section surveys; this evidence is examined in conjunction with that mapped from the aerial photography series.

Modification to the Gila River's baseflow regime is analyzed by comparison of streamflow records from the undiverted segment of the study reach with estimates of discharge remaining in the stream channel downstream of the first two diversion points in the valley. Relative ground- and surface water elevations are evaluated for insight into the factors influencing shallow groundwater flow paths and the relationship between in-channel discharge and floodplain groundwater levels.

**Floods and the riparian corridor, ca. 1882–1930**

Depositional and erosive cycles among streams in the American southwest before 1900 have been studied by a number of researchers. Leopold and Snyder (1951) describe evidence from the Gallup, New Mexico area of an extended depositional cycle dating from 1300 a.d. Between 1875 and 1900, widespread erosion of southwestern stream channels occurred (Bryan, 1925; Hastings & Turner, 1966; Meyer, 1989; Swift, 1926). Speculation as to the role played by various factors in the most recent of these downcutting episodes is contentious, well-known, and ongoing; Graf (1988b: 221–222) provides an excellent review of the debate. Whatever the causes, its regional basis suggests that major floods were common in the Southwest during the latter part of the 19th century.

If one or more floods on the Gila River were capable of scouring floodplain vegetation or creating lateral or downward erosion in the absence of channelization work, this would be one piece of evidence that levee construction may not be responsible for the river's current condition in the valley. The following sections summarize historic accounts of flooding located for the period prior to establishment of the Gila gage in 1928 and results obtained from mapping and evaluation of the SGO (ca. 1884) and Johnson (1918) surveys.

Annual average precipitation in the Gila River watershed above the gagesite at higher elevations is about 16 inches, and at Cliff, about 14 inches. It arrives in a somewhat bimodal pattern, in which the months of April, May, June, and November tend to be driest, and July through September the wettest (USDA SCS, 1954; Western Regional Climate Center, 2003). However, precipitation is extremely variable, ranging from about six inches to 26 inches per year in the period between 1940 and 2000. The river's flow regime, both intra- and inter-annually, is likewise highly variable. (See Table 1 for estimated and known flood dates and peak discharges at the Gila gagesite between 1891 and 1997.)

**Gila Valley floods, pre-1928**

***Bear Creek flood.*** Flood records prior to establishment of the Gila gagesite in 1928 are spotty. One of the more intriguing pieces of evidence for late 19th-century flooding on the Gila comes from the SGO Public Land Survey of the area. According to the SGO survey, Duck Creek joined the Gila upstream of—that is, north of—the river's confluence with Bear Creek. In fact, the

New Mexico State Engineer's Office probably relied on the SGO survey in erroneously listing Duck Creek as the upstream of the two tributaries in its 1964 *Gila River Hydrographic Survey Report*. In reality, the confluences occupied their present-day positions by the time of Johnson's survey in 1918, in which Duck Creek is shown reaching the Gila downstream of the Bear Creek confluence.

There are obvious imprecisions in the earliest surveys. For an example, check the surveyed reach of the Gila River upstream of Mogollon Creek in Figure 15. An error in the 1904 survey places the Gila River's west to east reach in this area in a location where it would be flowing steeply *uphill*[2]. Nonetheless, an error of the magnitude required to reverse the Duck Creek and Bear Creek confluences seems unlikely. Maps of the confluence area compiled in 1873, 1880, 1864, and 1903 depict the area in various ways that fail to resolve the issue. Documentation of early flooding on Bear or Duck Creek was sought as possible evidence for a major channel shift at the confluence area, and the flood most likely to have rearranged the confluence area seems to have occurred on Bear Creek in 1897.

Silver City lies about 30 miles to the southeast of the Bear Creek/Duck Creek/Gila River confluences. Silver City's infamous "Main Street floods" around the turn of the century are well documented. According to the *Silver City Enterprise*, eight major floods occurred in Silver City between 1886 and 1909. These floods congregated in San Vicente Arroyo (Main Street) from creeks and arroyos generally to the north and northwest. Their watersheds lie immediately south of the ridges and hills separating them from the Bear Creek watershed, and 10 to 15 miles south of the uppermost Gila River watershed. The localized nature of summer storms in the region (Western Regional Climate Center, 2003) suggests that summer floods on Bear Creek would more often correspond with those in Silver City than with those on the mainstem Gila upstream of its Bear Creek confluence.

However, Bear Creek and Silver City floods are not invariably simultaneous. A story in the *Enterprise* on 10 September 1897 mentioned no significant flooding in Silver City in its description of an enormous Bear Creek flood at its Gila River confluence—from which two men barely escaped in the middle of the night—that washed away 100 tons of hay and a 30- by 100-foot store building. Olmstead (1919, cited in Aldridge & Hales, 1984) estimated Bear Creek's

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[2] Some public land surveys were notoriously inaccurate; see Worster (2001: 340) for a description.

discharge as 110,000 cfs—a truly epic flood for the creek's watershed of approximately 160 $mi^2$. (By contrast, the December 1978 flood on the mainstem Gila, with a recurrence interval of >100 years, reached a peak of 32,400 cfs at the Gila gagesite—where the watershed area comprises 1864 $mi^2$.) It is unknown how Olmstead arrived at his estimate, and I was unable to obtain the original document in which it appeared. (It is worth considering the possibility that Olmstead made his calculations not in cubic feet per second, but in "miners inches," a now-unused unit of discharge. The exact volume represented by a miner's inch varied from state to state, but was equivalent to 1/40$^{th}$ or 1/50$^{th}$ of one cfs. In these terms, Olmstead's estimate for the Bear Creek flood becomes about 2200 cfs or 2750 cfs, still a major flood for a watershed the size of Bear Creek's, and perhaps one capable of carrying away a large building. Without locating Olmstead's original report, however, this remains only a possibility.)

Whatever the actual discharge, a flood of considerable magnitude apparently occurred on Bear Creek in 1897. A more complete account of flood evidence from Duck and Bear Creeks and of historic maps of the area appears in Soles (2002). Aldridge and Hales (1984) also note that Olmstead (1919) estimated 41,800 cfs for a flood on Duck Creek that occurred on an unknown date prior to 1916—perhaps in 1897. No mention, however, was made in the *Enterprise* of flooding farther upstream on the Gila River in 1897.

***Gila River floods.*** The *Enterprise* (October 14, 1904) did report extensive flooding on the Gila River in October 1904. Floods occurred throughout the region: on Mangas Creek to the south, on the Mimbres River to the east, and on the Gila itself. The Gila River flood originated in its headwaters on the Gila Forest Reserve, the *Enterprise* noting that "the ground is thoroughly saturated…even on the mesas seven or eight thousand feet above sea level…" (1). The newspaper also noted flooding throughout the Gila Valley:

> Practically every ranchman on the Middle Gila was damaged to some extent by the high water…the ranches of P.M. Shelly [sic], William Doyle, the Rice brothers, T.J. Clark and others were all damaged to some extent. The stage road across the Gila at Cliff has had to be abandoned on account of the boggy condition of the banks on either side… (1,4)

USGS (2003) notes that "major floods occurred [near the Gila Valley] in November 1905, December 1906 and January 1916." Aldridge and Hales (1984) also note a major flood on the Gila in February 1891, although they note that "data are not available for the flood…upstream from the San Francisco River [which meets the Gila near Safford, Arizona]" (21). Anecdotal evidence they gathered from a resident of Gila Hot Springs (well upstream of the Gila Valley) suggested that the floods of 1891, 1905, and 1906 originated somewhere between Gila Hot Springs and Safford, but exactly where is unknown. However, USGS maintained a gage near Cliff between 1904 and 1907, below the Gila River's confluences with Mogollon, Duck, and Bear creeks (Figure 17). All are potentially significant tributaries. The agency estimated discharge of 13,640 cfs for the 1905 flood and only 4175 for the 1906 flood at the Cliff gagesite (USGS, 1906; USGS, 1908). On the other hand, one valley resident told me about a neighbor who had a photograph of the 1906 flood, significant because it was the "first channel-filling flood they'd seen" since they arrived in 1879 (interview, February 2001).


**Figure 17. The first "Gila near Cliff" gagesite, in operation from 1904 to 1907. Courtesy Center for Southwest Research, University of New Mexico.**

A local resident's archive of family historical documents includes a letter written by "Lucy" on January 14, 1905 [spelling as in original]:

> …my but wasn't that a flood the watter run over our field, it came in over our alfalfa and all over Mr. Clarks field the watter run a way up on the orchard. the river looked like a sea of watter some horsed desided to swim the river and waves threw one horse so high out of the watter…Max Moss was saying last night the river washed all their fenses away and did not leave land enough to set more posts… Bill F [?] lost about one hundred hed of his goats in the flood. (McKissick, July 2000).

The letter was written from the family's property at The Gila Hotel in Riverside. Lucy was therefore probably describing the Gila River flood at a location not far from the Cliff gagesite—but the flood occurred in January, rather than November, of 1905.

USGS maintained another gage on the Gila River (designated as the "near Silver City" gagesite) between 1912 and 1915 (USGS, 1949). The gage was located immediately downstream of the East and West Fork confluence, far upstream of the Gila Valley. The largest floods measured at this gagesite all occurred late in 1914. The largest was on October 4 (3530 cfs), and a series of seven, ranging from over 1100 to nearly 2900 cfs, occurred on consecutive days in late December.

The US Army COE (1962; cited in Aldridge & Hales, 1984) described a flood on the Gila River in January 1916 as equal to other major floods (those in 1884, 1891, 1905, and 1906) at the head of the Safford Valley in Arizona. But little information about 1916 floods in the Gila Valley is available. No gage was operating on the river in or near the valley that year (USGS, 1949), and the source of the January 1916 floodwaters is unknown. A smaller flood probably occurred in October of 1916, at least downstream of Duck Creek. Aldridge and Hales (1984: 52) give Olmstead's (1919) estimate for Duck Creek during this flood as 10,600 cfs. Simultaneous flooding on the mainstem Gila in the Gila Valley upstream of Duck Creek may or may not have occurred.

From the overall evidence of floods on the Gila and its tributaries documented between 1891 and 1916, it seems apparent that at least one major Gila River flood came through the Gila Valley between the 1884 and 1918 surveys. Most likely, significant flooding occurred in 1904, 1905, and 1914.

## Historic map interpretation

Gila River planforms during selected years between 1882 and 1995 are mapped in Figure 15. The locations of three major tributaries—Mogollon Creek, Bear Creek, and Duck Creek—are also mapped for the same time period. River planform during the 1882-1884-1904 SGO surveys conducted for the Surveyor General's Office in Santa Fe is combined in the maroon river line and the reach mapped during each of those surveys is identified along the right edge of the map. Farmed areas are generally those between the irrigation ditches depicted by dotted lines farthest east and west of the river. Note that in all descriptions that follow, river "left" and "right" are facing downstream, by standard hydrologic convention.

***Changes in the river corridor: ca. 1882 to 1930***. Figure 15 depicts straightening of the river channel that occurred between 1882 and 1918, apparently in response to floods. A mile-long series of meanders between Guerrero and Domingues Canyons virtually disappeared, as did the enormous meander extending downstream from near Northrup Canyon, past the present-day Highway 211 bridge (in 1918, a trolley crossing), nearly to Duck Creek. Elimination of the meander around the trolley crossing left the channel in virtually the same location that it occupies today. The 1882 channel was still evident enough to Johnson in 1918 that he mapped it as "Abandoned Channel," and a line of huge cottonwoods trace its course even today. Straightening of the river channel in this reach may have been the result of at least one major flood between 1882 and 1918 (see Floods, above). Floods between 1882 and 1918 may have deposited enough sediment and debris atop already existing sediments to have shifted the river's channel east; alternatively, the loss of channel meanders in the area by 1918 suggests some form of channel erosion. Perhaps both occurred, sequentially. One possible consequence of such floods is scouring of near-channel riparian vegetation.

Few data describing the extent of riparian area in the Gila Valley between 1884 and 1918 were located, but Johnson's 1918 survey depicts "Waste Lands" between the river channel and regions described as "Timber and Brush." The 1918 survey includes the river and what Johnson labeled "waste lands" contiguous to its active channel. Unfortunately, while Johnson's survey notes survive in the library of the State Engineer's office in Santa Fe, they include no definition of the term "waste lands." However, he separately labeled "timber and brush" areas on his map, and these lay generally between the "waste land" area and actively farmed fields. A glance at any airphoto of the valley suggests that "waste land" might comprise largely unvegetated floodplain nearest the active channel, while "timber and brush" occupy floodplain surfaces and adjacent terraces shoreward. Given the location of waste lands adjacent to the river and Johnson's identification of "timbered" areas, it seems likely that the waste lands occupy unvegetated floodplain areas.

***Beaver?*** A number of residents recalled accounts from the early part of the century that described an area between Duck Creek and the present-day Highway 211 bridge as a giant marsh or slough inhabited by ducks and geese (interviews, February 2001). It is also likely that beavers inhabited the "marsh," and constructed dams there. Beaver dams slow water velocities and thereby allow "bank storage" of water and deposition of sediment from slow-moving water (Stromberg, 1993a). By damming and spreading water, they can function as part of a feedback loop that results in establishment of riparian and aquatic vegetation on sediments, creating additional deposition and even an eventual shift in the channel's location (Olson & Hubert, 1994). The historic presence of beaver on the Gila River in this area, and their subsequent demise, was documented by Pattie (1833) and other early trappers. Loss of the beaver probably had major consequences for the riparian environment. Dobyns (1981) believes that "the ecological aspect of the behavior of Anglo-American beaver trappers cannot be overemphasized" (108), noting that beaver trapping on the scale practiced by these early entrepreneurs

> became ecologically significant because beaver ponds seem to have constituted a vital stream defense again erosion…Hundreds of beaver ponds along those creeks slowed floodwaters, and thus precipitated soil carried by run-off water…A healthy beaver population kept its dams in constant repair, so that ponds functioned at maximum efficiency as erosion control devices. [Beaver] were abundant on the streams comprising the Gila River watershed when Anglo American fur trappers arrived [in the mid-1820s]. (105-6)

So-called "bank" beavers—beaver colonies that do not construct dams—still occupy parts of the study reach. Beaver also attempt to colonize all of the ditches in the valley, where riparian growth often tends to be luxuriant, thus providing them a ready food source (interviews, February 2001; personal observations, 1999 through 2001). They frequently build dams on the ditches. These efforts generally lead to their removal, since their dams inhibit functioning of the ditch systems. At least two beaver colonies have also dammed small overflow channels on the river floodplain in the study reach. Both provide impressive examples of the effects of beaver work on soil saturation levels, sediment deposition, and vegetation response. One colony lives in the reach downstream of Spar Canyon, the other, just upstream of the Highway 211 bridge. This group's dam, on the floodplain between the river and the fields to the east, was slightly damaged but not removed by a small flood in August 1999 (Figure 18). Fine sediments accumulate in and around the ponds created by the dams. Whether or not beavers were responsible, the very word "marsh" as a description for the trolley crossing area strongly suggests that a thick layer of fine sediments covered the area in the late 19$^{th}$ century.

***Erosion evidence.*** Duck and Bear creeks join the river about a mile downstream of the trolley crossing. When Johnson mapped the confluence area in 1918, he labeled broad bands of floodplain (up to 1000 feet wide) along both creeks and the river as waste lands. However, waste land areas narrow conspicuously moving upstream from this point toward the trolley crossing. Timbered areas near the trolley extend across the floodplain to the very edge of the river channel. This pattern suggests a possible scenario for the effects of floods around the turn of the last century on the river corridor. Loss of vegetation in the confluence area, but not upstream,

**Figure 18. Overflow channel with beaver dam and pond, adjacent to left silt cutbank at cross-section 9, July 1999.**

suggests that the greatest erosion of floodplains and channel may have occurred around the confluence area, perhaps during the 1897 Bear Creek flood. Such erosion could create a drop in base level at the confluence and induce upstream migration of erosion, or headcutting, along the Gila River (Schumm, 1999). A later flood or floods on the mainstem Gila, perhaps the 1904–1905 events, could then have cut through fine sediments in the marsh area. During major floods, channel banks are overtopped and water tends to flow in a straighter, down valley line than under low flow conditions, sometimes—although by no means always—straightening the river channel (Leopold, Wolman, & Miller, 1964). On the Gila, such a series of events could have eliminated the 1882 meander.

Alternatively, it is possible that the marsh area around the Highway 211 bridge was deliberately drained and cleared by local farmers, desiccating the floodplain and leaving the area vulnerable to erosion (Poff et al., 1997; Simon & Darby, 1999). No one interviewed, however, suggested that this had occurred, nor does the presence of near-channel "timber" on Johnson's map suggest that the area was cleared.

The channel planform left after a significant flood event may mostly depend on the timing of sediment and water flows in the mainstem and tributary channels as well as on flood recession conditions (Brakenridge, 1988; Brookes, 1996; Kirkby, 1999). For example, when a majority of flood discharge is carried by the mainstem channel rather than tributaries, material deposited previously at the base of tributary channels may be transported downstream, removing the meanders they once formed. Channel braiding across alluvial fans within the main river valley may also follow erosion of streambanks and subsequent widening of the channel after a flood (Fujita, 1989; Meyer, 1989).

In 1884, at the Spar Canyon reach near the head of the valley, the large alluvial fan formed at the base of Spar Canyon had been cut by mainstem flooding at some previous period, confining the river next to the high terraces that form the eastern side of the valley. By 1918, the river split into two channels around a huge midstream bar just upstream of Spar Canyon as a result of some flood or floods. The midchannel bar was formed by alluvium deposited from tributary canyons. Immediately downstream of Spar Canyon, the right river channel in 1918 is pinned against the base of Gila conglomerate bluffs on the west side of the river. One local resident remembered that a flood in 1916 was responsible for moving the river at this spot from "the far east side of the valley" to the bluffs on the west (interview, April 2000). The river's movement west in this reach suggests that at some time between 1884 and 1918, flooding in Spar Canyon moved sufficient material into the Gila River channel to force its channel westward. Subsequently—either during the same flood or during a later one—mainstem flooding was powerful enough to again cut through the eastern edge of this fan to return part of the river, the left channel, to near its 1884 location.

Throughout the valley, loss of meander bends would have decreased the overall channel length, resulting in increased stream slope and velocity (Parker & Andres, 1976; cited in Brookes, 1996). As a general rule, river channels tend to move from a meandering to a braided pattern as stream power increases (Van den Berg & Bledsoe, 2003). Braiding evident on the aerial photograph from 1935 (discussed in the next section), also suggests flood-induced modification of the channel and floodplains after 1884 but prior to channelization work.

Had other large floods occurred in the valley in the ensuing decades, the river may have entered a cycle of erosion similar to the one that seems to have occurred between 1973 and 1999. But it did not. Remnants of the marsh near the trolley crossing persisted into the 1960s, although this was perhaps partly because, as one resident noted, part of the "old slough [abandoned channel] was used as a ditch," providing a continued water source to part of the area (interview, February 2001). Another told me that the marsh, both upstream and downstream of the bridge, was still present when he moved to Gila about 1963. He described a thick growth of riparian trees of varied ages in the area, especially on the east side of the river (interview, February 2001). Progressive downward erosion in the nearby river channel would have lowered groundwater levels and dried up the remaining marsh areas. The persistence of the marsh remnants suggests that widespread erosion and braiding of the river channel, of the sort seen today, had not yet occurred by the early 1960s.

***Early erosional phase: summary.*** The Gila River's channel and floodplains experienced scouring and lateral movement even prior to channelization efforts that began in the 1940s. A large flood on Bear Creek in 1897, perhaps coinciding with flooding on Duck Creek, may have been sufficient to rearrange the area at the confluence of the two creeks with the Gila River. This flood and/or others probably scoured vegetation around the confluence and perhaps induced some headward erosion within the main Gila River channel. In 1882, the river occupied a series of major meanders throughout the Gila Valley; these were no longer evident by 1918. Channel braiding, also suggestive of the effects of major flooding, was evident in a 1935 aerial photograph, as discussed below. However, other evidence suggests that channel erosion and vegetation scour were limited in spatial and temporal extent and that the river corridor entered a mostly depositional phase sometime between 1918 and about 1935. Documentation of this phase is presented next.

**Floods and the riparian corridor, ca. 1930–1996**

The river corridor appears to have been a mostly depositional environment during the period from about 1930 through 1970, in spite of intensive channelization and sediment control efforts that began around 1950. The 25 years after 1970, however, witnessed major channel and floodplain erosion, both downward and lateral. A series of some of the largest floods on record moved through the Gila Valley between 1970 and 1996.

The extent of floodplain area inhabited by riparian vegetation in the Gila Valley during each of the six airphoto dates from 1935 to 1996 was calculated by photogrammetry from each airphoto series. The extent of these areas was calculated by subreach between study cross-sections, from the gaging station to just below Iron Bridge. Riparian extent varied substantially during the decades between 1930 and 1996. Table 4 summarizes known flood peaks, channel construction activities, and variance in unvegetated floodplain surface within selected river subreaches during the period 1935–1996. Figures 19 through 21 summarize changes in extent of riparian vegetation as percentages of 1935 unvegetated floodplain, plotted against flood peaks greater than 2500 cfs and channel construction activities during the period 1935 through 1996.

The figures demonstrate the difficulty in distinguishing among the potential causative factors for erosion and vegetation loss along the Gila River. For example, some levees were constructed between the 1941 and 1949 flood events. The area covered by floodplain vegetation decreased within some reaches of the river between 1935 and 1950; was the loss due to construction (bulldozer) activity, floods, or both? Massive levee reconstruction in 1979 was prompted by one of the largest floods on record (in December 1978). The reconstruction was followed by a series of some of the largest floods to occur in the past 70 years, again confounding efforts to determine the relative roles of these factors in the river's current condition. Nonetheless, the available data suggest certain patterns to and possible causes for change within the Gila Valley riparian corridor. They are summarized in the following sections on depositional and erosive evidence and anthropogenic activities affecting the river during the 60-year period.

**Table 4. Summary of major Gila River floods after 1935, channel construction activities, and unvegetated area in selected reaches.**

| Date | Event | Unvegetated floodplain area (acres) | | |
|---|---|---|---|---|
| | | Gila gage to xsec 3 | xsec 3 to xsec 5 | xsec 5 to xsec 10 |
| **1935** | | 170 | 31 | 96 |
| 9/1941 | Flood: 25,400 cfs | | | |
| 1/1949 | Flood: 12,000 cfs | | | |
| 1949-1960 | Initial levee construction | | | |
| **1950** | | 217 | 69 | 56 |
| 1964 | Check dam construction | | | |
| **1965** | | 112 | 31 | 92 |
| 12/1965 | Flood: 6,240 cfs | | | |
| 10/1972 | Flood: 12,500 cfs | | | |
| **1974** | | 227 | 64 | 146 |
| 12/1978 | Flood: 32,400 cfs | | | |
| 1978-1979 | Levee reconstruction | | | |
| **1980** | | 237 | 95 | 192 |
| 10/1983 | Flood: 15,000 cfs | | | |
| 12/1984 | Flood: 35,200 cfs | | | |
| 9/1988 | Flood: 14,400 cfs | | | |
| 2/1993 | Flood: 14,200 cfs | | | |
| 11/1994 | Flood: 16,700 cfs | | | |
| **1996** | | 160 | 75 | 249 |
| 1997 | Flood: 18,200 cfs | | | |

Flood data per USGS (2003). Unvegetated surface area calculated by photogrammetry; see text. **Boldface** years in left column are dates of aerial photography.

## Deposition: ca. 1930–1969

Substantial evidence indicates that the relatively moderate flood regime on the Gila River from about 1930 through 1970 sustained a mostly depositional cycle in the riparian corridor until the arrival of very large floods in the 1970s through 1990s.

***Flood records.*** The Gila gagesite began operation in 1928. The ten largest flood peaks recorded at the gage between 1928 and 1969 are shown in Table 5. Floods during this period were of generally moderate discharge; only two of the ten greatest peaks of record occurred between 1935 and 1969, as shown in Figure 22. Calculated recurrence intervals (RIs) for all floods during the period 1928–1997 are also graphed in Figure 22.

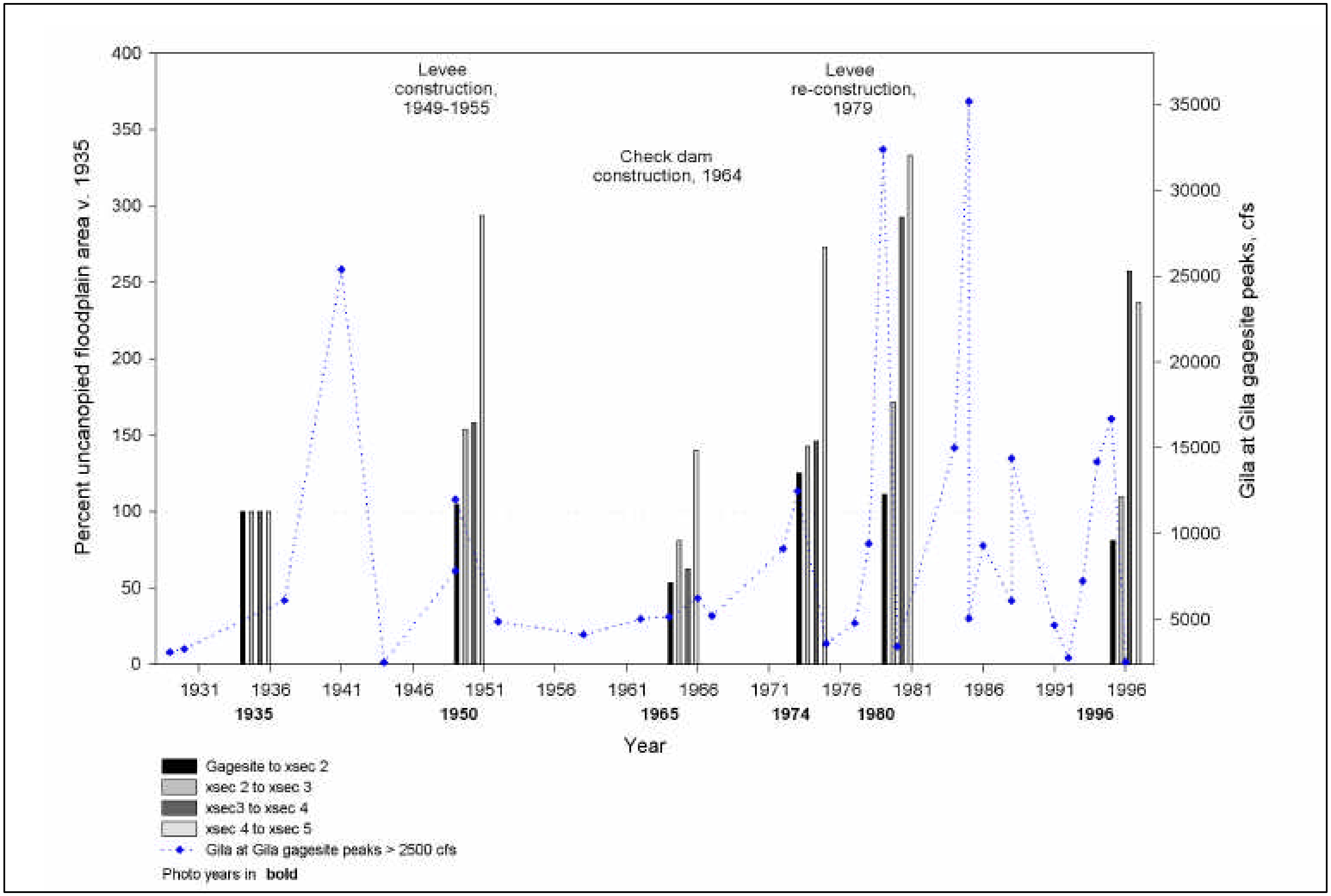



**Figure 19. Gila at Gila gagesite flood peaks, 1928–1996, and changes in unvegetated bar and floodplain surface area, 1935–1996, from the gagesite to cross-section 5. Change in unvegetated surface plotted as a percentage of unvegetated area in 1935.**

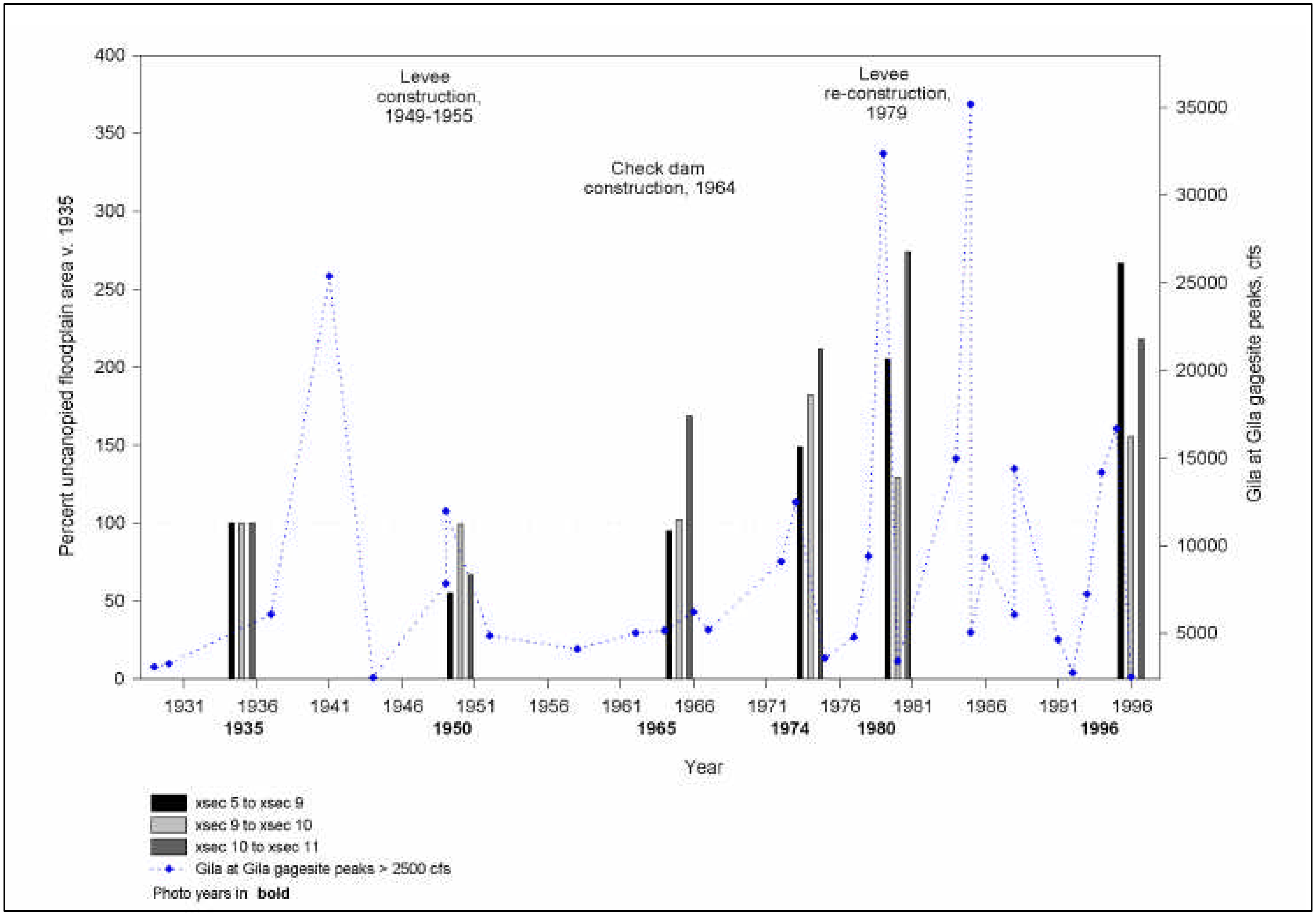



**Figure 20. Gila at Gila gagesite flood peaks, 1928–1996, and changes in unvegetated bar and floodplain surface area, 1935–1996, from cross-section 5 to cross-section 11. Change in unvegetated surface plotted as a percentage of unvegetated area in 1935.**

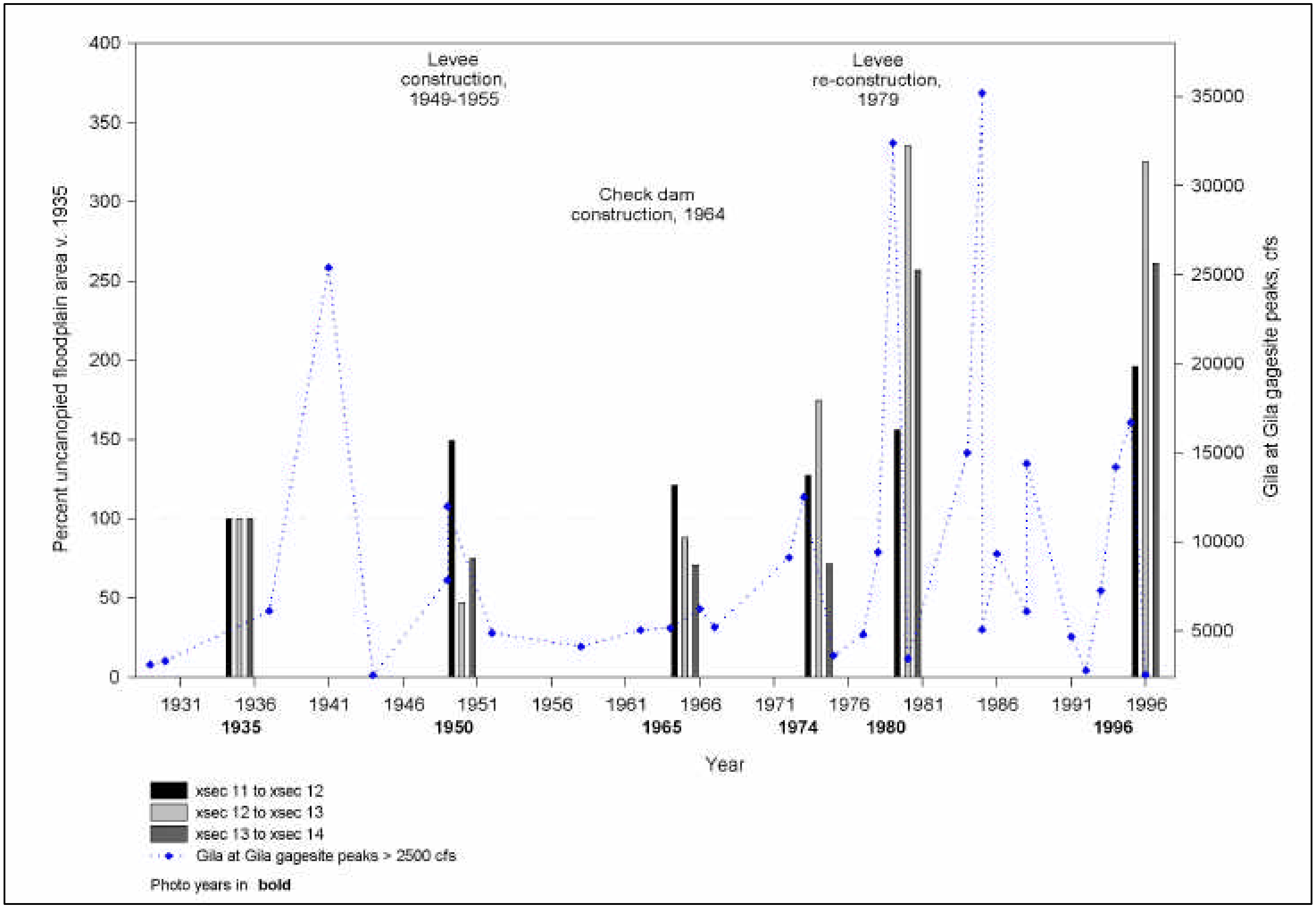



**Figure 21. Gila at Gila gagesite flood peaks, 1928–1996, and changes in unvegetated bar and floodplain surface area, 1935–1996, from cross-section 11 to cross-section 14. Change in unvegetated area plotted as a percentage of unvegetated area in 1935.**

**Table 5. Ten highest flood peaks, Gila River at Gila gagesite, 1928-1969 (USGS, 2003).**

| Date | Discharge (cfs) |
|---|---|
| 2/16/1937 | 6110 |
| 9/29/1941 | 25,400 |
| 12/28/1948 | 7850 |
| 1/13/1949 | 12,000 |
| 3/8/1949 | 5980 |
| 1/19/1952 | 4870 |
| 8/2/1962 | 5040 |
| 9/24/1964 | 5160 |
| 12/23/1965 | 6240 |
| 8/13/1967 | 5210 |

By far the largest flood that occurred in the period between 1928 and 1970 came through the valley in September 1941, peaking at 25,400 cfs at the Gila gagesite. It was described as "disastrous" by one valley resident, who noted that "the place was still a mess" when he arrived in 1946 (interview, April 2000). At least some flood scarring across fields that is visible on the 1950 airphoto could be from the 1941 flood. Two floods occurred in December 1948 and January 1949. The latter peaked at about 12,000 cfs at the gagesite. These were followed in magnitude by a 6240 cfs flood in December of 1965. Although virtually everyone interviewed who had experience of these earlier floods remembered the 1941 and 1949 floods, few even mentioned the 1965 event.

Local tributaries downstream of the Gila gagesite can add significantly to mainstem floods passing through the valley. Peak flow at the Gila gagesite during the 1949 flood was measured at 12,000 cfs at the Gila gagesite. This discharge has a calculated RI of about 15 years (see Figure 22). Although the relative contributions of tributaries within the valley are unknown, they added a combined total of at least 5000 cfs to the mainstem. A crest stage gage (known as the "near Cliff" gage) was installed on Iron Bridge, downstream of all major valley tributaries, around 1938 (interviews, April 2000 and February 2001). Crest stage records were located and showed that peak flow was 17,200 cfs at this location (Aldridge, 1970).

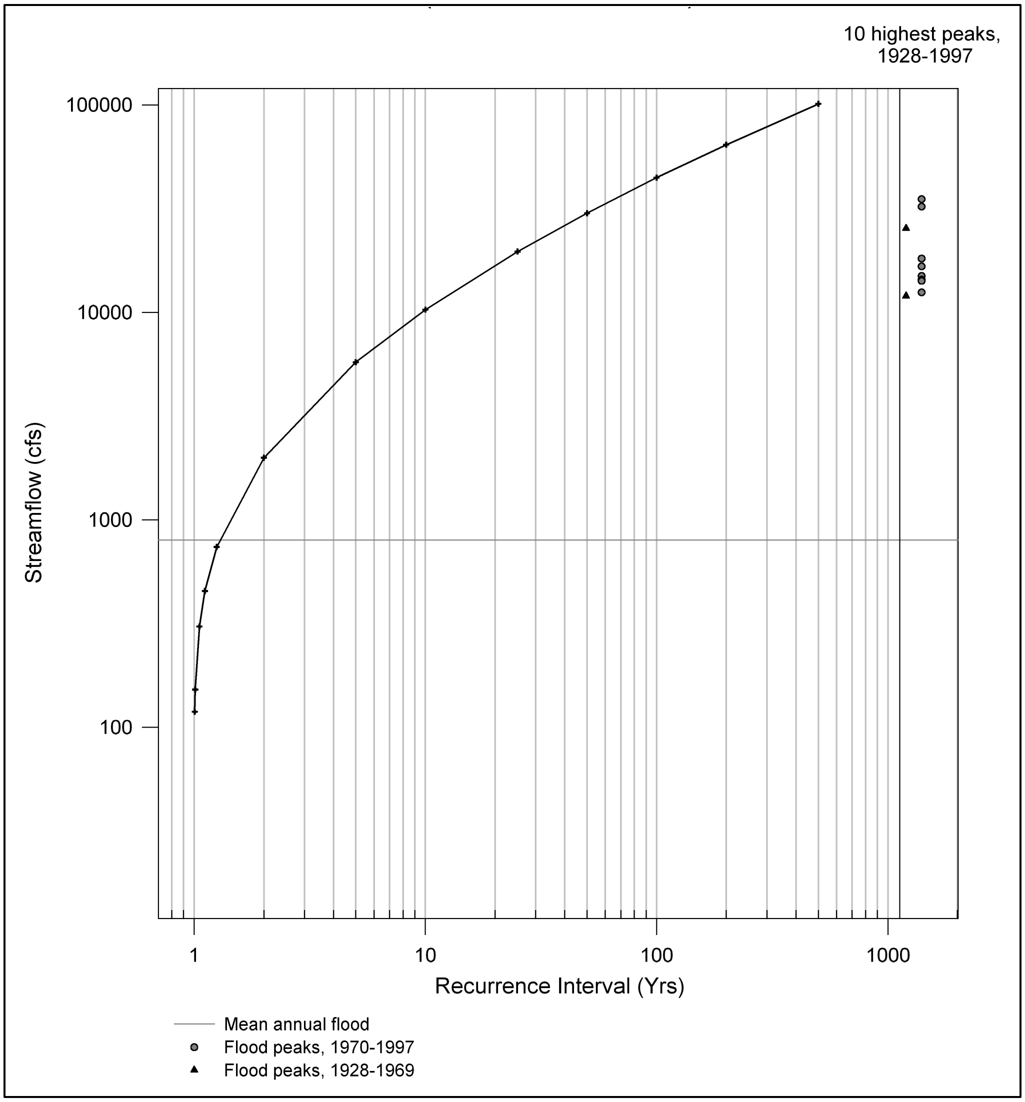



**Figure 22. Calculated recurrence intervals for Gila River at Gila gagesite peaks, 1928–1997, and 10 largest gaged flood peaks (USGS Bulletin 17B, 2003).**

Flooding in 1965 was similar. At the Gila gagesite on December 23, peak flows were measured at only 6240 cfs, with an RI of about six years. No discharge values are available from this time for Mogollon Creek, but Duck Creek peak discharge was calculated at 2970 cfs. Discharge calculated at the crest stage gage "near Cliff" was 13,500 cfs, suggesting that other tributaries between the gage and Duck Creek added something like 4300 cfs to the mainstem during the flood (all data from Aldridge, 1970).

***Aerial photography interpretation.*** River channel locations in 1935 and 1950 are outlined on Figure 23. Examination of the 1935 and 1950 aerial photographs found fewer major shifts in river planform during this period than in the previous period. However, the river's planform in 1935 is more braided than in 1950, indicating that at least one of the floods prior to 1935 was of sufficient force to create a complex of overflow channels across floodplains (Nanson & Croke, 1992). Meander scars that appear across fields in 1950 were probably caused by the 1941 flood, although little field loss to erosion seems to have occurred during either the 1941 or 1949 flood events (see interview data, below). The figure also shows that floodplain vegetation was widespread throughout the valley itself in 1935, but it appears spotty in places and not of uniform age. Upstream of Spar Canyon, however, unvegetated floodplain surfaces were extensive in 1935. A number of possible explanations suggest themselves. In this more constricted reach above the wider floodplains of the valley itself, floodplain vegetation may have been more completely scoured an earlier flood than it was downstream. Erosion may have cut a deeper channel here than in the valley, making reestablishment of vegetation less likely as well. Perhaps anthropogenic impacts, like extensive grazing of cattle in the riparian zone, were responsible. The exact cause for the difference is unknown.

Figure 24 maps change in extent of riparian vegetation between 1935 and 1950. As on all of the vegetation maps, layering of unvegetated areas depicts in gold those in which no vegetation existed at either of the two dates shown, while areas from which vegetation was lost between the two dates appear yellow. Figure 24 shows that little growth had been generated in the upstream end of the study reach even by 1950. Again, perhaps the greater constriction between canyon walls is responsible; the 1941 flood (25,400 cfs) may have scoured floodplains in this area and deposited their sediments downstream. In the valley itself, riparian vegetation was still dense in 1950, except—glaringly—where recent levee construction had occurred, between cross-sections 3 and 5, and downstream near cross-section 10. The Bear Creek confluence area, bare of vegetation in 1935, remained so in 1950.

Figure 25 shows the 1965 aerial photography mosaic, with the river channels of 1950 and 1965 outlined. Levees constructed by 1950 are also shown. River meanders and overflow channels visible in 1950 had been constrained by 1965 between levees which by then formed a nearly unbroken line—except for openings left for tributary drainages—along the riparian corridor. Levee construction accounts for the narrow band of cleared area that extends downstream from cross-section 4. Changes in extent of riparian vegetation from 1950 to 1965 are

**Cliff-Gila Valley, New Mexico**
**Base image: Semi-controlled mosaic, 1950 aerial photography courtesy Earth Data Analysis Center, Albuquerque**

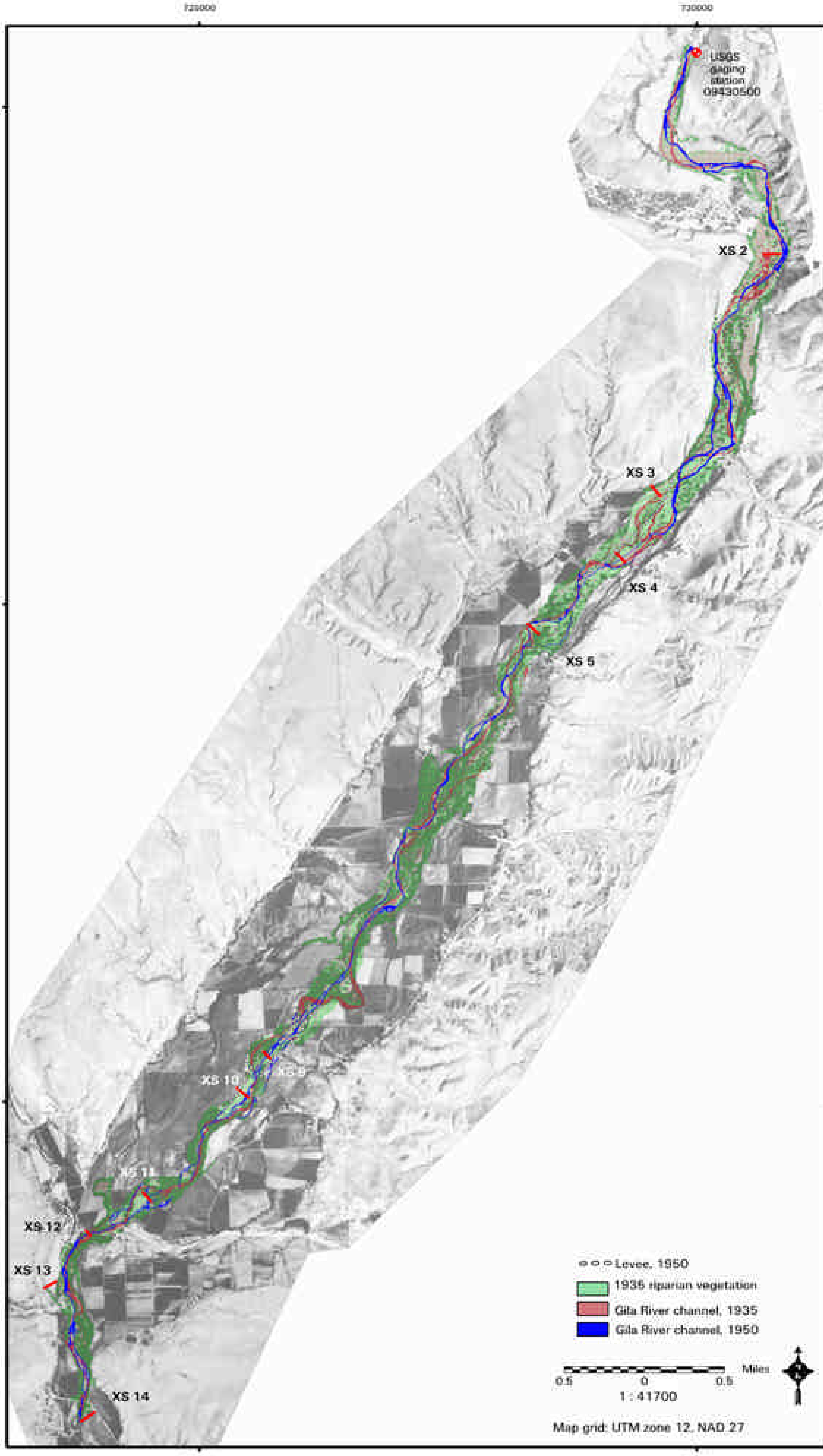



Figure 23. Map of 1950 aerial photography, 1935 - 1950 Gila River channel, and 1935 riparian vegetation.

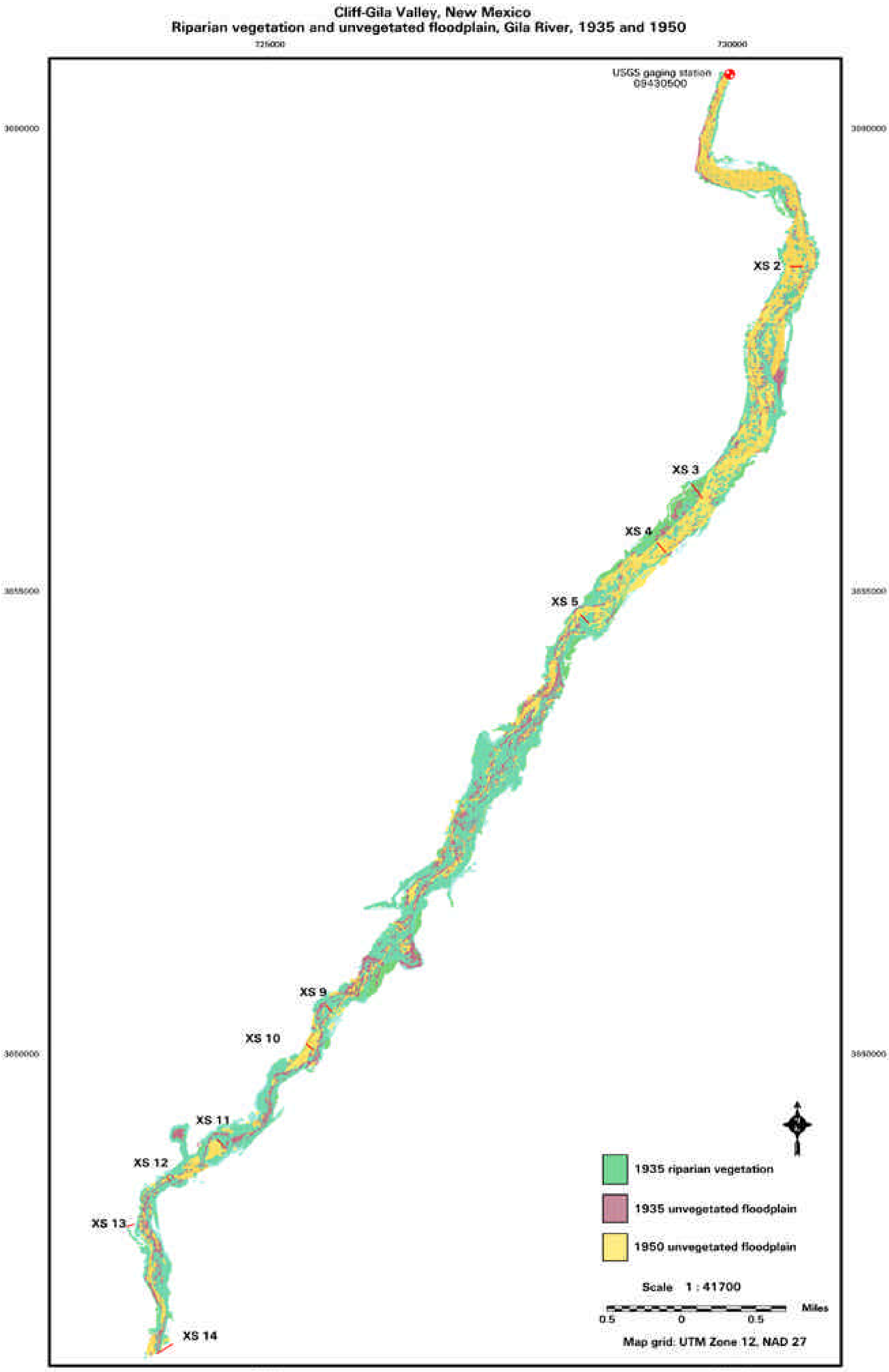



Figure 24. Riparian vegetation and unvegetated floodplain, 1935 and 1950.

shown in Figure 26. By 1965, vegetation had begun to regenerate in the previously scoured upstream reach above Spar Canyon, but the strip cleared during levee construction was continuous from cross-section 4 through the study reach, including the area between cross-sections 5 and 9, where riparian vegetation was intact across the entire width of floodplain in 1950. Vegetation on floodplains shoreward of the cleared strip remained in place.

***Interview and archival data.*** As described previously, some erosion and river braiding seems to have accompanied floods early in the century. But in 1935 major channel incision was not evident. In 1934 and 1935, USGS (1952) mapped the Gila River from Redrock, New Mexico upstream to the Middle Fork during a survey for potential dam sites. The channel was mapped on five-foot contours. On their survey map, the roadway approaching the Highway 211 bridge is only about three feet above the channel thalweg. Today the thalweg lies at least 10 feet below the roadway. At a point farther upstream, just below Spar Canyon, the 1934–5 survey mapped the channel at an elevation of about 4587 feet. The same location was surveyed by Gordon in 1997 at an elevation of 4576 feet, a drop of 11 feet.

Anecdotal accounts of the period between 1930 and 1970 also support the conclusion that these were mostly depositional years within the river corridor. Neither the 1941 nor 1949 flood appears to have created significant erosion. One local irrigator noted that during the 1941 flood "all the streams were flowing clear"; i.e., not carrying large amounts of sediment (interview, February 2001). This suggests an event during which little sediment was either deposited in fields or carried from them. Another said that both the 1941 and 1949 floods "had little effect" (interview, February 2001). Another resident, however, described the 1941 flood as depositing large amounts of flood debris across fields throughout the valley (interview, April 2000). One person interviewed (February 2001) watched the 1941 flood from Iron Bridge and saw "pigs, cows, and trees" being washed down the river. Water was "over the road waist-deep," he said, but the approaches to the bridge never washed out. A house on the west river bank just upstream of Iron Bridge was covered to the top by floodwaters; its inhabitants climbed the willow trees in their yard. The trees remained in place.

Two people interviewed suggested that floods previous to levee construction in 1950 were taken in stride by most residents. One told me that "before the dikes were built, we expected floods, and didn't think much of it" (interview, February 2001). Another noted the value that farmers placed on sediment deposited in their fields by earlier floods. "Cleanup is hard—and back then we used

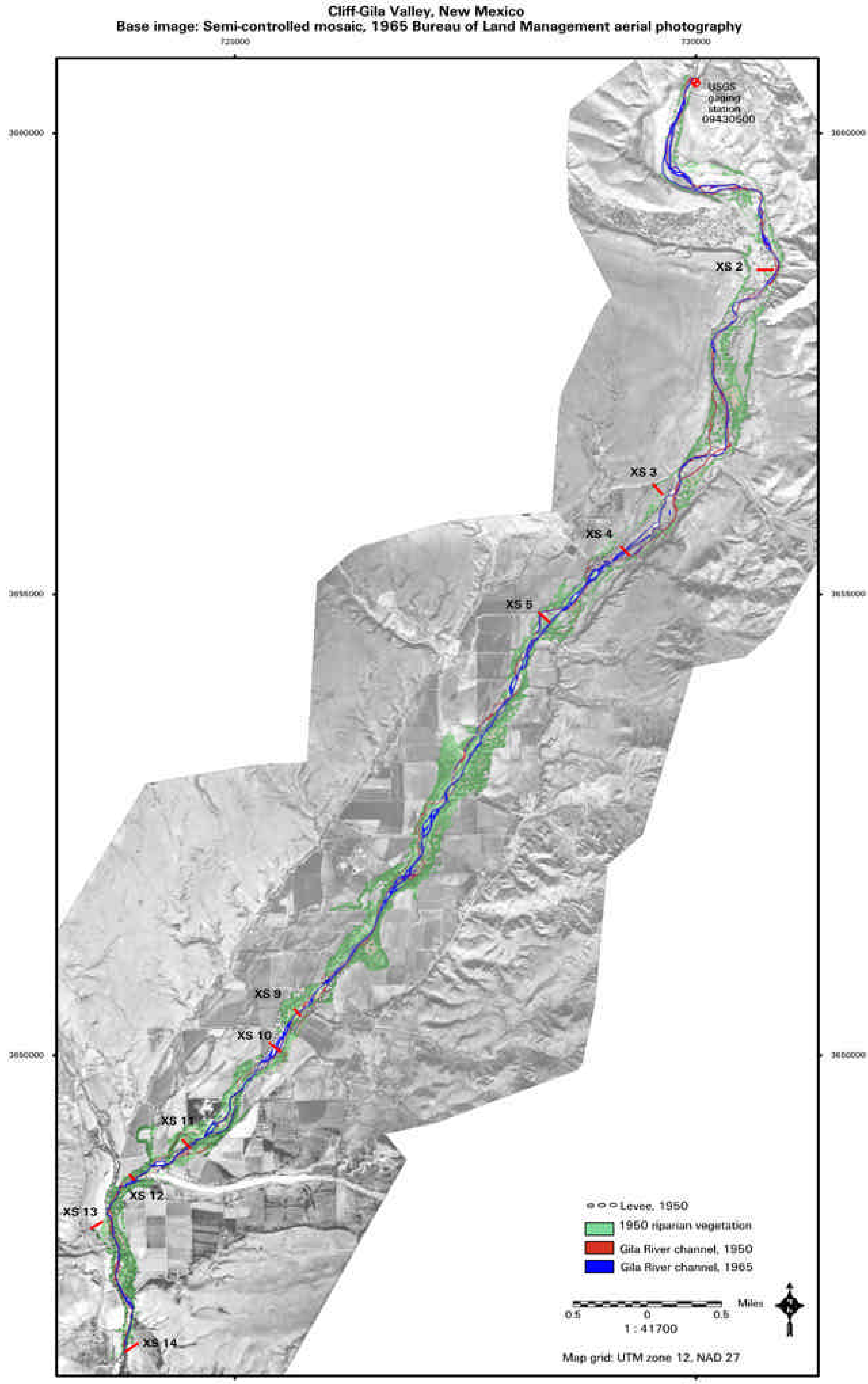



Figure 25. Map of 1965 aerial photography, 1950 - 1965 Gila River channel, and 1950 riparian vegetation.

## Cliff-Gila Valley, New Mexico
### Riparian vegetation and unvegetated floodplain surface, Gila River, 1950 and 1965

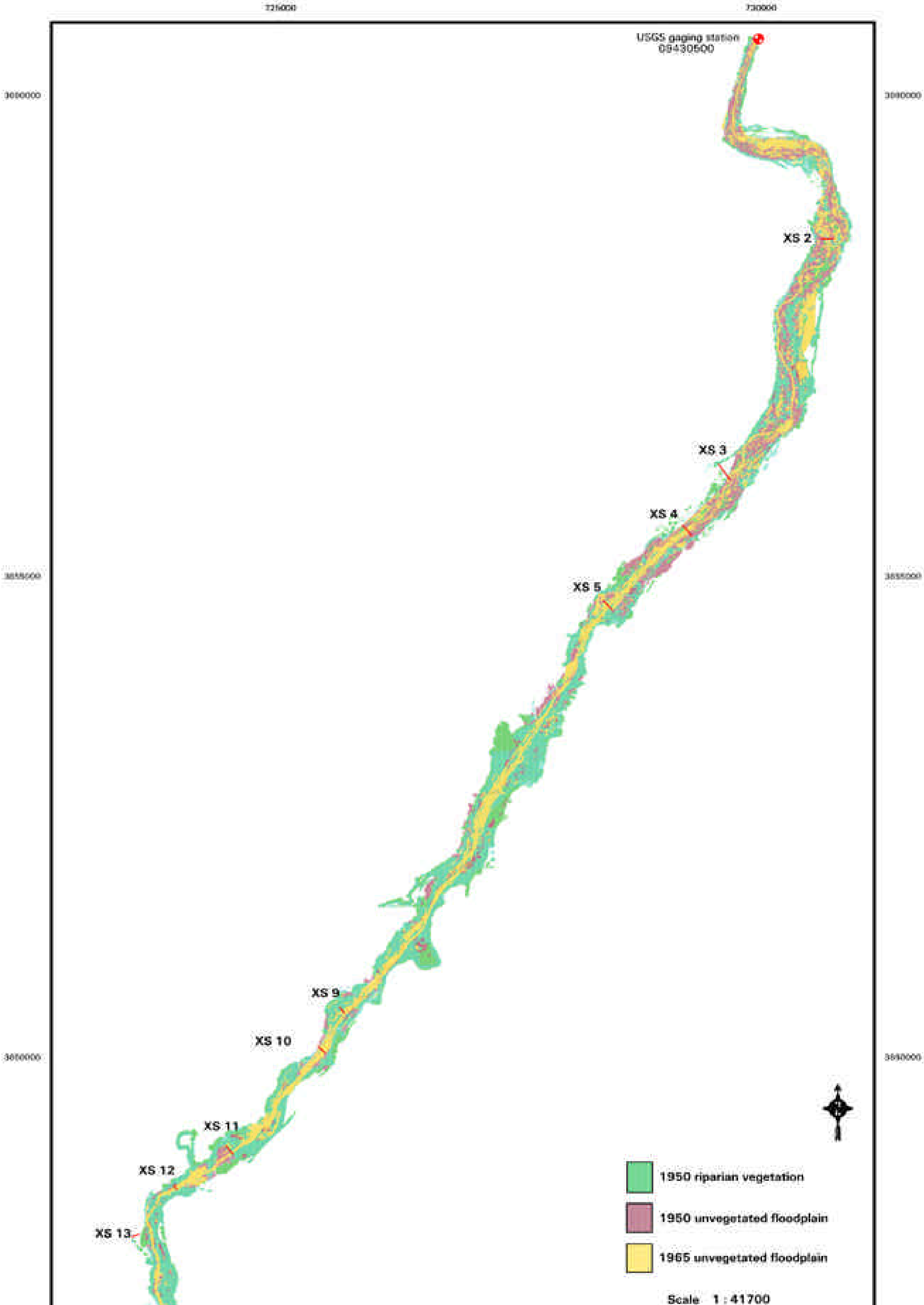



Figure 26. Riparian vegetation and unvegetated floodplain, 1950 and 1965.

horses [to clear flood debris]—but it was worth it," he said (interview, February 2001). Both statements indicated that farmers were less concerned with the potential *loss* of fields to erosion than with the time and work required to clear debris from fields. This is not to say that no losses were suffered from floods; floodwaters could and did damage crops, and as noted below, frequently forced extensive repair and cleaning of irrigation ditches throughout the valley.

Local residents requested assistance from the Bureau of Reclamation (BOR) and Army COE after the 1949 flood. Although neither BOR nor the Army COE was apparently much impressed by the 1949 flood (which peaked at 12,000 cfs at the Gila gagesite), it was significant enough to convince another federal agency, the Agricultural Adjustment Administration (AAA), to dredge the river channel and to construct dikes at the approach to the Highway 211 bridge to protect nearby fields from future floods (interview, April 2000). Their logic for constructing the dikes is instructive. The AAA found the river "riding on an 8-foot delta" around the Highway 211 bridge, above the level of nearby corn fields (interview, April 2000). One farmer also remembered a surveyor at about this time confirming that land along the base of hills west of the river near the bridge was "about three feet lower than on the east side." The surveyor told him that because "the river's going to go that way [toward the west]," no high levee was needed on the east. Nonetheless, the 1949 flood was extensive enough to enter the farmer's field at Northrup Canyon, on the east side of the river, and it "built up the sediment deposits in the field." (interview, February 2001).

The many small floods during this period were also depositional, by chance or by design. Many people described how farmers "created" land along the Gila River and Bear Creek by building small field dikes to deliberately capture floodwaters and allow sediment to settle onto field surfaces (e.g., interviews February 2001). Two residents were asked about what they remember of the appearance of the local channels, both the river's and its tributaries'. Both recalled that the river and Mogollon Creek, in particular, were aggraded. Both were bounded by "sandy, grassy plains," and their channels were mostly composed of "sand and gravel." Both were struck by the contrast between what they remember of the appearance of these channels 40 to 50 years ago, and the "rocky" floodplains and channels of today (interviews, April 2000). Floodplain material visible in the 1935 and 1950 aerial photographs is darker and more mottled than it appears in the 1965 and later airphotos, suggesting that the floodplains were once composed of varying parts of sand, loam, and small gravels instead of the coarse cobble that is now predominant. The persistence of dense riparian growth of varying ages near the Highway 211 bridge into the 1960s noted earlier suggests that the channel had not yet experienced significant downward erosion even by 1965.

Numerous interview statements attested to a lack of braiding and major erosion within the river's floodplains between about 1940 and 1970. One resident said that the river was deeper and had "more water" when he was young (in the 1930s and 40s), and that there was a heavy growth of "black willows" along the river just upstream of Iron Bridge (interview, February 2001). Two others remembered that the river was "deeper and colder, with more vegetation" in the 1940s (interviews, February 2001). Yet another (interview, February 2001) took a Christmas raft trip down the river "around 1956"; he recalls that the river channel near Riverside was then narrow, perhaps 50 to 60 feet wide, and that the water depth at the time of their trip was eight to 12 feet. Two other residents (interviews, April 2000) also remembered that the river was deeper and narrower, and seemed to have "more water," when they were children in the late 1960s. Interview statements strongly suggest that substantial widening, incision, and braiding of the channel in the river corridor did not begin for some years after the period of levee and check dam construction described below.

***Check dam construction.*** As noted above, local tributaries can contribute significant streamflow to the mainstem during flood events. They can also carry large amounts of sediment into the mainstem channel. For example, the alluvial fan at the base of Spar Canyon has played a major role in determining the location of the river channel during the past century, and flows entering from Spar Canyon even during moderate, localized precipitation events can be sufficient to "blow out" the 2-foot cobble berm at its base that diverts Gila River water into the Fort West ditch (personal observation, 2000; interview, February 2001).

Twelve local drainages ("arroyos") tributary to the Gila River were dammed between 1960 and 1964 under a plan prepared by the Grant Soil Conservation District (1959). They include every major tributary into the agricultural area of the valley except Spar Canyon. The dams were designed as sediment control structures for "[f]loods from the side arroyos [that] cause frequent damage to irrigated cropland, irrigation systems, levees, dikes, and roads" (5). The plan noted that crops suffered the "principal damage caused by floodwater," while irrigation canals sustained the most damage from sediment:

> Canals are filled frequently with sediment from the arroyos which require cleaning of the canals…Deposition of sediment on cropland during the growing season occurs with

> sufficient frequency to prevent full potential crop yields, and often requires re-leveling of the land. Arroyos which are channeled into the river deposit sediment and debris in the Gila River channel causing the river to flow against and erode the levees (6).

Although the report did not evaluate "streambank erosion on the Gila River" (8), erosion apparently was not extensive, since "[s]teep slopes at the edge of flood plain on both sides of the river define the approximate…division between the irrigated farmland and the grazing land" (3). In other words, the agency identified the river's floodplain at about the same elevation as farm fields, with no sharp vertical break between the two as exists today.

Spar Canyon was not dammed, but dams were constructed on every major tributary or "canyon" downstream of it in the valley (see Figure 5). The sediment detention ponds were estimated to have a useful life of about 50 years. Sediment has already been removed from at least one pond, on Bell Canyon; it was used to construct a secondary levee east of the Highway 211 bridge (interview, February 2001). Together, the detention ponds were estimated to capture 90 percent of the sediment that had previously entered the river channel from about 27,000 acres of watershed. The control structures were specifically designed with large enough outlet conduit pipe to drain any retained floodwaters within 72 hours of a flood event, typically into the nearest irrigation ditch. Water was conveyed by the ditch back to the river channel, in order to honor New Mexico's obligation to deliver Gila River water to Arizona (interview, February 2001).

One ditch official who has worked on the control structures said that no alluvial fans had been created at the base of the dammed canyons since construction of the dams, and that three or four of the sediment traps were nearly filled (interview, February 2001). Total sediment storage capacity of the detention ponds was 1828 acre-feet. No detailed analysis of the precise effects of diverting this quantity of sediment from the river channel was done for the current study. However, it seems clear that a potential impact of sediment diversion would be a reduction in Gila River sinuosity, as meanders once formed by alluvium transported into the river bed from tributary canyons were removed during mainstem flooding.

River sinuosity is counter to channelizing efforts, however, which are aimed at constraining both floodwaters and active floodplain area that might otherwise serve as farmland. As noted above in the Grant Soil Conservation District's 1959 report, the alluvial fans sometimes forced the river against levees on opposing banks, threatening the levee structure. On the other hand, loss of incoming sediment, especially coarse gravels and larger materials, can reduce channel roughness. Some of the river's hydraulic energy during floods is spent against channel roughness and in transport of these materials, and their absence from the channel may have increased the hydraulic energy available for erosion within the river channel and, ironically, the levees themselves (Bravard, Kondolf, & Piegay, 1999; Fujita, 1989).

***Levee construction.*** Levee and dike construction began in the mid-1940s with construction of a few small dikes along the river corridor. One resident, for example, told me that he and his father built a low dike in 1944 on river left, the east side, just above the Highway 211 bridge. The dike extended upstream to their property at Northrup Canyon. He remembered Northrup as a problem. An opening was left in the dike for flows down the canyon. The river entered their field through this opening during the 1949 flood, washing away the levee in the process. They rebuilt the dike after the flood (interviews, February 2001).

Levees first appear on the airphotos in 1950 just upstream of the first irrigation diversion points, downstream of Spar Canyon, around the Highway 211 bridge, and on some tributary drainages near Iron Bridge. Work around the Highway 211 bridge was extensive. One resident (interview, April 2000) recalled that SCS or AAA cleared, channelized, and straightened the river both up- and downstream of the bridge. The agency also "got rid of the old meander on river right" around 1950. Their removal of this meander is clearly evident in comparison of the 1950 and 1935 channel locations at cross-section 9; another major meander bend just upstream may also have been mechanically closed off (see Figure 23). Although one person remembered that no dikes were built below the bridge until sometime during the 1950s (interview, February 2001), one very obvious levee appears on the 1950 airphoto just downstream of the bridge on river right.

Large-scale construction of levees in the valley began about 1950. One resident said that, beginning that year, levee construction was ongoing "all the way upriver" from the 211 bridge—except for around Domingues Canyon (interview, February 2001). Another recalled that levees were constructed "all the way up" both sides of the river from the 211 bridge beginning about 1950 (interview, February 2001). One rancher described the levees built by 1950 in the reach just downstream of Spar Canyon as "re-centering" the river in the valley downstream of Spar Canyon (interview, April 2000). By 1965, nearly all the levees that would be constructed in the valley had been built, and they lined long reaches of the river throughout the valley. An April 1979 US Army COE report itemizes approximately 11 miles of levee from Spar Canyon to Iron Bridge. Their apparent locations on the 1965 aerial photographs were verified against maps produced for the New Mexico State Engineer's (1964) *Hydrologic Survey Report.* The 1964 report also maps "pilot channels" (excavated overflow channels) downstream of the Highway 211 bridge and along both sides of Bear Creek near the confluence.

Two people interviewed described construction of the levees and noted that, by law, levee borrow material was taken from the floodplain between the river and proposed levee site (interviews, February 2001). One remembered that early levees, around 1950, were constructed by valley residents with government funding, although he wasn't sure which government agency was offering the money. As a consequence, he said, "people were building dikes all up and down the river." They rented bulldozers for the levee construction work. Borrow material came from the floodplain, not the river channel itself, and "basically created another channel between the river and the field" (interview, February 2001).

***Depositional phase: summary.*** One major flood, in 1941, and a number of small to moderate floods between 1930 and 1970 had little erosive effect in the Gila Valley. Rather, these floods resulted in net deposition of sediment in the river channel and on floodplains. Most sediment was gravel-sized and smaller; some floods were “trained” by farmers onto fields in the valley to build soil. The river channel itself was described during this period as being “deeper,” with “more water” than it carries today. Extensive levee construction was completed along both sides of the river before 1965, and in some reaches, meander bends were closed by engineering work. Check dams constructed between 1960 and 1964 prohibited sediment previously deposited from major tributary drainages within the valley from reaching the river or floodplains. Riparian vegetation lost from upstream areas during the period before 1935 regenerated by 1965 and vegetation across floodplains throughout the study reach that year was intact, except for a relatively narrow, barren band flanking the active channel and delineating the area of levee construction. Levees were built close to the active channel, and where they existed on both sides of the river, it was rather tightly constricted between them.

**Erosion: 1970–1996**

The depositional environment in the Gila Valley gave way to erosion beginning with a 12,500 cfs flood in 1972. Flood erosion after 1980 was especially damaging. Data on floods and flood peaks during the period 1970 through 1996 appear below, followed by a comparison of relative flood magnitudes and frequencies during the depositional and erosional phases. Evaluation of erosional evidence for the period 1970–1996 from the aerial photograph series, from interview data, and from cross-section surveys completed in 1999 and 2000 follows.

***Gaged flood peaks.*** Floods since 1969 have left extreme impacts within the valley. Eight of the ten largest floods during the period of record for the Gila gagesite have occurred since 1969 (see Figure 22). Table 6 lists the ten peak floods during the years 1970–2001.

**Table 6. Ten highest flood peaks, Gila River at Gila gagesite, 1970-2001 (USGS, 2003).**

| Date | Discharge (cfs) |
|---|---|
| 10/20/1972 | 12,500 |
| 11/25/1978 | 9430 |
| 12/18/1978 | 32,400 |
| 10/02/1983 | 15,000 |
| 12/28/1984 | 35,200 |
| 10/11/1985 | 9320 |
| 9/21/1988 | 14,400 |
| 2/20/1993 | 14,200 |
| 11/12/1994 | 16,700 |
| 9/22/1997 | 18,200 |

A flood in October 1972 of 12,500 cfs resulted in the valley's being designated a federal disaster area (Clark, 1987: 422). The 1972 flood was dwarfed by those of December 1978, when flows peaked at 32,400 cfs, and December 1984, when they reached 35,200 cfs (USGS, 2003). The 1984 flood is said to have filled the valley "hill to hill" (interview, April 2000).

As during the previous period, valley tributaries contributed substantial discharge to the Gila during some floods. For instance, one resident remembered that Bear, Mogollon, and Duck Creeks were all major contributors during the flood of October 1972 (interview, April 2000), and another that Bear Creek, which crosses Highway 211 east of the river, "closed the road" for a week (interview, April 2000).

During the 1978 flood, discharge was measured at 32,400 cfs at the Gila gage at 11:30 pm on December 18. Discharge calculated from the gage located 12 miles upstream on Mogollon Creek was 10,100 cfs at about the same time. The Gila River crest therefore reached the valley before the Mogollon flood peak, but combined flood discharge within the valley probably reached about 35,000 cfs. Meanwhile, a crest stage gage on Duck Creek recorded a gage height of 9.36 feet, corresponding to a discharge of 5800 cfs (all figures from Aldridge & Hales, 1984), possibly increasing discharge to around 40,000 cfs near Riverside, a few miles downstream. The flood of record occurred in December 1984, reaching a peak of 35,200 cfs at the Gila gagesite. Gaged discharge on Mogollon Creek was more than 6000 cfs on the previous day, and its flood crest may have reached the Gila River confluence at roughly the same time as the mainstem crest, resulting in a flood of more than 40,000 cfs within the valley that year.

***Comparative flood magnitudes***. Instantaneous peak flood values from the Gila gagesite are available for the years 1928–1999 (USGS, 2003). The Gila gagesite measured two floods exceeding 11,000 cfs during the 40 years before 1970, but seven floods of greater than 11,000 cfs in the 29 years that followed, 1970 to 1996 (USGS, 2003). Selected daily mean flood magnitudes and frequencies are given in Table 7. The Gila gagesite is upstream of the valley, and therefore variances in flood magnitude and frequency are not the result of human-imposed change within the valley.

**Table 7. Selected mean daily flood magnitudes and frequency of occurrence at Gila gagesite, 1929-1969 and 1970-1996.**

| Flood magnitude (cfs) | 1929-1969 | | 1970-1996 | |
|---|---|---|---|---|
| | Number | Frequency | Number | Frequency |
| 1000-2500 | 124 | 0.3 years | 199 | 0.1 years |
| 2000-8000 | 28 | 1.5 years | 70 | 0.4 years |
| > 5000 | 3 | 13.7 years | 20 | 1.4 years |

From 1929 to 1969, moderate floods were the rule; a 25,400 cfs flood in 1941 proved the major exception during this period. Between 1970 and 2001, the valley experienced a closely-spaced series of major floods. Four of these carried discharge of greater than 15,000 cfs (RI > 15 years); more of these floods occurred during the "winter" months of November through March than during the 40 years previous. Figure 27 shows "winter" and "summer" peaks above 2500 cfs during the years 1928–1999.

IHA (2001) analysis was used to compare flood magnitudes and durations at the Gila gagesite during the period of gage record. The year 1969 was selected as a somewhat arbitrary dividing point to match the low flow impact analysis (see Groundwater analysis, below). Using 1969 as a division also splits the period between 1965 and 1974, when the third and fourth of the six airphoto sets were taken.

IHA may be calculated by either parametric or nonparametric analyses, where variation in streamflow is defined by deviation from mean or median values, respectively. Parametric analysis typically relies on a value of one standard deviation from the mean to measure significant alteration in streamflow. Parametric analysis of Gila River data frequently resulted in a value for one standard deviation from the mean that fell beyond the data range or below zero. When tested for normality in JMP (v. 3.2.1, 1997), the data from the period of gage record were strongly skewed. Therefore, non-parametric analyses, using percentile definitions of variation from the median, were utilized for all data runs. Figures 28 and 29 show high pulse durations and counts for each period. IHA defines a high pulse as streamflow greater than the 75$^{th}$ percentile of all daily means during the period of analysis. By this analysis, the number of floods did not greatly increase during the latter period (Figure 29), and were of only somewhat longer duration than floods during the earlier period (Figure 28). IHA calculates "hydrologic alteration" as

$$\frac{\text{Observed - Expected}}{\text{Expected}},$$

where *Observed* = frequency with which years fall within +/- 25$^{th}$ percentile of the median in the post-impact period, and *Expected* = frequency with which years fall within +/- 25$^{th}$ percentile of the median in the pre-impact period. Floods during the "post-impact" period, here defined as 1970 through 2001, demonstrated a modest hydrologic alteration of 0.25 for duration and only 0.13 for number. However, because the much shorter period of record for the Mogollon Creek gagesite precludes including its discharge in the analyses, they do not take into account any effects it may have introduced into variation between flood durations and counts between the two periods.

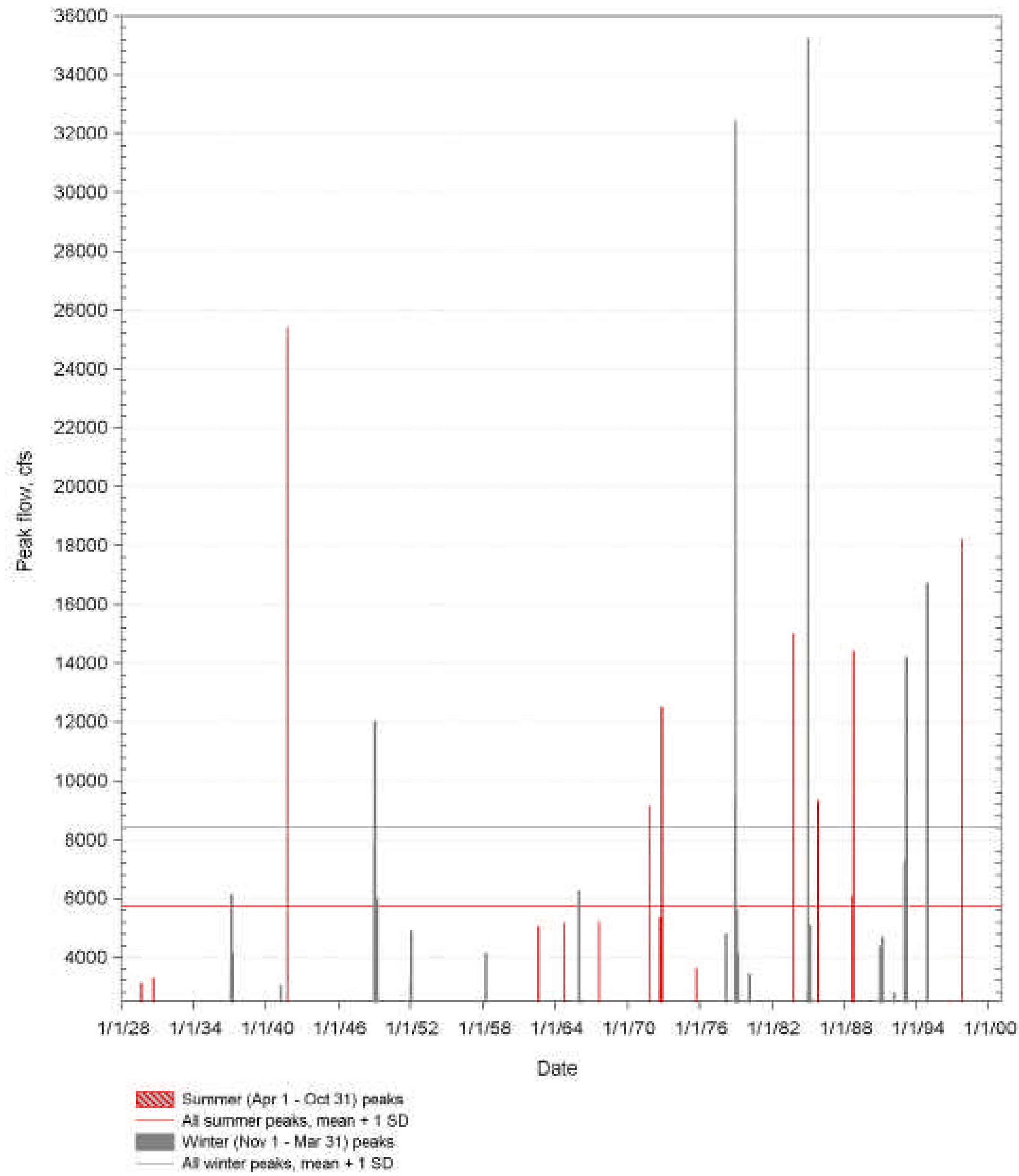



**Figure 27. Summer (April–October) and winter (November–March) peaks greater than 2500 cfs at the Gila at Gila gagesite, 1928–1999.**

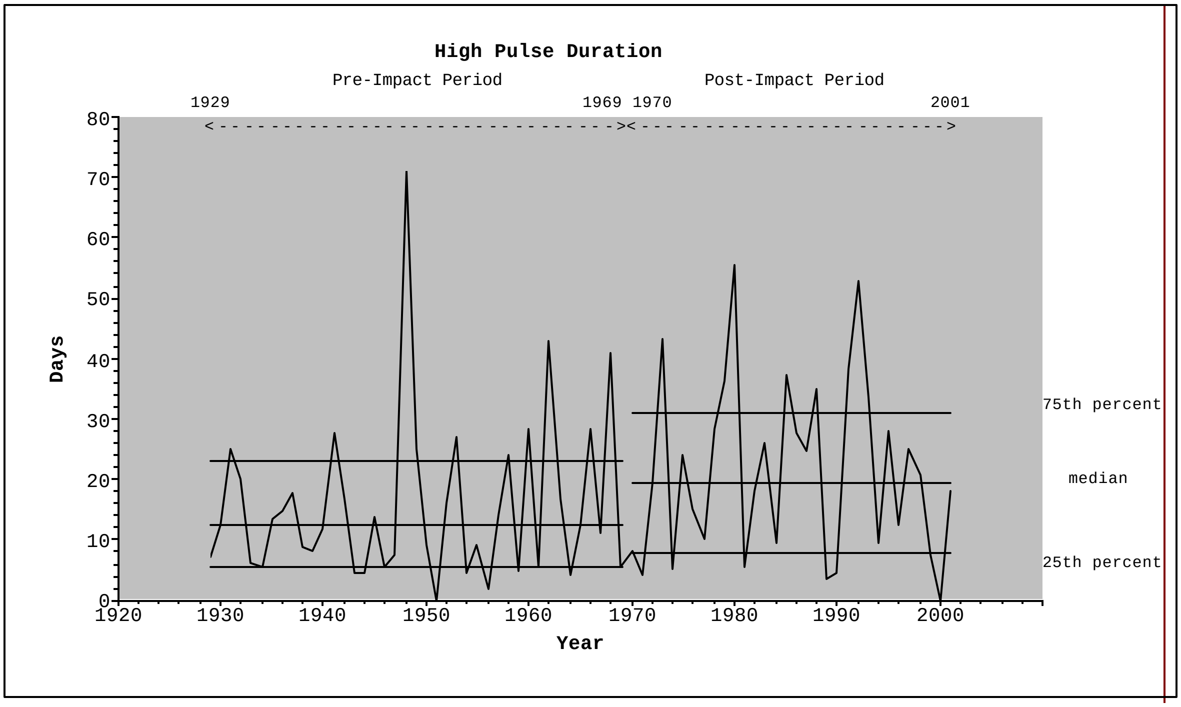



**Figure 28. IHA comparison of annual high pulse durations at Gila gagesite, in days, during 1929–1969 and 1970–2001 periods.**

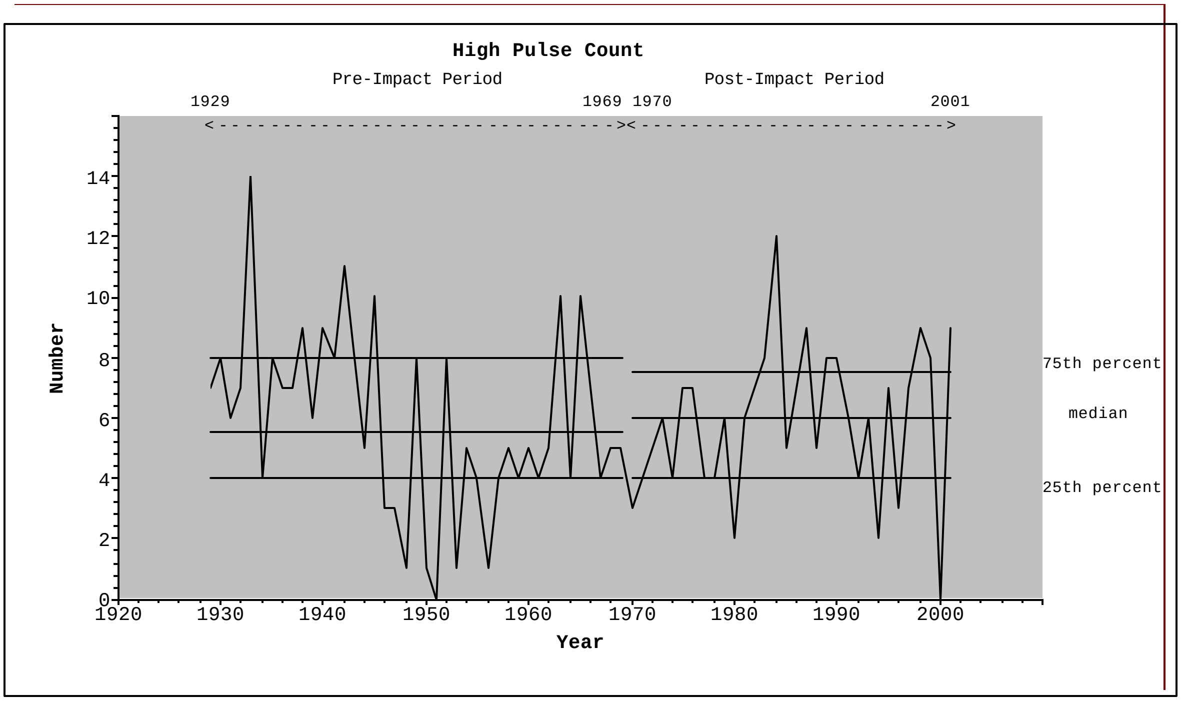



**Figure 29. IHA comparison of annual number of high pulses at Gila gagesite during 1929–1969 and 1970–2001 periods.**

Maximum discharges during 7-day and 30-day periods were also compared for the two periods, and showed a more dramatic variation. Maximum streamflow over these periods is calculated as the average from the appropriate number of days each year with extreme discharge values. The variance between the 1929–1969 and 1970–2001 periods appears in Figures 30 and 31, where the median for daily streamflow during the latter period falls above the 75$^{th}$ percentile for streamflow values during the earlier period. Calculated hydrologic alteration for each category was 0.35.

***Aerial photography interpretation.*** Between 1965 and 1996, the river and floodplains changed dramatically in appearance. The generally single thread of the 1965 Gila River channel became braided among a complex of islands, bars, and overflow channels and its vegetated banks were transformed into broad expanses of nearly barren floodplain. By 1996, large-scale incision and lateral erosion of the river channel was evident throughout the valley.

*1965 to 1974.* Shifts in location of the Gila River channel that appear after a 12,500 cfs flood in October of 1972 are probably the result of the river's occupying areas excavated for borrow material at the streamside toe of some levees. Figure 32 shows levees constructed by 1965, and the location of the Gila River channel in 1965, before the flood, and afterwards, in 1974. Green arrows point at locations where the 1974 channel shifted from the center or far side of the river corridor to the immediate toe of a levee. Although the figure depicts the levees as they existed in 1965, levees had been breached at about half of these locations, especially downstream of cross-section 5, by 1974. Possible ramifications of these shifts are evaluated in the Discussion, below.

The 1972 flood also appears to have cleared a much wider swath of vegetation than had been the case in 1965 (Figure 33). Although no large-scale reconstruction projects were undertaken after this flood, local residents probably attempted some repairs; bulldozers are used routinely in the river channel to rework diversion berms or other areas (Figure 34). On the other hand, it is unlikely that repair efforts would result in the scale of vegetation loss seen in Figure 33. No other major floods occurred between 1972 and 1974.

*1974 to 1980.* A massive flood (of probably about 35,000 cfs; see Gaged flood peaks, above) occurred in December 1978. Most of the original levees were "essentially destroyed" (Donegon, 1997) during this flood. Figure 35 shows the results of a preliminary assessment of the

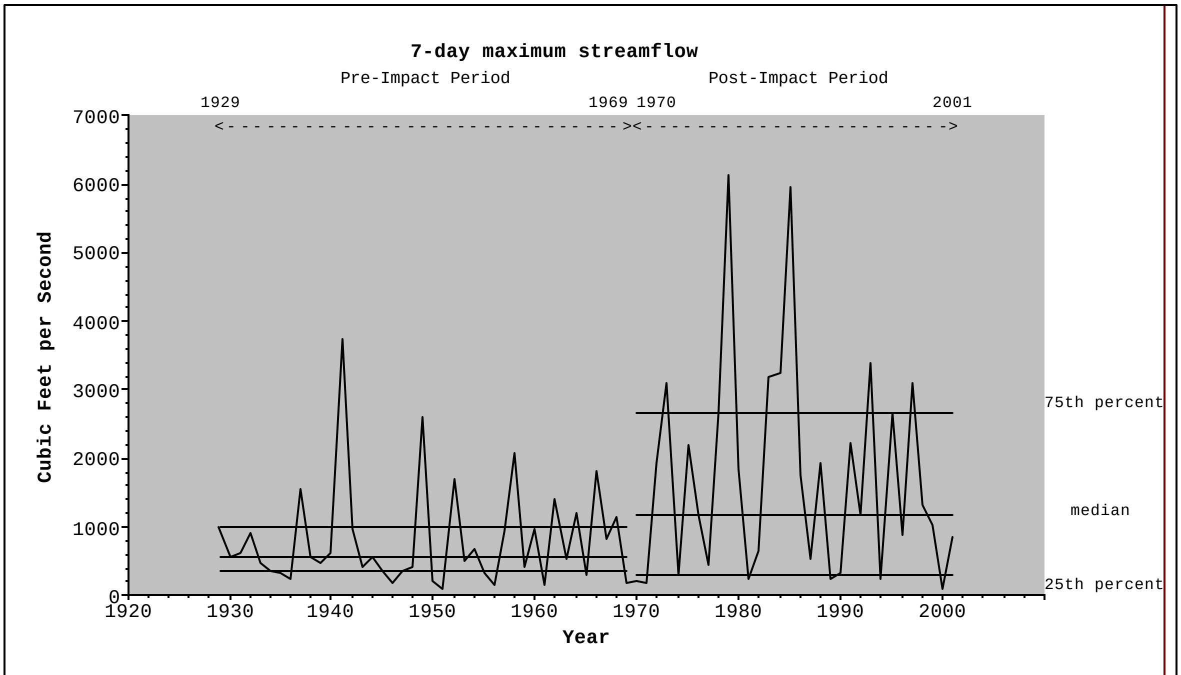



**Figure 30. IHA comparison of 7-day maximum daily mean streamflow at Gila gagesite during 1929–1969 and 1970–2001 periods.**

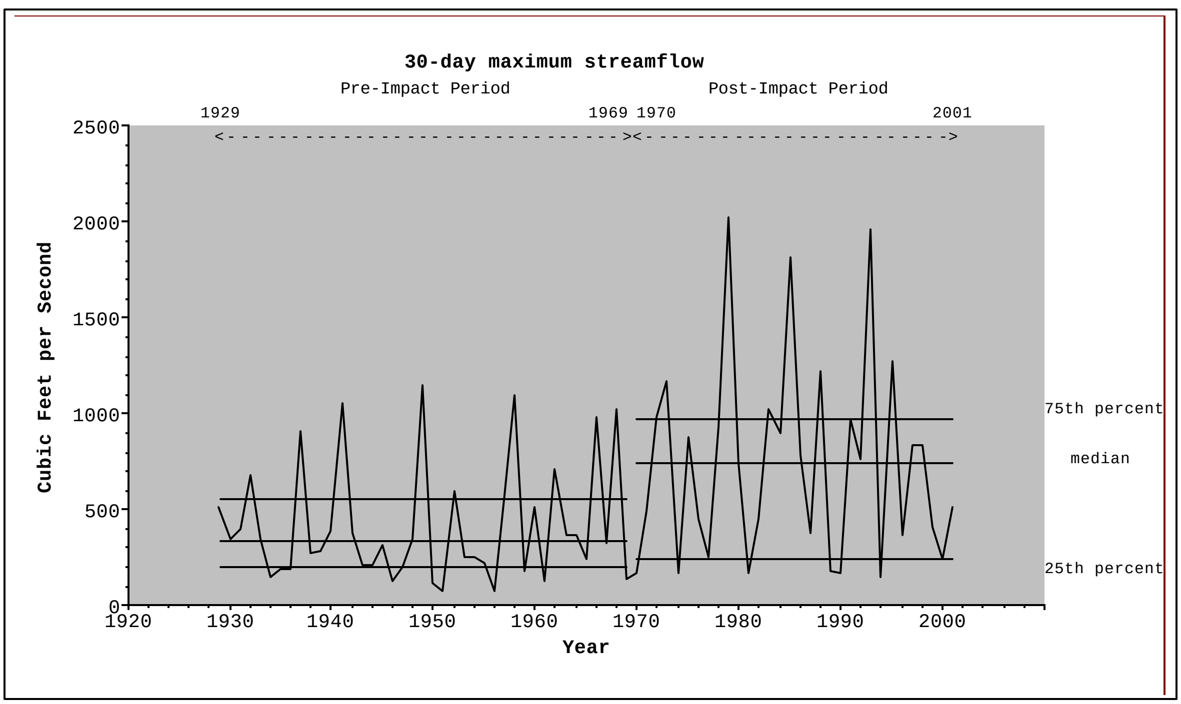



**Figure 31. IHA comparison of 30-day maximum daily mean streamflow at Gila gagesite during 1929–1969 and 1970–2001 periods.**

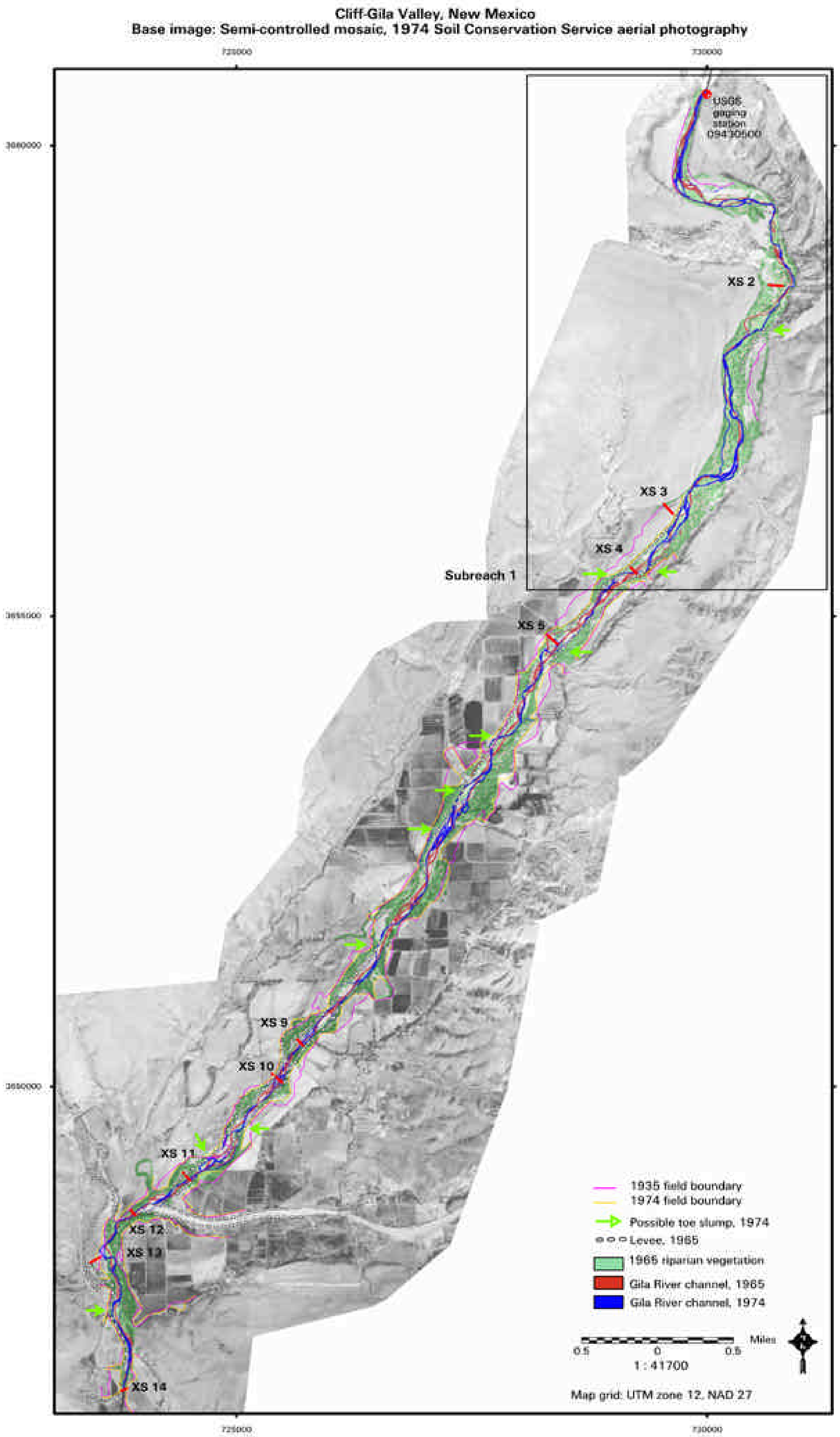



**Figure 32.** Map of 1974 aerial photography, 1965 - 1974 Gila River channel, and 1965 riparian vegetation.

## Cliff-Gila Valley, New Mexico
## Riparian vegetation and unvegetated floodplain surface, Gila River, 1965 and 1974

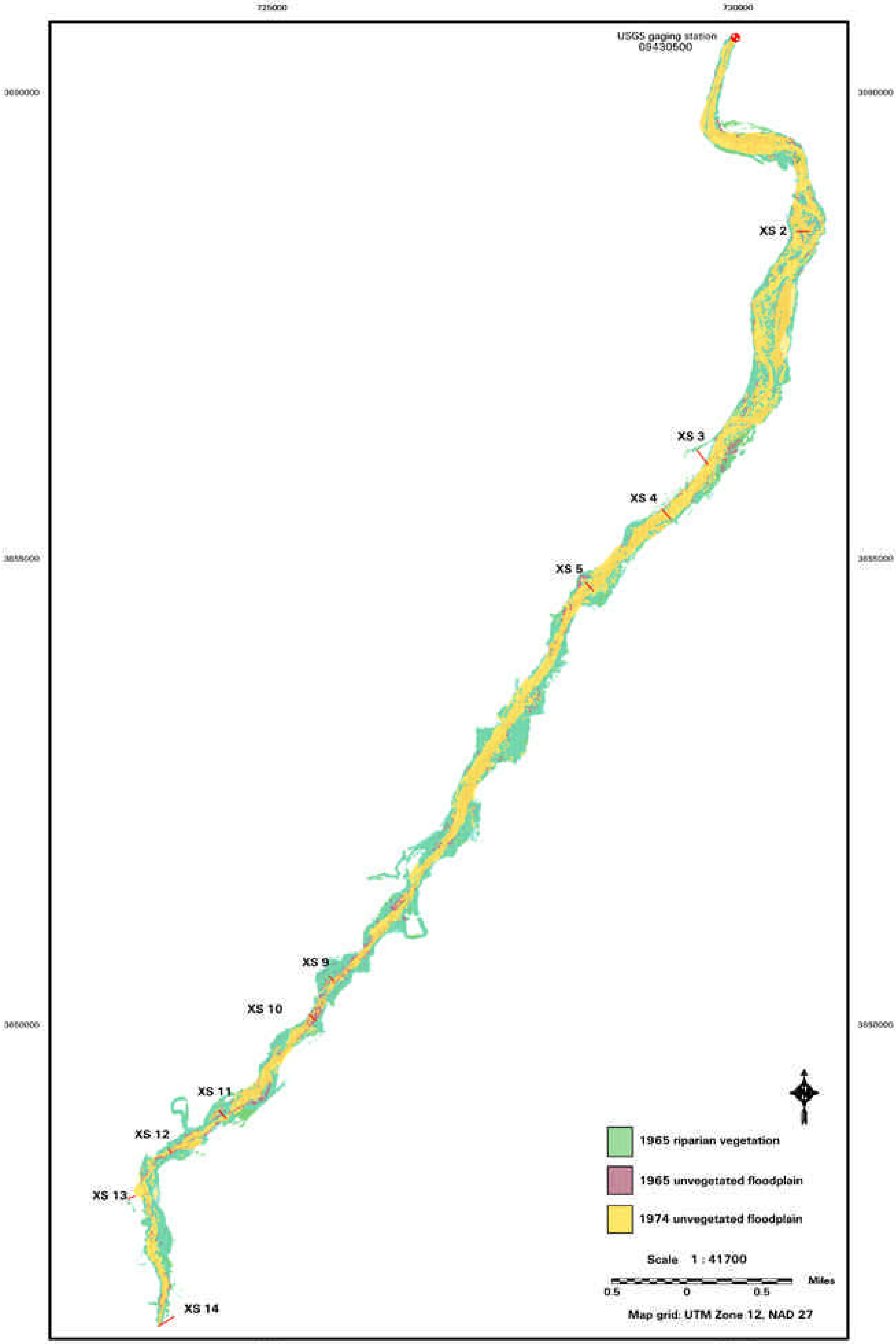



Figure 33. Riparian vegetation and unvegetated floodplain, 1965 and 1974.

**Figure 34. Recent bulldozer work at cross-section 5, September 1999.**

upstream ends of meander scars left across farmland after the 1978 flood. Floodplain vegetation remaining by 1974 was already much sparser than it had been in 1965 (cf. Figure 33). In Figure 35, vegetation from 1974 was mapped onto the 1980 orthophotoquad sets, and the upstream points at which meander cuts left by the 1978 flood were located (green arrows). Comparison of these points with 1974 vegetation shows that at 10 of the 13 meander cuts found, the band of vegetation between the floodplain and cultivated land in 1974 was sparse to nonexistent. This was the case between the levee at cross-section 3 and the field west of it; the resident who owns the field said that during the 1978 flood, the river cut through the levee to move back toward its 1918 channel. By 1984, the rancher had lost 32 acres of land during floods (interview, April 2000). No levees were in place in 1974 at four of the meander cut locations; whether additional levees had been constructed by 1978 is unknown. No meanders cut through a thickly vegetated area, or entered at the upstream end of one, although at three locations the river meandered into fields near the *downstream* ends of bands of vegetation.

Cliff-Gila Valley, New Mexico
Base image: 1980 Canteen Canyon and Cliff orthophotoquads, USGS

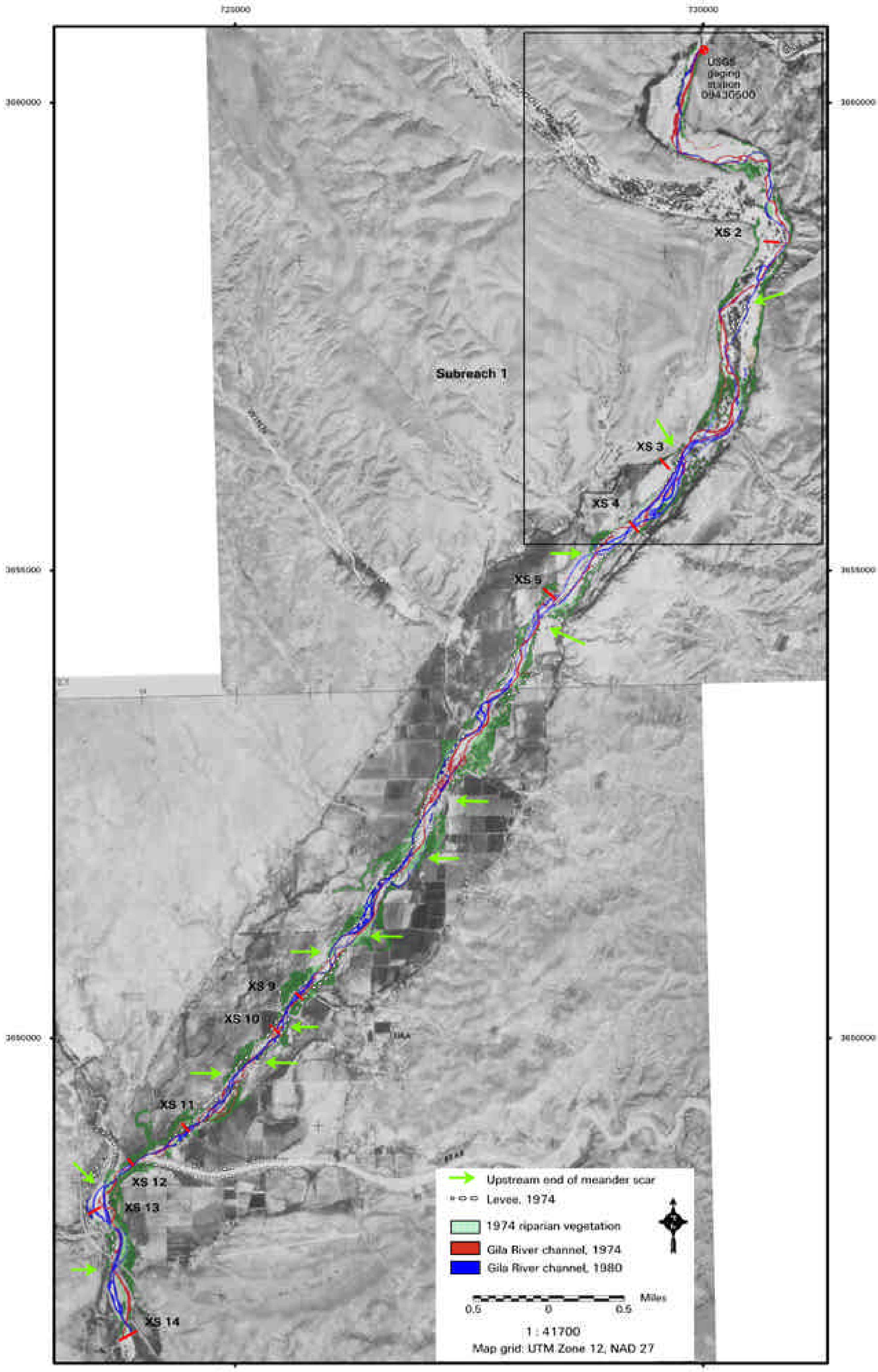



Figure 35. Map of 1980 aerial photography, 1974 - 1980 Gila River channel, and 1974 riparian vegetation.

The aerial photograph evidence suggests that the flood widened the swath of unvegetated floodplain within some reaches of the river and straightened the river channel, but extensive levee reconstruction in 1979 makes it impossible to determine from the 1980 airphoto where the main Gila channel was immediately after the 1978 flood. For example, the river was straightened and "recentered" in the valley between cross-sections 3 and 4 during the reconstructions (interview, April 2000).

It is clear, however, that widening and braiding of the river channel between 1974 and 1980 occurred throughout the valley, most extensively through the reach from Spar Canyon to cross-section 5 (Figure 35). The flood also sliced through the base of the alluvial fan at the mouth of Spar Canyon. Therefore, it seems likely that within the valley, the 1978 flood was driven more by waters arriving from upstream on the Gila River than from nearby tributaries like Spar Canyon. Precipitation records for the 10-day period preceding the 1978 flood were examined from three climate data sites: Gila Hot Springs (east headwaters); Glenwood (west headwaters), and the town of Cliff (Western Climate Data Center, 2001). Over 80 % of total precipitation was recorded at Glenwood and Gila Hot Springs, indicating that the majority of flood waters did reach the valley from the river's headwaters. This mainstem flood effect cleared a swatch through the riparian corridor upstream of Spar Canyon and probably downstream of it as well, at least on river left (again, post-flood reconstruction work on the long levee on river right between cross-sections 3 and 4 makes it impossible to say exactly how much vegetation was scoured by flood and how much by bulldozer). Vegetation loss from 1974 to 1980 is pictured on Figure 36. The band of cleared vegetation is considerably wider than in 1974, except between cross-sections 9 and 10. The river was constrained at this location by levees and by the Highway 211 bridge. However, just upstream of cross-section 9, a meander cut laterally across the floodplain into the same area the river had occupied in 1935. Vegetation at the meander point remained intact.

*1980 to 1996.* The December 1984 flood, a 35,200 cfs event, is the flood of record at the Gila gagesite. Like the 1978 flood, it was driven by heavy precipitation in the headwater regions of both the Gila River and Mogollon Creek. Precipitation records from Glenwood, Gila Hot Springs, and Cliff for the ten days previous to this flood show that 40% of precipitation recorded for the region was received at Gila Hot Springs, and another 38% at Glenwood (Western Climate

## Cliff-Gila Valley, New Mexico
### Riparian vegetation and unvegetated floodplain surface, Gila River, 1974 and 1980

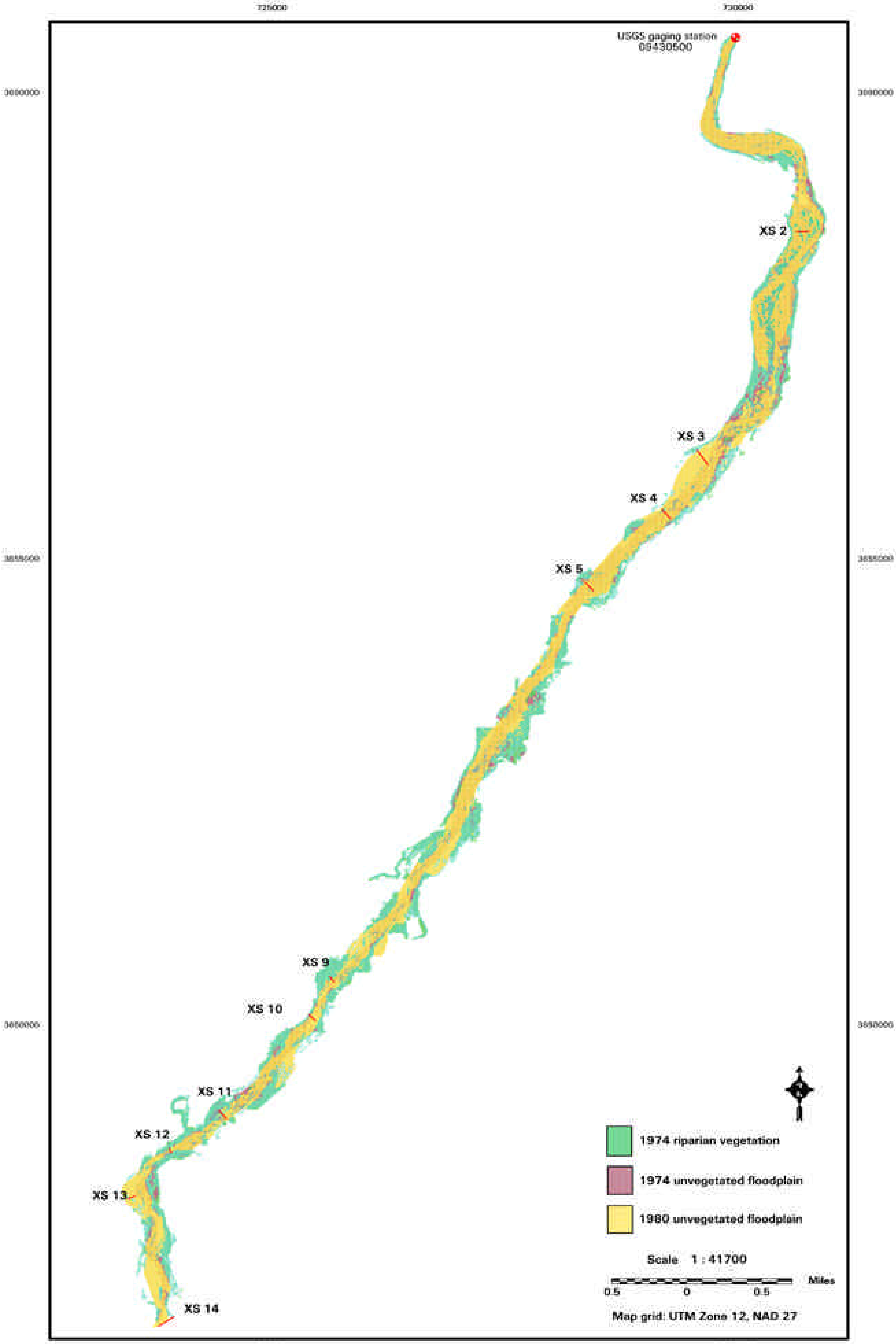



Figure 36. Riparian vegetation and unvegetated floodplain, 1974 and 1980.

Data Center, 2001). Levees in the valley were mostly destroyed again during this flood (Donegon, 1997). They were not reconstructed.

The levee on river right between cross-sections 3 and 5 was destroyed when the river breached the upstream end of the levee to reoccupy its historic location on the western edge of the floodplain. The breach spot is located at the upper end of a 1918 irrigation ditch that appears on the historic map (Figure 15). (Early ditch builders, in fact, may have may have taken advantage of a pre-1884 historic river channel in choosing the location of the ditch.) The river turned sharply back to the east to breach the midsection of the levee upstream of cross-section 4, probably forced eastward by older, coarse alluvium at the base of Miller Canyon, which confluences with the west side of the river in this reach. A 1987 (USGS) color infrared aerial photograph, not reproduced here, shows that after the 1984 flood, the river channel occupied roughly the same location and pattern as shown in the 1996 aerial photographs (Figure 37). The 1987 airphoto shows that remnant levee material from the downstream breach of the levee has been piled along the right bank about midway between the river's farthest west and east bends in the reach.

Three more floods of greater than 14,000 cfs occurred between 1984 and 1996. In the period between the 1980 and 1996 airphoto sets, major meanders were reintroduced to the river channel throughout the study reach: just downstream of Spar Canyon, near the base of Northrup Canyon, and through the reach between Bear Creek and Iron Bridge. For example, during one or more of these floods (in 1988, 1993, and 1994), lateral erosion moved the river channel to the current southern extent of its deep meander between cross-sections 3 and 4. The 1984 levee breach was widened, and levee material was pushed downstream to form the Gila's *left* bank just above cross-section 4.

Sinuosity is a measure of channel meander, defined as channel length/straight down-valley length. In the reach from Spar Canyon to cross-section 4, Gordon (1997) documented increases in sinuosity from 1.05 in 1982 to 1.16 in 1995, and to 1.18 in 1997. Flood meander cuts into fields throughout the study reach show up distinctly in Figure 38 as clear yellow ovals within the remaining band of shoreward vegetation. Of the eight that appear on the figure, all but two cut into fields on the west side of the river. It is perhaps significant that the longest stretches of continuous levee were also constructed on the river's west floodplain (1965 levee locations are shown in Figure 32; 1980 locations in Figure 37). On the other hand, the river's tendency to meander toward the west may be a function of relative elevation on the either side of the river—

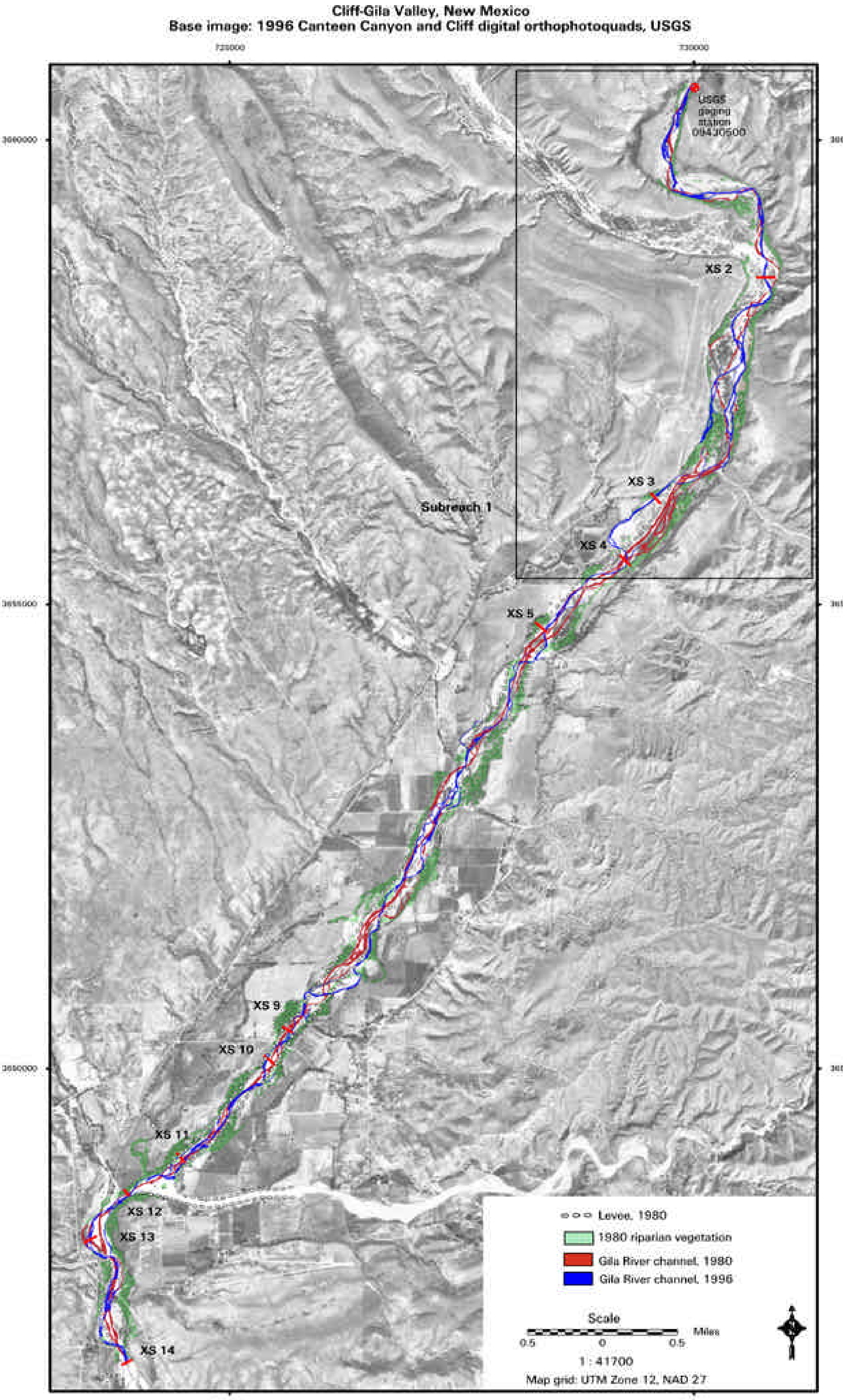



**Figure 37.** Map of 1996 aerial photography, 1980 - 1996 Gila River channel, and 1980 riparian vegetation.

Cliff-Gila Valley, New Mexico
Riparian vegetation and unvegetated floodplain surface, Gila River, 1980 and 1996

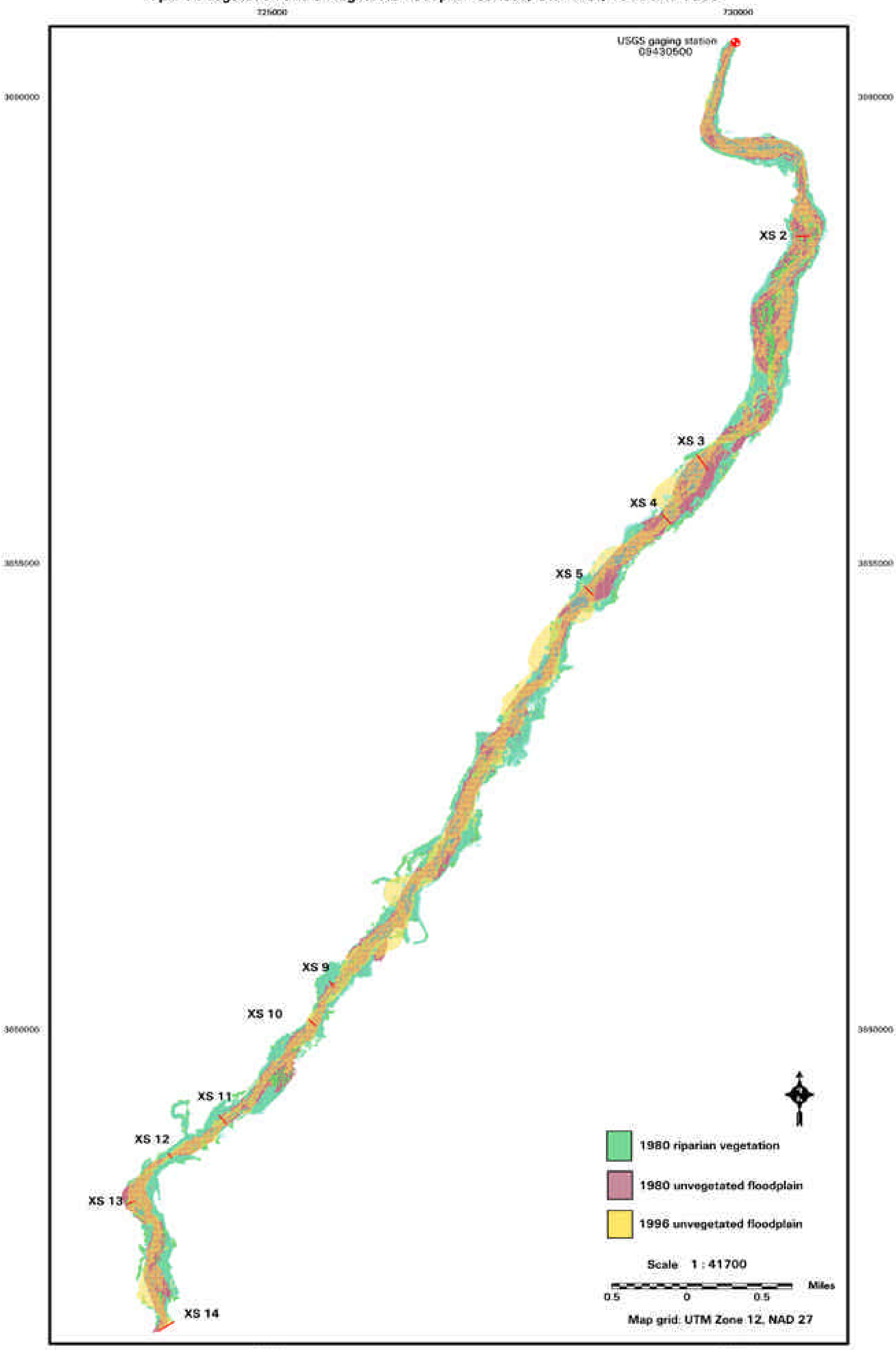



Figure 38. Riparian vegetation and unvegetated floodplain, 1980 and 1996.

this study could not include a topographic survey of the scale required to substantiate such a possibility—or of the typical size of alluvium deposited prior to 1964 from tributaries on either side of the valley. Some tributary canyons in the valley are steeper than others and tend to deliver coarser materials to the river (personal observation, 1999-2000; interview, February 2001).

***Channel incision.*** The lateral erosion documented on the airphotos from 1980 and 1996 (Figures 35 and 37) was accompanied by continued channel incision, at least in some locations, during the 1990s. Just upstream of cross-section 3, the river has flowed since about 1984 through a constriction created by coarse levee materials and Spar Canyon alluvium on river left, and the vertical face of Gila conglomerate that supports the Upper Gila ditch on the right. Gordon (1997), citing a New Mexico Environmental Department (NMED) survey of the reach in May 1995, noted that a four-foot drop in this reach occurred during the two years between the NMED survey and hers. Since the thalweg in this reach is 11 feet lower than in 1935 (USGS, 1952), as noted earlier, about seven feet of material was removed from the channel here sometime between 1935 and 1995, almost certainly between 1978 and 1995.

***Interview and archival data.*** Persons interviewed frequently confirmed the extent of damage and erosion resulting from floods within the valley during the 1970s through 1990s. Most people interviewed remembered the 1972 flood for the death of a local resident, Louise Overstreet, who was washed from the Highway 211 bridge (interviews, April 2000). The bridge was rebuilt after the flood (interview, February 2001). One resident (interview, February 2001) remembered that an old John Deere tractor wheel was exposed by the 1972 flood “at a snag [in-channel flood debris]” just downstream of Iron Bridge on the river's west side. He also recalled that after the 1978 flood, a steam boiler that dated back to near the turn of the century was exposed at the Greenwood Canyon confluence with the Gila. (They excavated the boiler and moved it to the house of another local rancher.) One resident whose property lies about halfway between cross-sections 5 and 9 lost "about a third" of his land to the river in "two swipes,” during the 1978 and 1984 floods. The second flood also took three enormous cottonwood trees and much of his farm equipment, although he tried to move it far enough from the river to save it (interview, February 2001). Another remembered "huge snags" throughout the river channel after the 1978 flood, suggesting bank erosion and subsequent toppling of riparian trees into the river channel (interview, February 2001). A field rented by one resident near the Highway 211 bridge was "lost" during the 1978 flood—apparently when the river temporarily reoccupied the meander bend that 1950 engineering efforts had closed (interview, April 2000) (see Figure 35). Approaches to the Highway 211 bridge washed out in both the 1978 and 1984 floods (interviews, March 2000 and April 2000).

The locations of ditch diversion points are another indicator of erosion, especially incision. All ditches in the valley are gravity-fed. Therefore, ditch diversions must be moved upstream when the river bed erodes and lowers the water surface below the existing diversion point. A member of the Fort West ditch association, Linda Stailey, (2000) compiled a brief history of the ditch. In it, she notes that

> major flood events in 1904–1905 and in 1944 [sic?] resulted in the diversion channel being moved several times. The original diversion channel of the Fort West Ditch from the Gila River was located approximately 300 yards above Maldonado Canyon… Flood events in 1978, 1984, and 1995 have resulted in the diversion channel being moved upstream, approximately ¼ mile. (3)

Incision occurred not just within the valley, but for a number of miles upstream. Examination in 2000 of the reach upstream of the Gila gagesite, where the river is more narrowly confined between canyon walls, revealed unstable sand terraces ten feet high along the river channel. The surface composition of in-channel bars and low floodplain surfaces is mixed; sand and gravel form some of these surfaces; others are composed of coarse gravel and cobble. Willow, cottonwood, sycamore, and baccharis that appear of relatively young age (cottonwoods less than 15 feet tall and two-inch diameter) grow along most banks and low bars.

**Cross-section survey interpretation**

Survey data from ten cross-sections mapped during 1999 and 2000 were examined for further evidence of the relative effects of vertical and lateral erosion during the 1970–1996 period. All ten cross-sections that were surveyed during site visits are reproduced here for documentation purposes. Baseline data from the cross-sections, including identification, location, slope, bed material, and roughness factors, are summarized in Table 8. The cross-sections were repeatedly resurveyed during a 14-month period from March 1999 to April 2000.

Evaluation of cross-section data is most focused on the area delineated as Subreach 1 on Figures 32, 35, and 37. The Subreach 1 area is reproduced at a larger scale for the same years

**Table 8. Cross-section data summary.**

| XSEC no. | [1]UTM crd., L pin | Feet DS of gage | WS slope (month) | D50 May | D50 Sept | D84 May | D84 Sept | Mannings *n* |
|---|---|---|---|---|---|---|---|---|
| 2 | 0730764 E, 3658514 N | 3185 | .005 (May 99) | 28 | 40 | 80 | 154 | 0.047 |
| 3 | 0729583 E, 3656137 N | 6230 | .002 (July 99) | 0.38 | 10 | 20 | 56 | 0.036 |
| 4 | 0729283 E, 3655425 N | 7150 | .003 (July 99) | 56 | 40 | 109 | 80 | 0.0506 |
| 5 | 0728414 E, 3654695 N | 8210 | .004 (May 99) | 40 | 20 | 56 | 80 | 0.052 |
| 9 | 0725676 E, 3650453 N | 13880 | .002 (May 99) | 28 | 56 | 56 | 80 | 0.03 |
| 10 | 0725420 E, 3650092 N | 14340 | .003 (May 99) | 10 | 28 | 56 | 80 | 0.034 |
| 11 | 0724515 E, 3649001 N | 15820 | .002 (May 99) | 14 | 20 | 56 | 56 | 0.053 |
| 12 | 0723917 E, 3648636 N | 16520 | .002 (May 99) | 7 | 7 | 14 | 28 | 0.039 |
| 13 | 0723480 E, 3648145 N | 17250 | .002 (July 99) | 10 | 3 | 56 | 28 | 0.034 |
| 14 | 0723942 E, 3646865 N | 18720 | .003 (May 99) | 20 | 28 | 40 | 56 | 0.035 |

XSEC no. = original NRCS number; DS = downstream; WS = water surface; D50 = active channel median particle diameter (mm); D84 = active channel 84$^{th}$ percentile particle diameter (mm). May = May 1999; Sept = September 1999, after 2800 cfs flood event. Manning's *n* used for hydraulic calculations estimated via Arcement & Schneider (1984) method. [1] UTM coordinate at left pin per NRCS (1998).

(1974, 1980, and 1996), in Figures 39 through 41. This reach is representative of morphological changes throughout the study area during the 1980s and 1990s, and also brackets a reach that begins above and ends below the upstream-most levees and irrigation diversions. In the upstream end of this reach (from the gagesite to Spar Canyon), the river floodplain is exposed to full flows year-round. From the Spar Canyon confluence downstream to cross-section 4 is one of the most heavily modified reaches in the valley. This reach was one of the earliest to be leveed, and the levee constructed there was one of the longest in the valley. It is also the reach most likely to be dry during the irrigation season, since it lies immediately downstream of the diversions for both the Upper Gila and Fort West ditches. On the other hand, other variables that may play a role in current channel condition are little present in this reach. Cattle grazing in riparian areas is nearly nonexistent and no roads cross the channel; although bulldozers are used to maintain irrigation

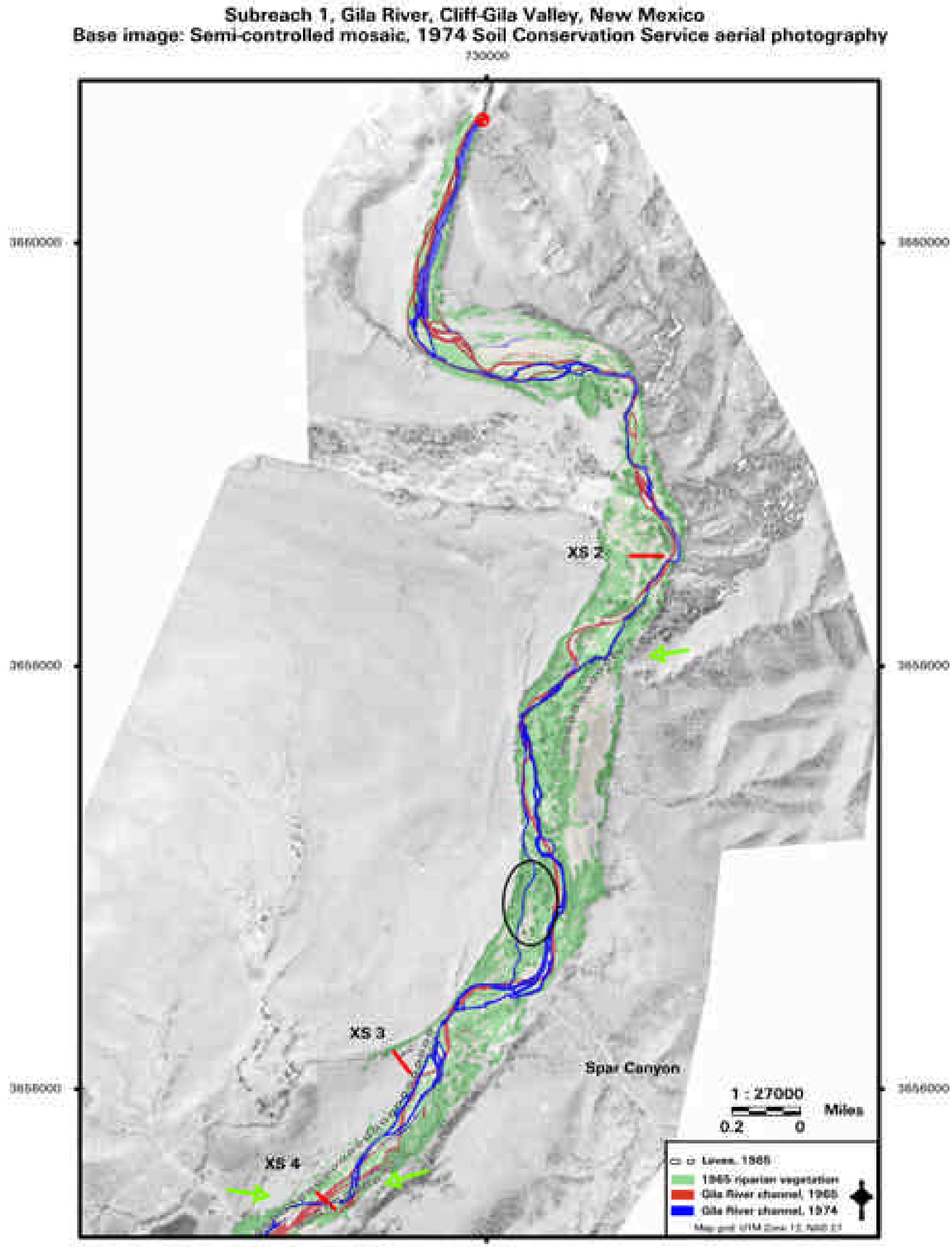



**Figure 39. Subreach 1: 1965 and 1974.**

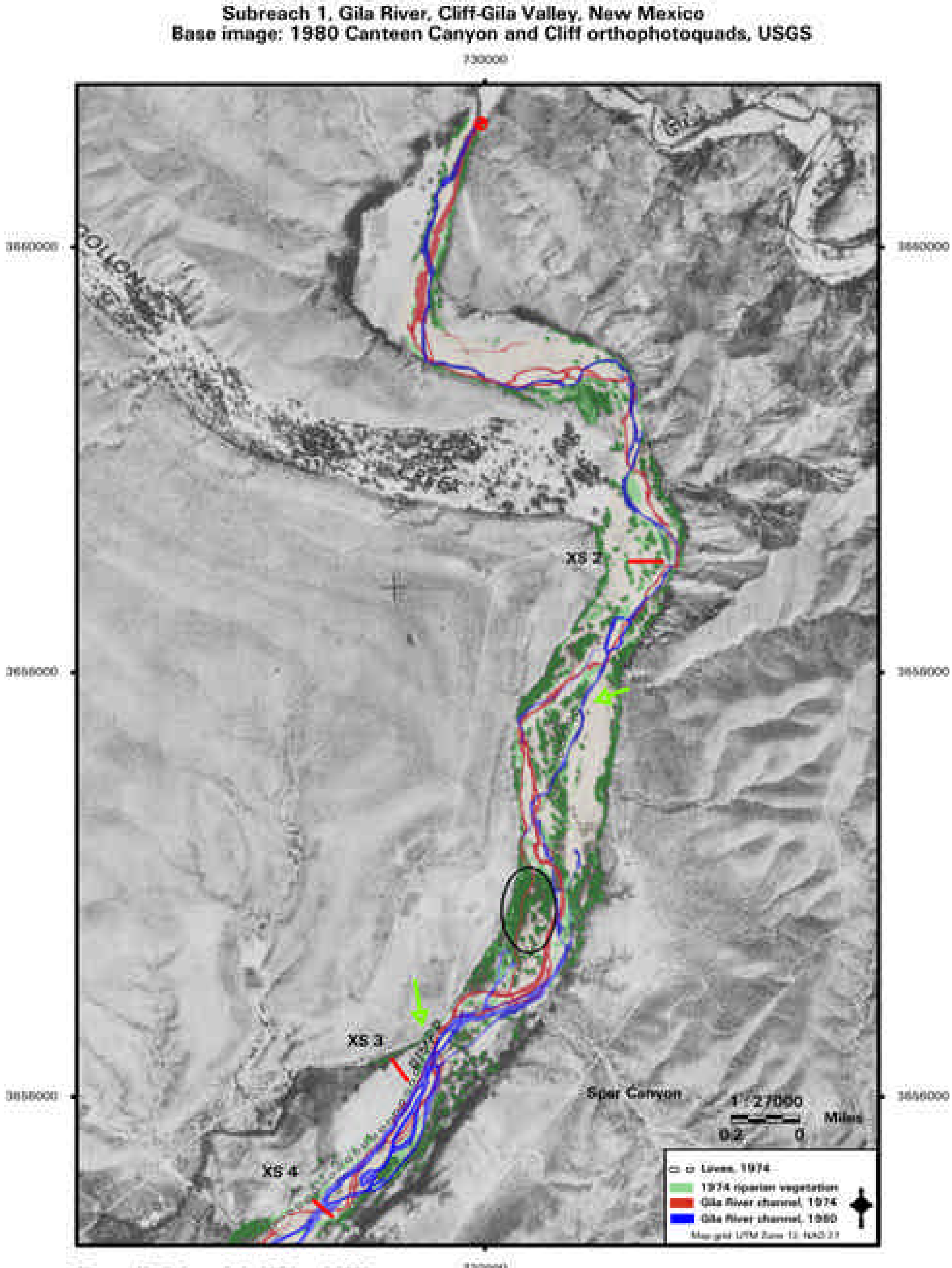



**Figure 40. Subreach 1: 1974 and 1980.**

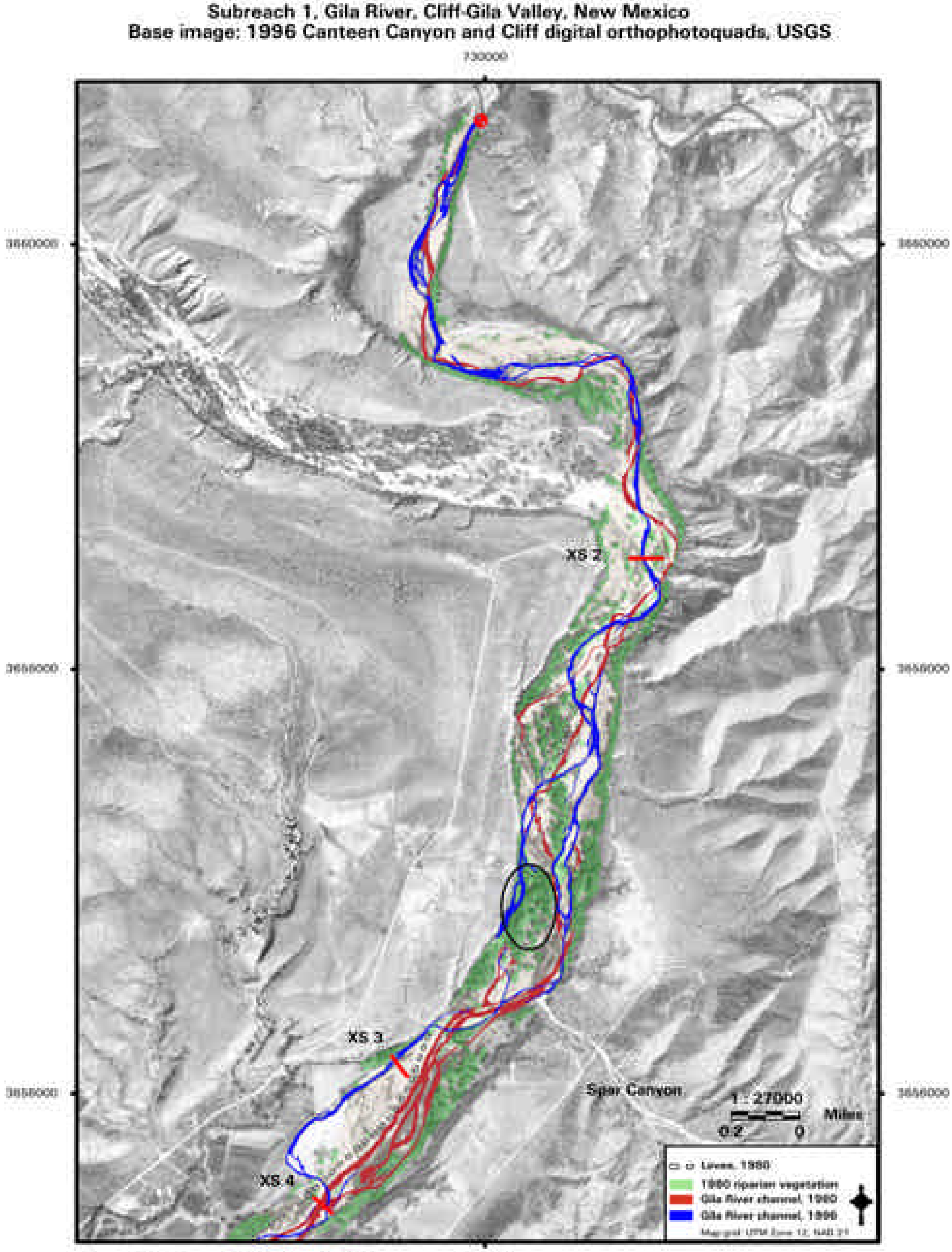



**Figure 41. Subreach 1: 1980 and 1996.**

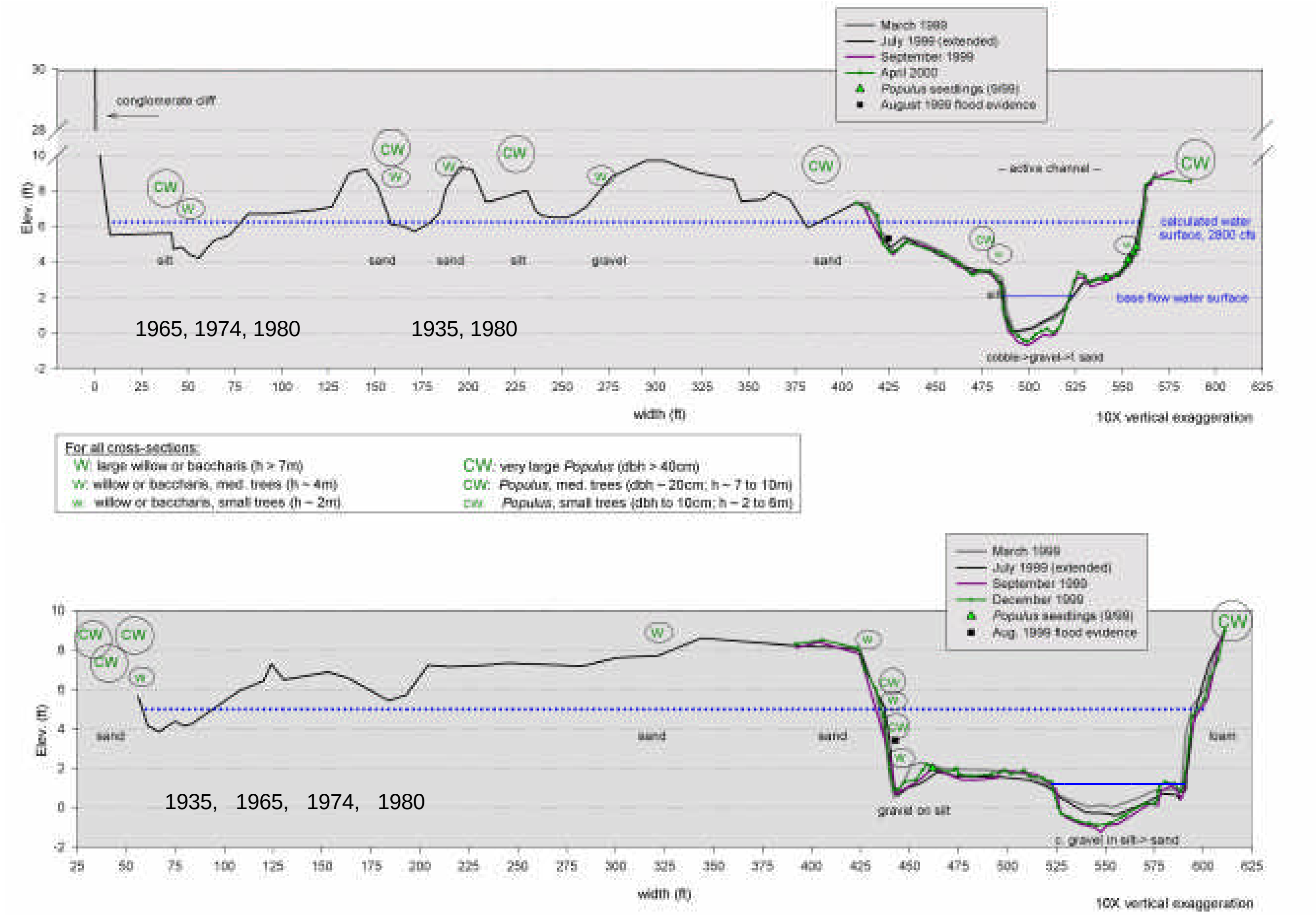
berms, their impact in this reach was much less than that observed at locations downstream (e.g., at cross-section 5 or around the diversion for the Gila Farms ditch).

No significant changes were found at the cross-sections except after a moderate flood of 2800 cfs on August 6, 1999. Therefore, for ease of interpretation, only data collected in September 1999 and during the first and final study surveys are mapped in Figures 42 through 51. Data plotted on the figures include elevations of flood debris and cottonwood seedlings found after the August 1999 flood, calculated water surface elevations for estimated flood discharge of 2800 cfs, descriptions of surficial sediments, and locations of existing riparian vegetation. All cross-sections are viewed facing downstream.

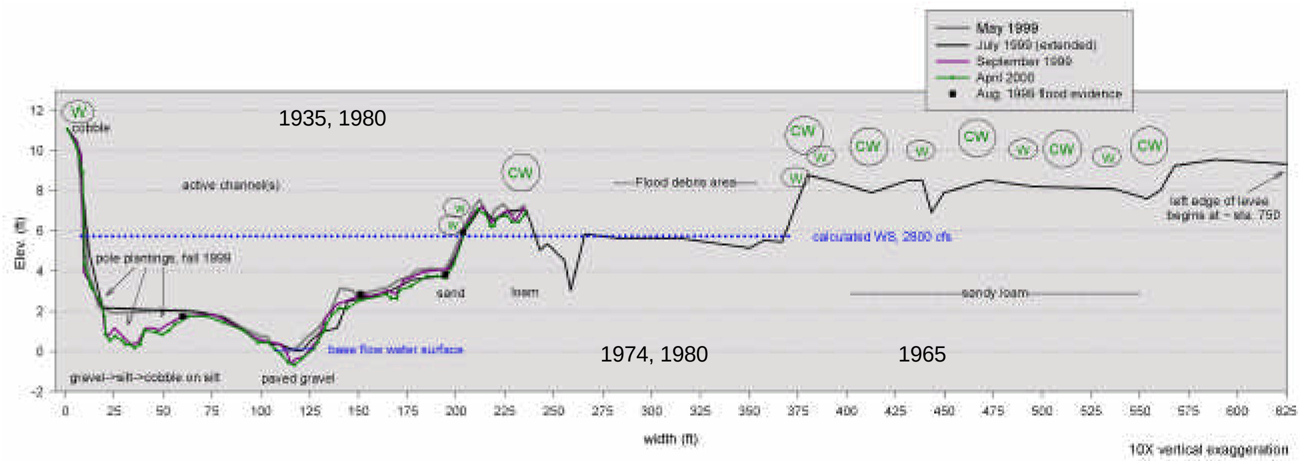
***Abandoned and active channel locations.*** Dates of active channel occupation of now abandoned channels are identified on the drawings. At each cross-section except the first two downstream of Bear Creek, the elevation of the current active channel is well below that of, and shifted laterally from, the river's earlier channels.

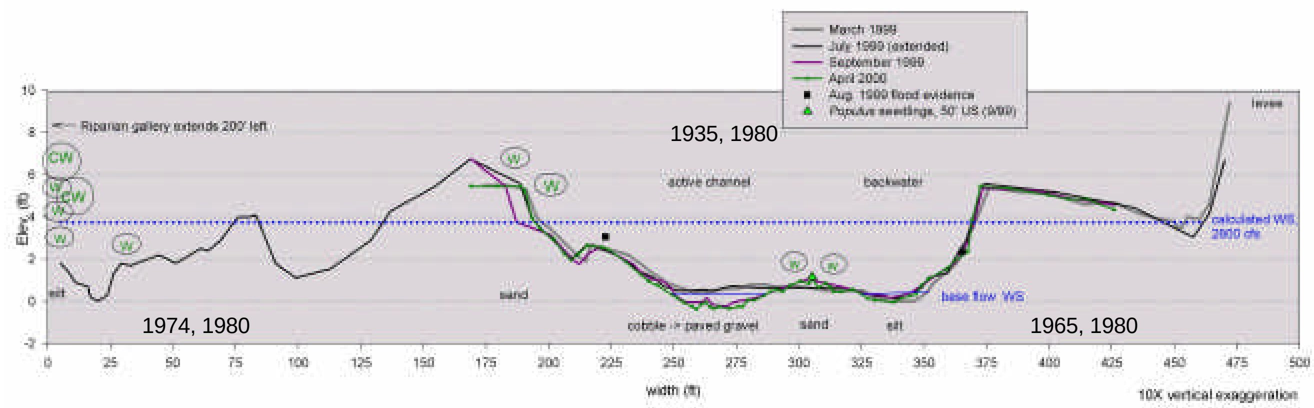
Typically, surface deposits in the abandoned channels are composed of sand and fine gravels, while cobble and coarse gravel lie exposed within the active channel. Riparian stand density is also greatest on the banks and adjacent floodplains of abandoned channels, and fine surficial sediments are especially predominant in these vegetated areas. At cross-section 2, for example, the Gila River channel in 1974 was located on the far left floodplain, against the base of a Gila conglomerate cliff. After the 1978 flood, the river braided to occupy both its 1974 channel and an overflow channel just to the right, now thickly vegetated with medium-sized willow and cottonwood trees. By 1996, the river had shifted laterally far right to its current position, where the thalweg is five to six feet below the 1974 and 1980 channel. When the study began, a dense, narrow band of small cottonwood and sycamore trees lined the left bank; only clover grew on a low cobble bar on the right side of the channel. No levee construction has taken place at cross-section 2, but high bars throughout the reach between the cross-section and the diversion split downstream are unvegetated and composed of coarse gravel and cobble. Dense stands of cottonwood, willow, baccharis, and some alder grow along overflow channels throughout the area.

At cross-section 3 the active channel cut through fine field sediments shoreward of the levee constructed along its right floodplain in 1979. The channel is now "pinned" between

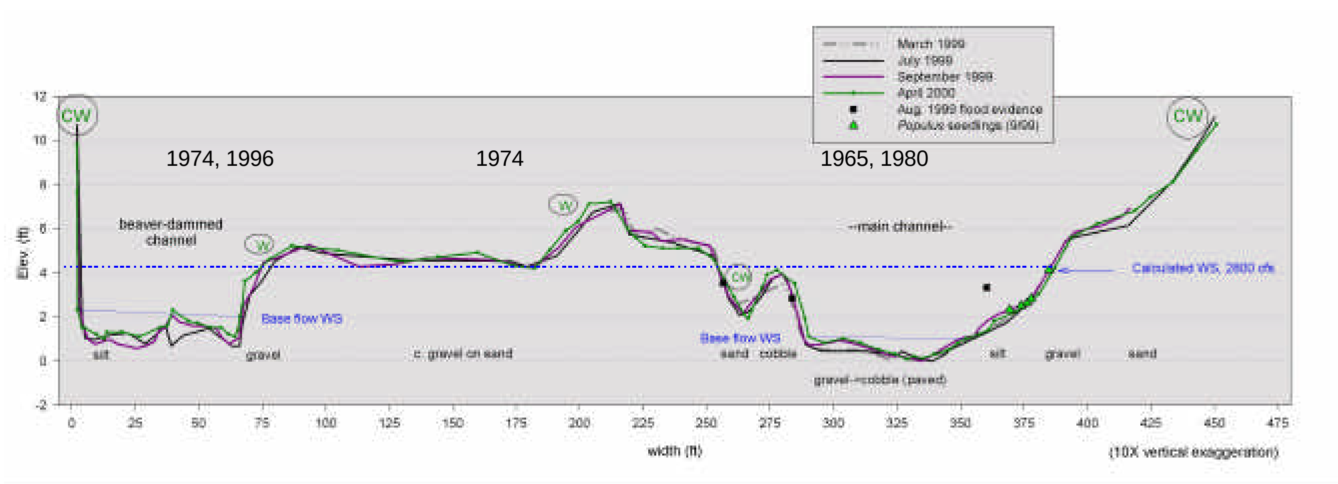


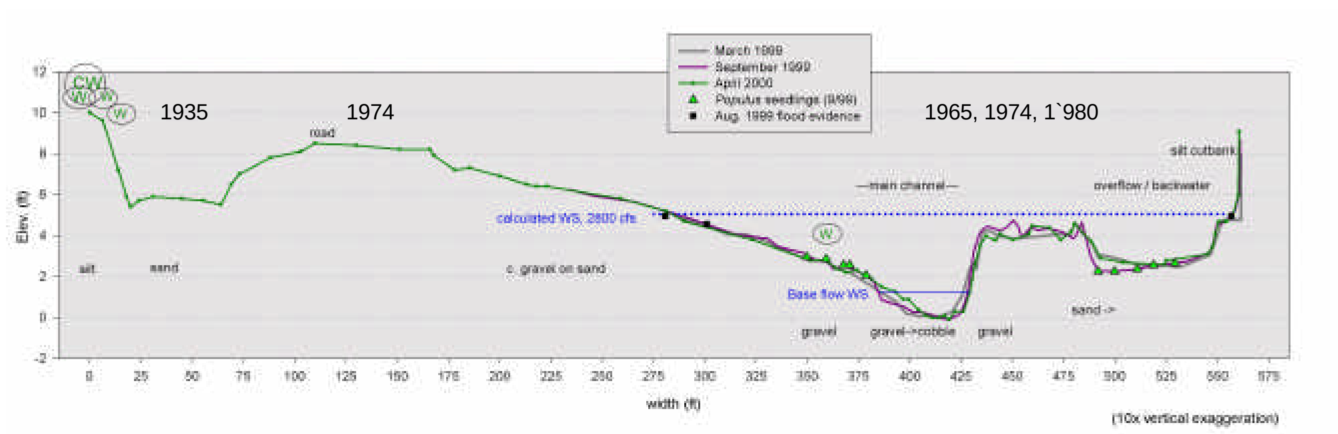

**Figures 4 2 and 43. Cross-section 2 (top) and cross-section 3 (bottom) survey data showing locations of vegetation, surface sediments, seedlings and flood debris found September, 1999, base flow stage, and calculated stage for 2800 cfs. Channel location during specific photo year as shown.**



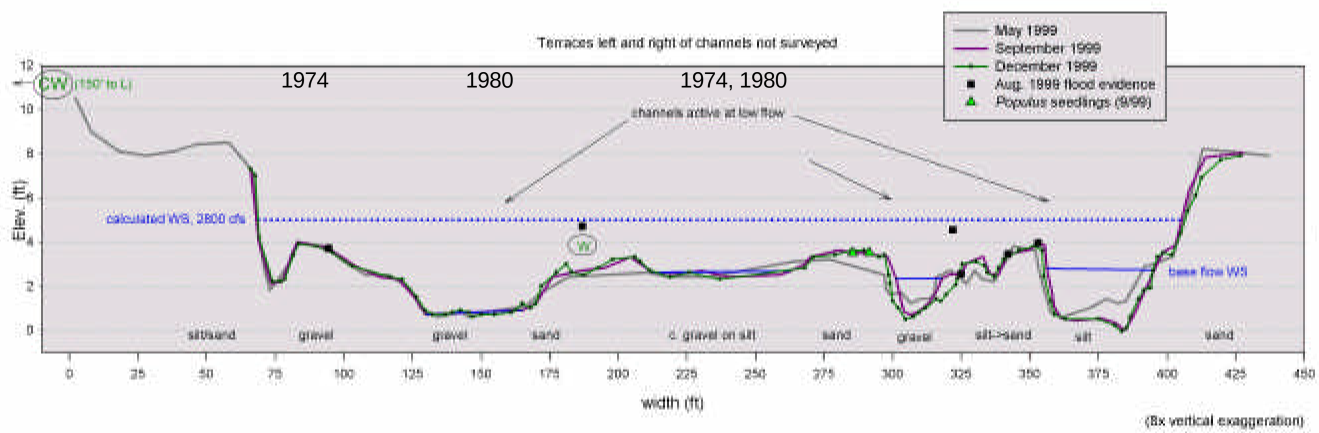



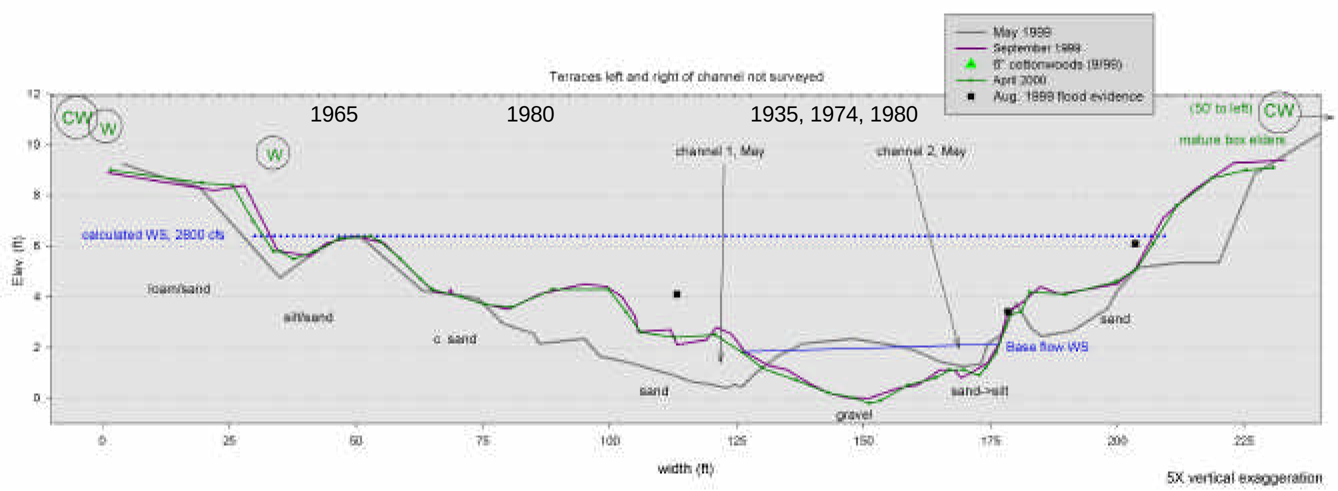

**Figures 44 and 45. Cross-section 4 (top) and cross-section 5 (bottom) survey data showing locations of vegetation, surface sediments, seedlings and flood debris found September, 1999, base flow stage, and calculated stage for 2800 cfs. Channel location during specific photo year as shown.**



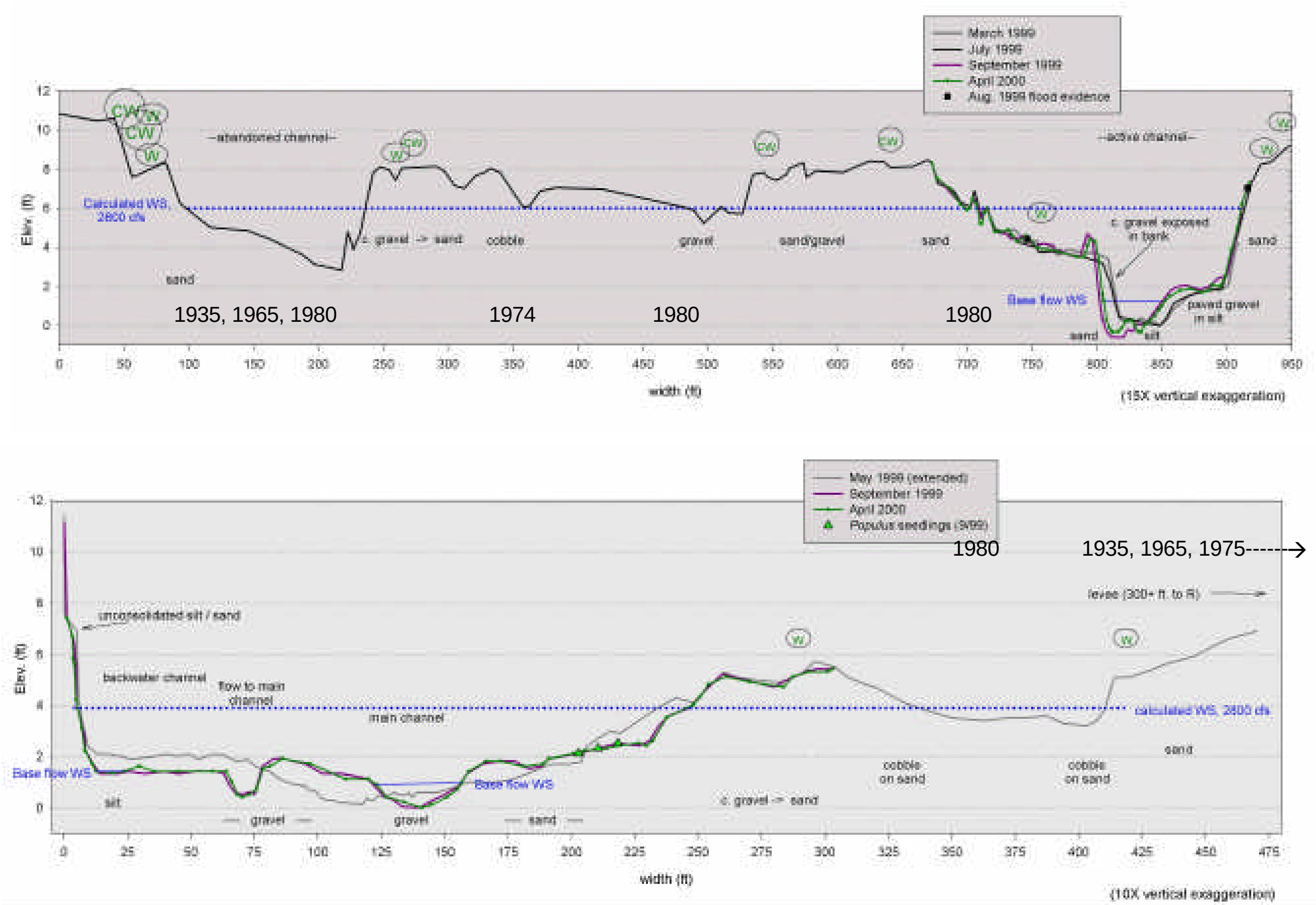




**Figures 46 and 47. Cross-section 9 (top) and cross-section 10 (bottom) survey data showing locations of vegetation, surface sediments, seedlings and flood debris found September, 1999, base flow stage, and calculated stage for 2800 cfs. Channel location during specific photo year as shown.**




**Figures 48 and 49. Cross-section 11 (top) and cross-section 12 (bottom) survey data showing locations of vegetation, surface sediments, seedlings and flood debris found September, 1999, base flow stage, and calculated stage for 2800 cfs. Channel location during specific photo year as shown.**




**Figures 50 and 51. Cross-section 13 (top) and cross-section 14 (bottom) survey data showing locations of vegetation, surface sediments, seedlings and flood debris found September, 1999, base flow stage, and calculated stage for 2800 cfs. Channel location during specific photo year as shown.**

remnant levee on the left and a nearly vertical silt bank on the right. The river in 1935 occupied both the current channel location and the location in which the 1974 and 1980 channels were mechanically “centered” in the valley. The older channel location is about 500 feet left of the active channel. A thick gallery of cottonwood and willow lines the left side of the abandoned channel area, where sand covers the surface. Gravel and cobble are exposed along the right bank of the old channel. The current channel thalweg lies about five feet lower than its 1974-1980 counterpart. In this reach, water velocity tends to decrease, allowing fine sediments to drop from transport, and the bottom of the active channel is cobble somewhat buried in fine silt. Little vegetation other than grass grows along either edge of the channel, except downstream where the landowner has installed pole plantings of willow.

Cross-section 4 offers one of the best examples of lateral and downward channel migration in the study reach. In 1965, the channel was in an area now more than eight feet higher than the active channel, and about 300 feet left of what remains of the western levee in this reach. Loamy sand covers this area and a dense gallery of 50-foot cottonwoods grows there. The 1974 channel is shifted left and down about two feet; thick flood debris covers this old channel. In 1980 the river occupied both this channel and the current channel, where no vegetation grows along either bank. Willow and baccharis grow on a sandy terrace 100 feet right of the river. A sheer cutbank of unconsolidated silt and sand forms the river’s left bank. The active channel has displaced the levee that was built along the left floodplain before 1965, and is now partly located in the borrow pit area for the levee.

The pattern of lateral and downward movement from abandoned channels to active channel tends to be consistent throughout the study reach (personal observation, 1999–2001). (The major exceptions are cross-sections 5 and 11, where evidence of bulldozer activity in the main channel was observed on a number of occasions and modifications to channel morphology have probably been significant.) At cross-sections 9 and 10, overflow channel depths are nearer that of the active channel. At cross-section 9, floods cut a meander into the field against the levee on river left, leaving one channel caught between the field and remnant levee materials. A “pilot” channel excavated previous to 1965 still exists at cross-section 10. At cross-section 10, the active channel has completely removed the levee on river right and flows through the borrow excavation for the levee. Between the two cross-sections, the river is constrained by bridge abutments. The pattern of obvious vertical and lateral erosion from abandoned to active channel reappears downstream, at cross-section 12 and 13 near Bear Creek, and 14, downstream of Iron Bridge.

***Erosional phase: summary.*** The cross-section survey data tend to corroborate temporal relationships between changes in channel morphology and location and the sequence of floods between 1970 and 1996. Floods during this period created both channel incision and lateral erosion into cultivated fields. After the 1978 and 1984 floods, the active channel often occupied borrow pits from which levee construction materials had been excavated. The river channel became braided between islands and bars composed of coarse gravels and cobble. Dense riparian vegetation in at least some reaches of the Gila River was quite resistant to flood scouring effects, but much floodplain vegetation was mechanically removed during levee reconstruction efforts in 1979. Flood waters were less likely to enter fields when a wide band of riparian vegetation existed between the field and floodplain, again suggesting its relative resistance to flood effects.

However, in constricted reaches upstream of the valley itself, floods, rather than bulldozer work, appear to be responsible for the loss of some vegetation during the period. The ability of major floods in desert streams to thoroughly scour riparian vegetation is recognized (e.g., Asplund & Gooch, 1988; Campbell & Green 1968). In such cases, floodplain vegetation may then regenerate only under quite specific flood conditions. The role of overbank flows in cottonwood seedling recruitment, for example, is well established (e.g., Kondolf et al., 1987; Stromberg, 1993b). The cross-sections document deep incision of the active channel between nearly vertical banks in some reaches of the Gila River; greater discharge will be required to overtop these banks than those existing in 1974, for example. What are the implications of the Gila River's current condition for regeneration of riparian vegetation? Evidence left behind by a fortuitous, moderate flood event in August 1999 suggests likely patterns for reestablishment of floodplain vegetation.

***August 6 flood evidence***. A moderate flood on August 6, 1999 offered an opportunity to observe the impacts on floodplain vegetation, bed material, and overflow channels from discharge great enough to overtop low banks, bars, and floodplains. The first site visit following the flood was made in September 1999. Flood effects were documented in the field and analyzed via WinXSPro (1998). Comparative survey data from before and after the August 1999 flood were analyzed for changes in channel morphology and bed material. Relative elevations of riparian seedlings, ranging in height from three inches to about one foot, and flood debris found at the cross-sections after the flood were mapped. Flood debris evidence was used in refining stage–discharge curves (WinXSPro, 1998) at three cross-sections (numbers 2, 3, and 4) in order to evaluate discharge required to overtop existing channel banks.

Peak discharge on August 6, 1999 was measured at 2800 cfs at the Gila gagesite. USGS (2003) frequency tables give a return interval of 2.8 years for the event. Discharge at the Mogollon Creek gagesite peaked at 203 cfs on August 5 (USGS, 2003). Streamflow in the creek was evident at the confluence area on August 6, according to local residents, but exact discharge that day at the time of the peak on the Gila River is unknown. Therefore the known value of 2800 cfs was used for all WinXSPro calculations. Stage heights calculated by WinXSPro at each cross-section for discharge of 2800 cfs are shown on the extended cross-section graphs. They correspond well to flood debris elevations that were mapped in September at many of the cross-sections. However, because exact discharge at each cross-section is unknown, the precise meaning of the correspondences that were found is uncertain. For example, every cross-section site except number 2 is below the Spar Canyon–Gila River confluence. Discharge was carried by Spar Canyon into the river during August 6, but how much is unknown.

WinXSPro calculated a stage height approximately one foot higher than the highest flood debris found at cross-section 2, nearest to the gagesite. Flood evidence was found at an elevation, relative to the September channel thalweg, of about 5.75 feet. At this stage, WinXSPro calculated discharge of only about 1300 cfs. Furthermore, cross-section 2 lies about 1000 feet downstream of the Mogollon Creek confluence (see Figure 16). Assuming that discharge measured at the Gila gagesite is accurate, this suggests that the complex system of overflow channels that currently exists across floodplains in the study area captures streamflow during even moderate flood events. In fact, what had been a shallow second channel on river left, above cross-section 2 and immediately downstream of Mogollon Creek, appeared to be both considerably deeper and steeper in September than on previous visits. Dense non-woody vegetation growing to a height of more than 5 feet on the bar left of this channel had been completely flattened, indicating that it was inundated during the flood. Thick stands of young cottonwood and sycamore that crowd the left bank of the channel at the cross-section retained flood debris nearly 2 feet above the ground. No trees were downed by the flood, nor were there significant changes to the left channel bank. Bed material at this cross-section is composed of a matrix of fine gravel and sand that deepens from left to right side of the channel; cobble is exposed on the left and buried on the right.

Scouring of gravel and sand from the channel thalweg deepened it by about 0.6 feet from July to September. *Populus* seedlings were found at cross-section 2 shoreward of a small bar on river right after the August flood. The bar surface is cobble on silt; the small depression in which the seedlings were located is filled with sand.

At cross-section 3, farther downstream, WinXSPro also calculated stage heights greater than flood evidence found along the active channel. Again, this may indicate infiltration of flows into low floodplains, bars, and overflow channels between the Gila gage and this site. Evidence of flow was found in the abandoned channel shown on the far left of the cross-section 3 graph. A substantial portion of flow may also have been diverted into irrigation ditches. The Fort West ditch apparently captured some flood discharge at the diversion point upstream of cross-section 3. Just upstream of cross-section 4, a ditch that carries overflow away from the Fort West ditch confluences with the river channel. The overflow ditch retained evidence of high flows, and flood debris elevations at cross-section 4 match the 2800 cfs stage height calculated by WinXSPro. About 4 inches of sand and gravel were deposited on the inside bar at the meander bend immediately upstream of the cross-section. At the cross-section, the thalweg of the active channel, composed of paved medium-sized gravel, was only slightly eroded. More than a foot of bed material was removed from an overflow channel to the left, however, where the river is constrained by a high silt cutbank. Bed material in the overflow channel is a sorted mixture ranging from silt to cobble. No emergent riparian vegetation was found in September near the cross-section.

As noted above, some flood discharge was diverted into the Fort West ditch upstream of cross-section 3, and discharge reaching cross-section 3 was reduced as a consequence. At this cross-section, WinXSPro again calculated a stage height for 2800 cfs streamflow considerably higher than the elevation of flood debris found at the cross-section. Cross-section 3 lies about 300 feet downstream of the lower end of the long, high gravel bar that separates excess flow returned to the river channel from the Upper Gila diversion (to the right of the bar) from the river channel downstream of the Fort West diversion (left of the bar). The two flows merge at the bar's downstream end. However, flood discharge entering the Upper Gila ditch and eventually reaching its overflow shunt would be attenuated, at least temporarily, by the reservoir and high diversion berm at its upstream end.

During the flood, flow across the bar from the river channel to the return channel made lateral cuts across the bar at 5 or 6 locations. There the water runs directly into a high silt/conglomerate cutbank beneath the Upper Gila irrigation ditch, undercutting the ditch. The roots of a line of alders growing from this cutbank are half-exposed. New vegetation has no opportunity to establish itself on this vertical face, leaving the bank highly vulnerable to erosion. At the cross-section, low bars on either side of the river do offer an opportunity for vegetation recruitment, but they are constrained between nearly vertical banks. Only in a small depression between the left bank and bar were a few seedlings visible after the August flood event.

At cross-sections downstream, similar patterns of vegetation establishment and erosion were evident. For example, cross-sections 9 and 10, upstream and downstream of the 211 bridge, demonstrated the least change in response to August 6 flows. Cross-section 9 is in a well-paved gravel reach of the main channel. Levee remnants are still evident at this cross-section. Flows of this magnitude were incapable of disturbing the levee remnants. *Populus* seedlings were located among existing low vegetation (grasses and forbs) on the moderately sloped right bank at the cross-section. At cross-section 10, the river easily accesses both the lower part of its floodplain, to the left, and an overflow channel to the right. Small baccharis and cottonwood (5 to 8 feet in height) on the left bank were undisturbed by the flood. Again, cottonwood seedlings were found growing among this existing vegetation after the August flood. The densest area of seedling establishment was in the backwater formed by the overflow channel on river right.

Channel shifts and vertical erosion were most evident at cross-sections 12 through 14, where sand predominates as channel substrate. However, extensive deposition of sand and fine gravel onto channel banks was also found at these cross-sections. Deposits were more than two feet deep in some places. All three cross-sections are below the confluence with Bear Creek, whose channel and banks are of unconsolidated sand for more than two miles upstream.

Although little deposition was found precisely on cross-sections upstream of Bear Creek, observations throughout the study reach found deposits of sand and lightweight flood debris on some shallow, vegetated slopes at the active channel. Most deposition was noted upstream of the irrigation diversions, where riparian vegetation has reestablished adjacent to the active channel (e.g., at cross-section 2). A stand of small willow and baccharis also exists on the left bank upstream of the "diversion split" bar, where I installed a staff gage for monitoring river water surface levels. More than a foot of sand was deposited along this bank during the flood (Figure 52).

**Figure 52. Staff gage at diversion split, September 1999. More than one foot of sand was deposited on this bank by a 2800-cfs flood on August 6, 1999.**

***Evaluation of field observations.*** Comparison of channel scouring effects from the 2800-cfs flood in August 1999 showed that most scouring occurred at locations where the channel bed was not armored prior to the flood. The river channel is armored at cross-sections 9 and 10, and in the main channel at cross-section 4, for example. Little scouring occurred within the channel at any of these spots. At cross-section 3, an unarmored section, a foot of silt and sand was removed from the channel bed. The flood overtopped banks and low bars and sent water through many of the abandoned channels across the valley floodplain. It left debris in, but did not disturb, small- to medium-sized cottonwood, willow, and baccharis growing near the active channel.

Three-inch to one-foot tall seedlings of *Populus fremontii* were found near many cross-sections in September 1999. No seedlings were visible during a site visit in July 1999. Typically cottonwood seed dispersal occurs in the spring months (Patten, 1998), and cottonwood seeds are viable for only one to eight weeks (Fenner, Brady, & Patton, 1984). Presumably seed dispersal on the Gila occurred by June; June and July were comparatively wet months in Cliff that year. (Nearly an inch of precipitation was recorded in June, and more than five inches in July [Western Regional Climate Center, 2003]). August was relatively dry, but the flood would have saturated banks and floodplains, initially raising groundwater levels and then reducing the rate of its decline. Viable seedlings were generally, though not always, found in semi-protected areas: growing among already existent low vegetation on sloped-back or flat banks or in abandoned channels removed from the force of active channel streamflow. They were always found well below the elevation of the highest flood debris left by the flood, and generally not more than one foot above the base flow water surface.

In late spring, during seed dispersal by riparian species, seedling establishment and survival is dependent on moderately high streamflow and relatively slow recession to maintain high groundwater levels beneath the soil surface (Cooper, 1993; Fenner, Brady, & Patton, 1985; Glinsky, 1977; Kondolf et al., 1987). The roots of cottonwood seedlings may grow up to 6 mm per day (Fenner, Brady, & Patton, 1984), and Mahoney and Rood (1991) observed highest rates of root growth when water table decline was less than two inches (4 cm) per day. The last phase of this study examined the implications of groundwater levels on possibilities for riparian seedling survival within the valley. What impacts, if any, do irrigation diversions have on the potential for seedling establishment? To address this question, variance in the Gila River's flow regime under conditions of unimpacted and reduced discharge conditions was analyzed and the relationship between surface flow elevation in the river and groundwater levels in nearby floodplain areas was studied.

**<u>Groundwater analysis</u>**

Irrigation diversions in the Gila Valley reduce flows within the river channel, and may create a dry channel at times when otherwise flows would be low to moderate. Riparian species of the American southwest are typically adapted to the erratic hydrographs of its rivers, and are dependent on groundwater during periods of drought (Jolly, 1996; Klotz & Swanson, 1997; Patten, 1998). Altering the base streamflow regime may impact streambank water storage and result in declining groundwater elevations, thus impairing the functioning of aquatic and riparian habitats (Barkdoll et al., 1997; Hill et al., 1991; Richter & Powell, 1996; Rojo et al., 1998). Determining the Gila River's baseflow requirements will become increasingly important if the state adds instream flow to the official list of "beneficial uses" that it recognizes for surface water (Beecher, 1990). Although the state has historically failed to recognize instream flow as a beneficial use for purposes of water rights filings (Berrens, Ganderton, & Silva, 1996; Clark, 1987: 329), a recent opinion issued by the state Attorney General may signal an impending change in its position on this matter (Udall, 1998).

Dewatering the channel can also hinder riparian vegetation reestablishment during and after major flow events (Fenner, Brady, & Patton, 1985; Siegel and Brock, 1990), thus increasing channel bank susceptibility to erosion. Channel incision between vertical banks can decrease seedling survival by reducing the chances for seeds to lodge in a place "protected from removal by subsequent disturbance" (Scott, Friedman, & Auble, 1996: 328), in addition to lowering the local water table.

Analysis of the possible effects of irrigation diversions on low flows in the Gila River included calculations to estimate streamflow remaining in the river channel below the upstream-most diversions, and evaluation of the relationship between river stage and groundwater levels along an unimpacted reach of the river above the diversions.

***Low flow comparison, unimpacted and impacted***. Analysis of streamflow under natural (*Qgm*) and diverted (*Qnet*) conditions revealed significant variance in the river's low flow regime below the Upper Gila and Fort West diversion points. Percentages of zero streamflow days and of days when streamflow was less than 20 cfs and less than 50 cfs under the two conditions are graphed in Figure 53. For the period from 1969–2001, *Qgm* (undiverted) was never zero, while *Qnet* (diverted) resulted in zero flow during 3% of days during the irrigation season, April through October. The diversions resulted in a hundred-fold increase in the number of <20 cfs streamflow days, and more than doubled the number of <50 cfs streamflow days.

IHA (2001) calculates streamflow "targets" based on 25th or 75th percentile calculations of unimpacted streamflow for selected parameters. For this study of potential low flow impacts, 30- and 90-day minimum flows were chosen for analysis because of the relationship between groundwater levels and riparian seedling survival. IHA estimates of these targets and targeted minimum 7-day streamflow are shown in Figure 54. In no years did *Qnet* streamflow achieve the 90-day minimum streamflow target of about 44 cfs. It reached the targeted 30-day minimum only in 1991 and 1993 and the 7-day minimum target only in 1991.

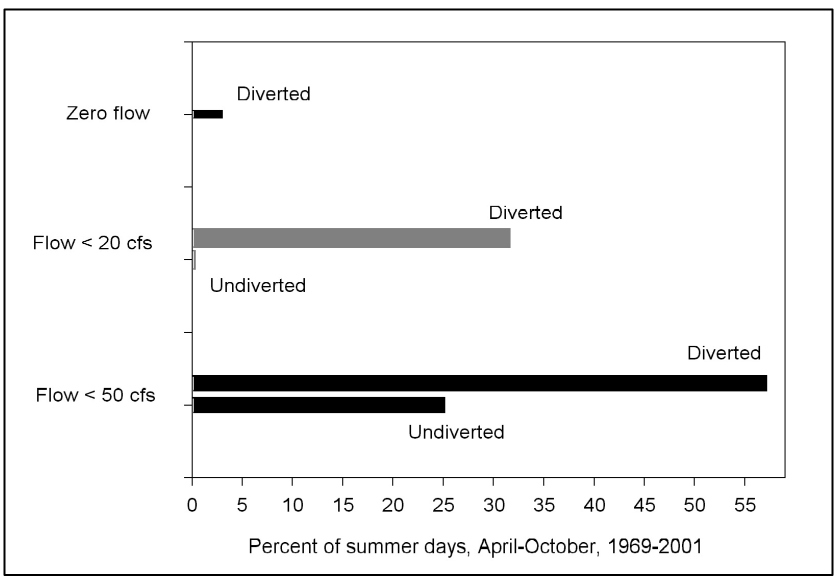



**Figure 53. Percentage of summer days (April–October) when calculated GM discharge was zero, less than 20, and less than 50 cfs under diverted and undiverted conditions, 1969–2001.**

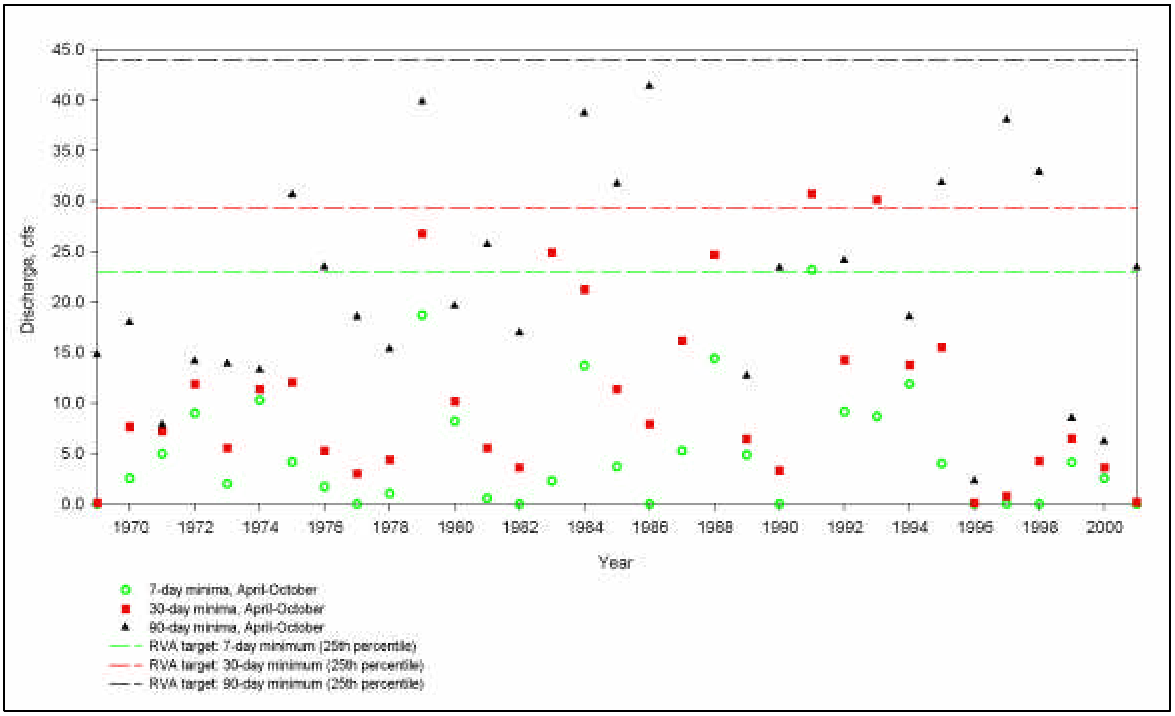



**Figure 54. *Qnet* annual minimum flows and IHA minimum flow targets for summer months, April–October, during the period of record 1969–2001.**

In Figures 55 and 56, variance between mean 30- and 90-day minima under undiverted and diverted streamflow conditions for the summer months (April–October) are graphed. In both cases, 75$^{th}$ percentile *Qnet* discharge is less than 25$^{th}$ percentile unimpacted discharge. IHA defines *baseflow* as the 7-day minimum discharge/annual mean. Baseflow will therefore decrease if the 7-day minimum decreases, or the annual mean increases. Variance in baseflow under the two flow conditions is shown in Figure 57. Duration of minimum *Qnet* flows, where minimum flow is less than the 25$^{th}$ percentile mean discharge, was also considerably longer than for undiverted *Qgm*, as shown in Figure 58.

These impacts on minimum flows may be at least partly responsible for the virtual absence of young riparian growth in 1998 near cross-sections 3 and 4. Durkin et al. (1996) examined riparian condition in the Gila Valley and concluded that while conditions at the sites upstream of diversion points were "good" to "excellent," below the irrigation diversions they were "characterized by severe channel and floodplain impacts" (119).

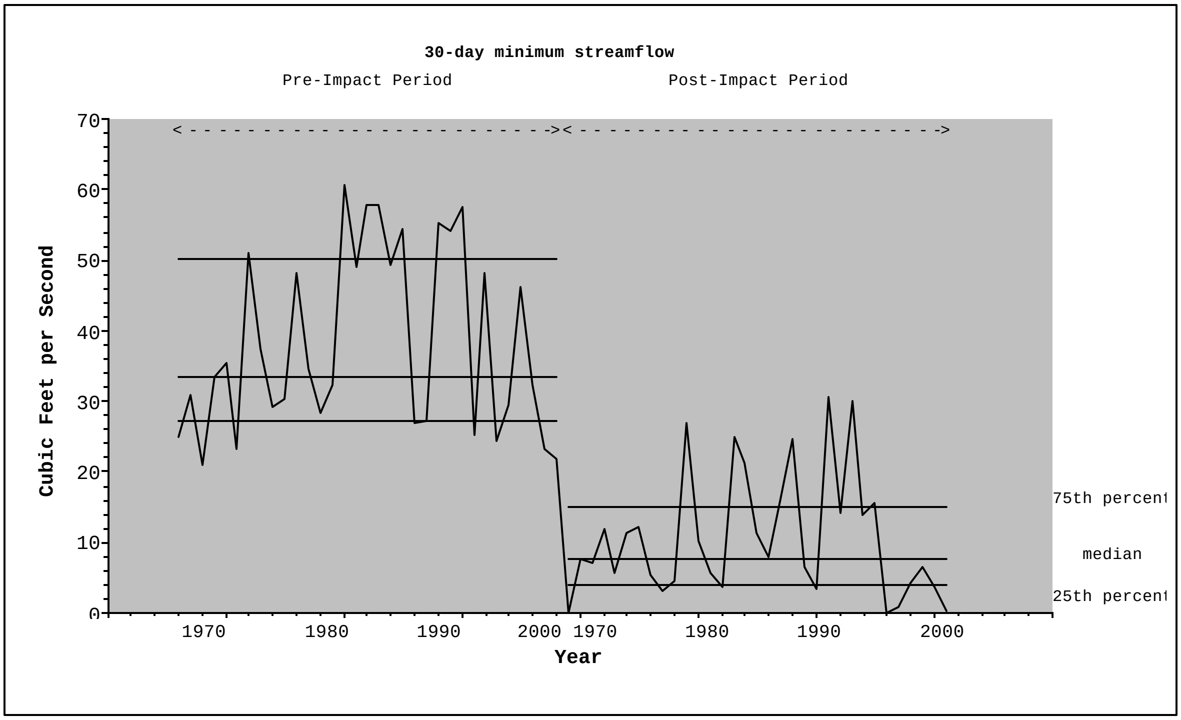



**Figure 55. IHA comparison of *Qgm* 30-day minimum flows under undiverted (left) and diverted *Qnet* conditions, April through October, for the period of record 1969–2001.**

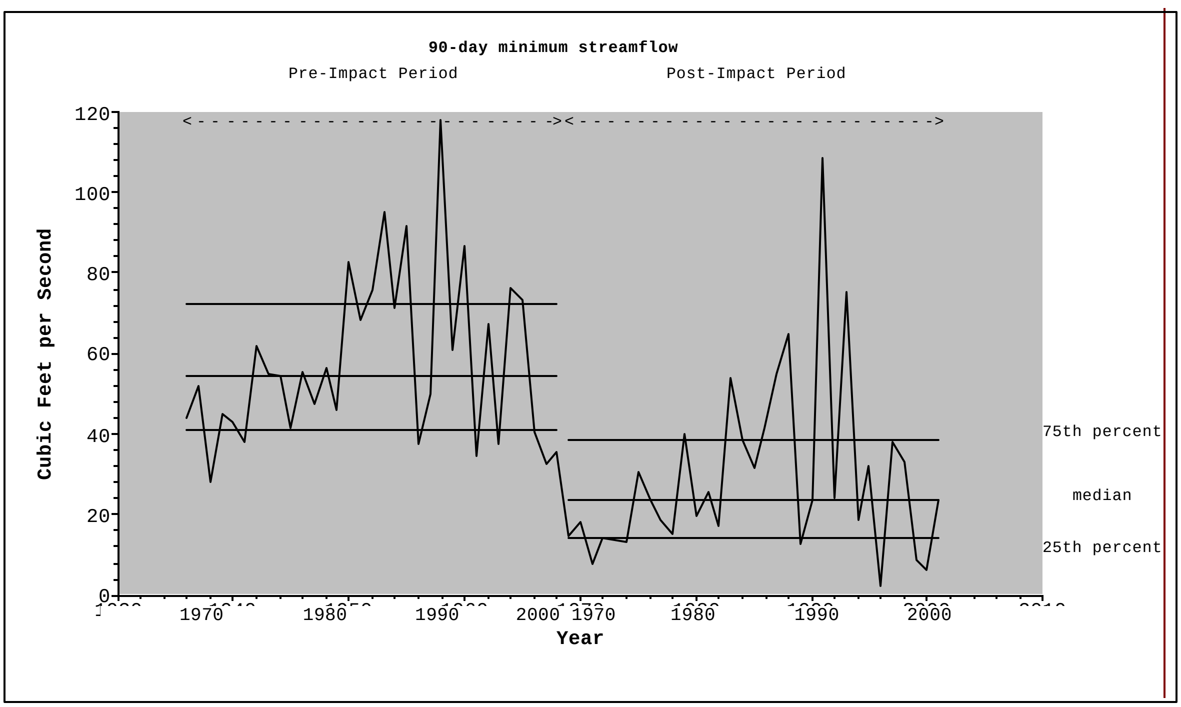



**Figure 56. IHA comparison of *Qgm* 90-day minimum flows under undiverted (left) and diverted *Qnet* conditions, April through October, for the period of record 1969–2001.**

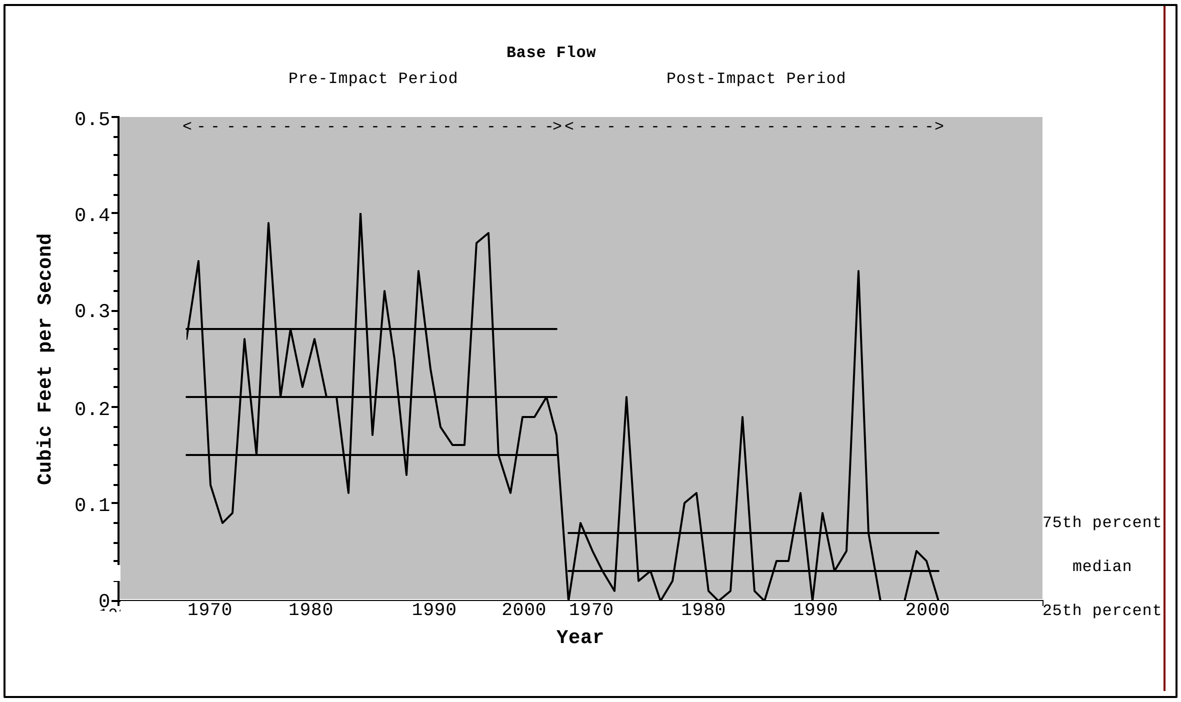



**Figure 57. IHA comparison of *Qgm* base flow under undiverted (left) and diverted *Qnet* conditions, April through October, for the period of record 1969–2001. Base flow is 7-day minimum flow/mean flow.**

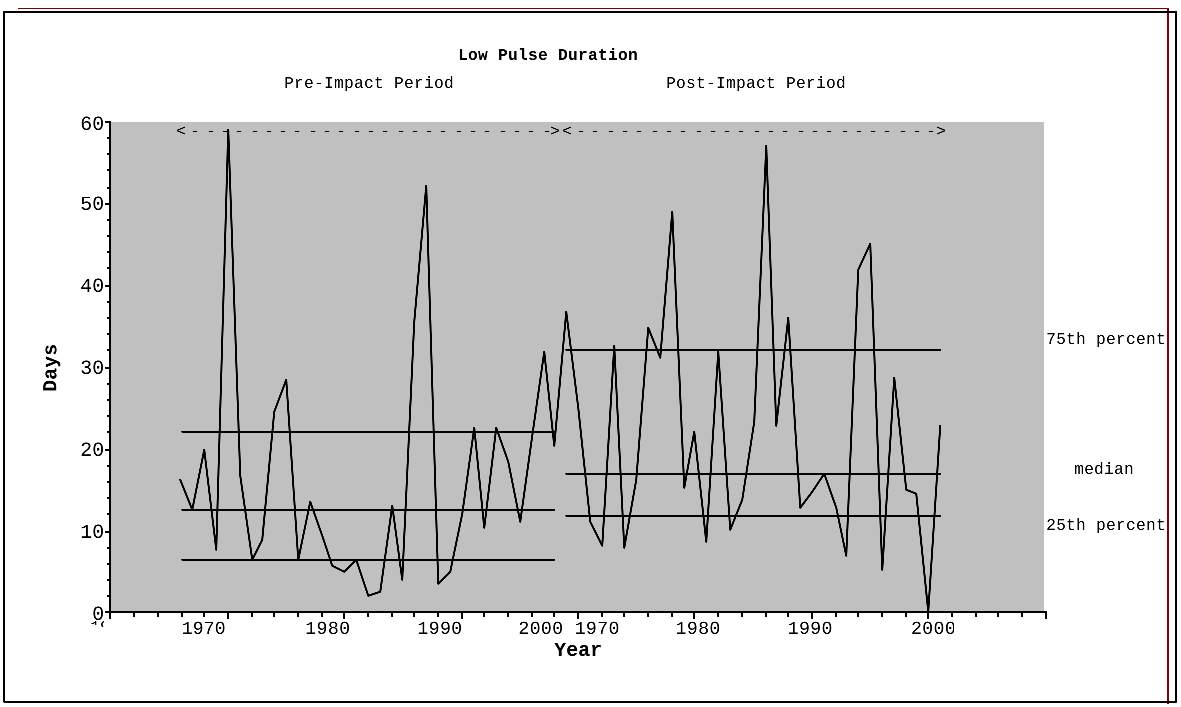



**Figure 58. IHA comparison of duration of *Qgm* low flows under undiverted (left) and diverted *Qnet* conditions, April through October, for the period of record 1969–2001. Low flow threshold is the 25$^{th}$ percentile of mean flow.**

***Surface and groundwater relations***. Results of the analysis of the interaction between surface flow and groundwater levels are based on full flow, since all piezometer sites are upstream of the diversions. Piezometers were placed only in substrate composed of fine sand to fine gravel. Local geology in and around the Gila Valley is complex, since the valley lies within the Transition Zone between the Colorado Plateau and Basin and Range provinces (Clemons, Christiansen, & James, 1980; Trauger, 1972). Volcanic flows and sedimentary deposits of Tertiary–Quaternary age underlie or form outcrops throughout the valley region. Some fine-grained lake deposits of late Tertiary age are present, particularly around the Duck Creek valley. Exposed Tertiary deposits of Gila Conglomerate are especially visible in the valley. The ancestral Gila River cut through these deposits. During later Quaternary time, its valley partially filled with alluvium, which today forms the highest benches above the river's current floodplain. More recent alluvial fill in the valley bottom, of Pleistocene to Holocene age, ranges in depth from 20 to 100 feet (Trauger, 1972; USDA SCS, 1954; USGS, 1923). The underlying Gila Conglomerate and lake deposits tend to form relatively impermeable layers supporting small perched aquifers in the alluvial fill, or accelerating groundwater movement down and across valley-facing hill slopes.

In spite of the area's geologic complexity, Trauger's detailed (1972) report suggests no reason to believe that groundwater/surface water interactions downstream of the diversions would generally differ from those measured at the eight piezometer sites. Local substrate composition affects groundwater flow rates significantly, however (Whiting, 1998). As a very general rule, elevation above the active Gila channel is more determinative of substrate material size than is downstream distance through the valley, at least above the Bear Creek confluence. Throughout the valley, terrace-level substrate near the Gila channel is generally composed of sand, sandy loam, and silt. Yet bars and low floodplain surfaces usually contain a high percentage of coarse gravel and cobble. These surfaces, only slightly higher than the river water surface at low flow, are well below terrace levels—often by six to ten feet. Groundwater elevations beneath bars and floodplains are probably kept relatively high by their proximity to active surface water flows; conversely, the material of which these surfaces are generally composed allows water to drain quickly.

Other variables—density of streamside vegetation, for example—can also affect the interaction between ground- and surface water. In the Gila Valley, two anthropogenic factors could also influence groundwater–surface water relationships downstream of the diversions, where nearly all residents live. Pumping from residential wells, in addition to those used to supplement surface water for irrigation, may decrease groundwater levels. On the other hand, field seep and ditch losses, estimated at 60% of diversion flows by Wilson (1998), tend to elevate groundwater levels. All ditches in the valley are unlined. Irrigation tailwater returned to the Gila River downstream of cross-section 5 frequently provides a significant boost to in-channel flow (interview, February 2001; personal observation, 1999–2001). None of these factors could be quantified in this study.

Even under the relatively uniform conditions at the piezometer sites, relative changes in Gila River water elevations and groundwater elevations varied substantially. Figure 59 shows the variance between surface water and groundwater elevations for each measurement taken, from July 1999 through January 2001. According to field notes, the valley received “monsoon” rainfall from mid-July through early September 1999 (Julian 195 to 260). No rain fell in the Gila Valley from mid-September until December 24 (Julian 358). Discharge in the Gila River rose and fell in response to precipitation during these months, and levels inside the piezometers appear, on the whole, to reflect changing river stage. (Although some precipitation may infiltrate soils and increase water elevations within the piezometers, soil surfaces in a 3-foot diameter around each piezometer were sealed with bentonite clay during installation.)

In general, water elevations within the piezometers were lower than in the river, suggesting that the river loses water to floodplain areas as it flows downstream. However, in the reach near the Mogollon confluence (and near an abandoned ditch diversion point discussed below), shallow standing water along the east river bank was consistently colder during summer months than the water flowing in the channel thalweg. This was the case even when the east bank had been in steady sunshine for five to six hours (personal observation, 1999–2000). Groundwater flow was therefore from floodplain to river channel at this spot, at least during summer site visits.

At piezometers 3 and 4 (P3 and P4), measurements showed consistently higher groundwater elevations in P3, east of the river, than in P4, on the west floodplain. The apparent gradient of this groundwater movement changed over time, however. During Julian days 580 to 660 (roughly July through September 2000), groundwater elevations east of the river decreased while those on the west increased.

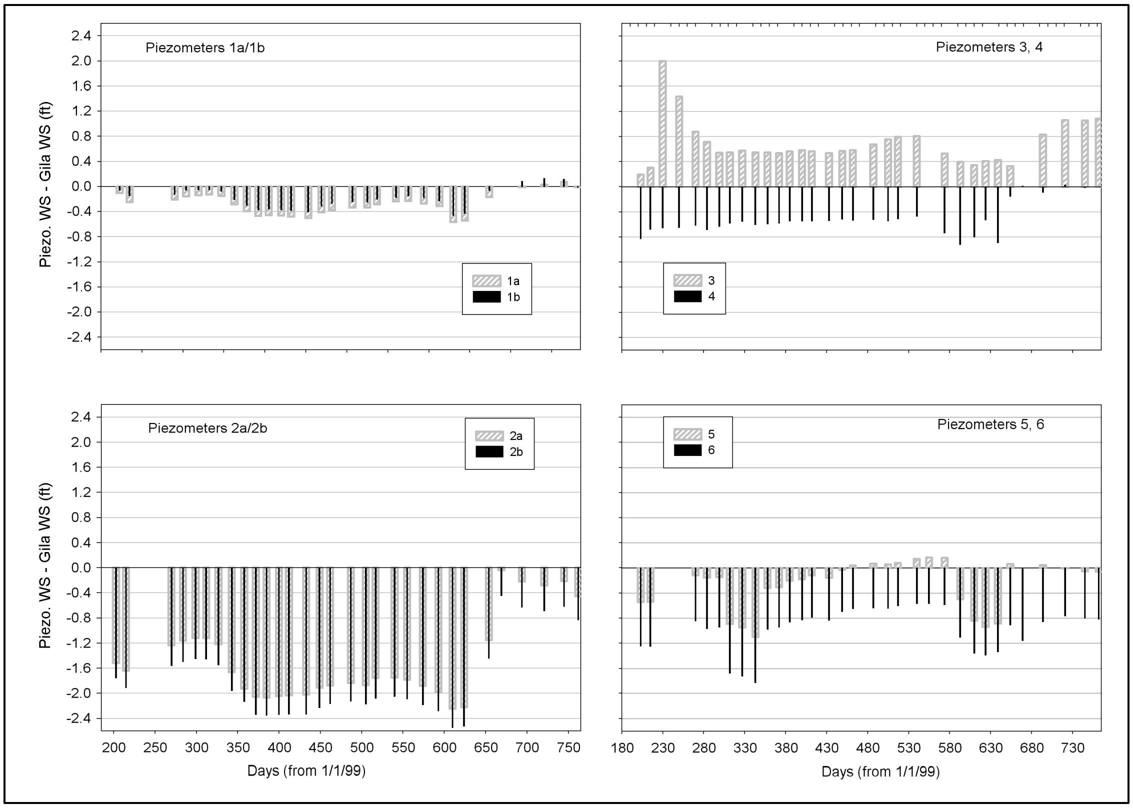



**Figure 59. Variance in feet between measured Gila River water surface elevations and piezometer water elevations on each measurement day.**

P2a and P2b are both located on the right floodplain, and at nearly the same distance from the river. Yet water elevations inside P2a were consistently about 0.3 feet higher than those in P2b. P5 and P6 are located on opposite sides of the river and at about the same distance from it. P6, on the right, was placed in what is clearly an abandoned river channel, whose surface elevation is considerably lower than the sand terrace where we placed P5. Groundwater elevations inside P5 were always higher than those measured in P6, and in July 2000 were above the river water surface.

Interactions between ground and surface water are complex (Maddock, et al et al., 1995), and groundwater flow rates are strongly influenced by the relative permeability of substrate (Hawkins & Stephens, 1983). The apparent anomalies noted above suggest either large differences in substrate permeability between the river and piezometers at the different sites, greater uptake by vegetation at some sites than others, or the possibility that some groundwater was moving along paths more parallel with the river than perpendicular to it. These possibilities were also examined. Box-and whisker plots depicting variances between measured groundwater and Gila River surface elevations were constructed and are shown in Figure 60. Another set of plots was constructed in which the effects of piezometer–river distance were removed by standardizing all measured variances between water elevations by piezometer distance from river's edge (Figure 61). For both plots, the 25th and 75th percentile measured variations are outlined by each box, and the whiskers show 10th and 90th percentiles. Squares above and below each box are 5th and 95th percentile variation.

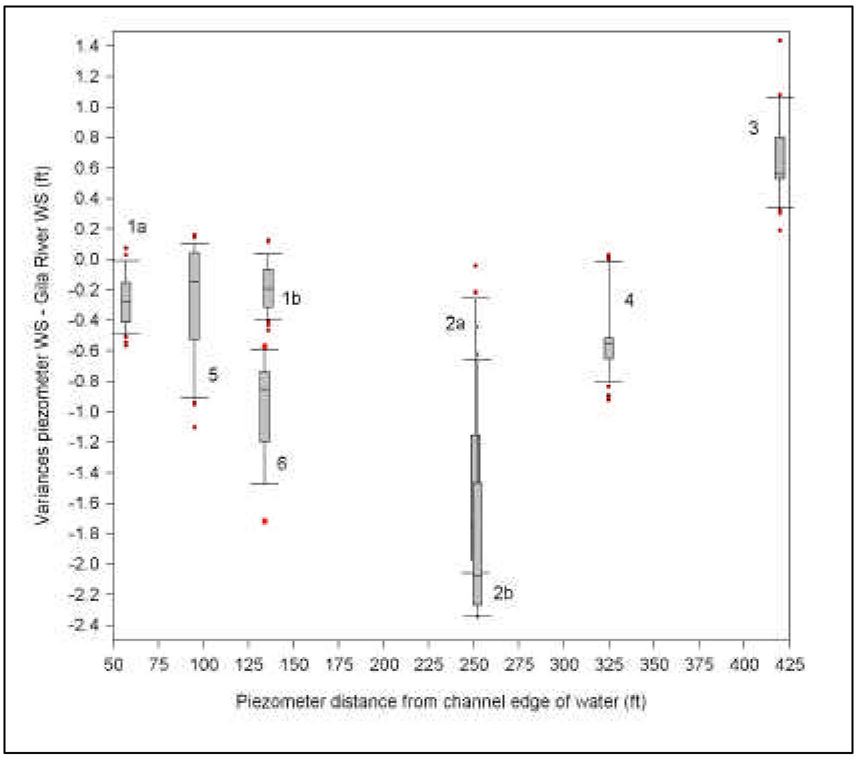



**Figure 60. Box-and-whisker plots of variance between measured piezometer water elevations and Gila River water elevation and piezometer distances from edge of water for period of measurement July 1999 through January 2001.**

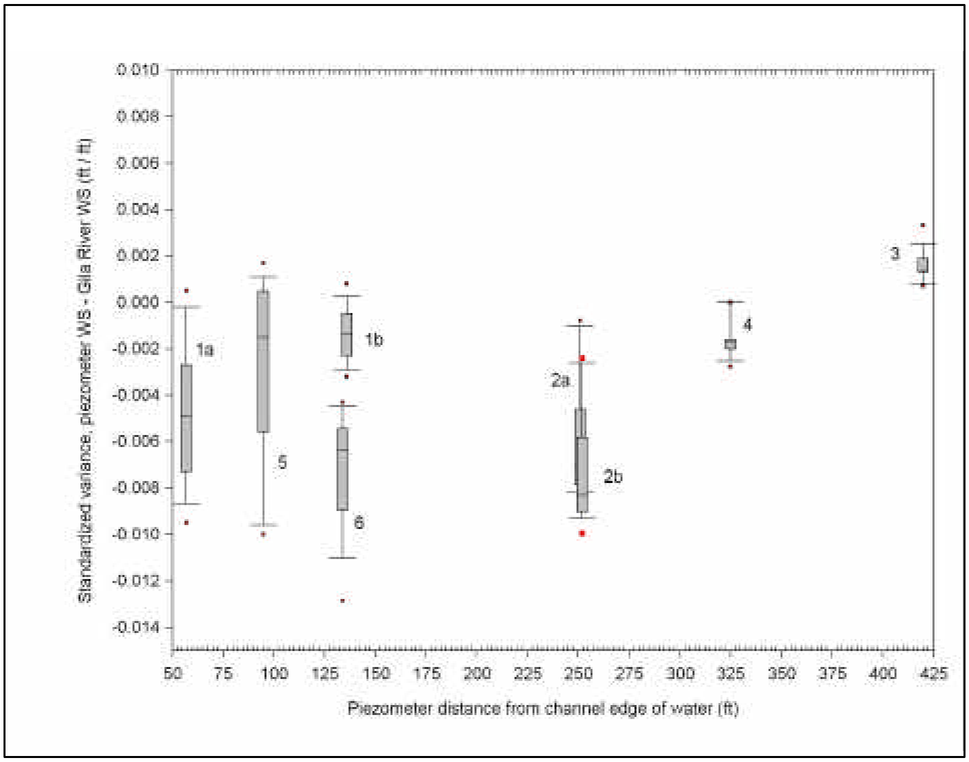



**Figure 61. Box-and-whisker plots of variance between measured piezometer water elevations and Gila River water elevation and piezometer distances from edge of water for period of measurement, July 1999–January 2001. All variances standardized by distance.**

In the nonstandardized plots, variance was highest in P2a and P2b, which are relatively far from the active channel, about two-thirds as far as the piezometers placed farthest from the river. Both P2a and P2b were placed in an abandoned river channel parallel to the main channel. The airphotos show this as the active channel in 1974. Substrate in the channel is deep sand. Water levels inside the piezometers tended to change in a pattern generally like the pattern of change in river stage, except during extended periods of low stage, when levels inside the piezometers continued to drop. Water elevations inside both P2a and P2b responded sharply to a small flood in October 2000 (of about 1100 cfs), increasing nearly four feet. Floodwaters did not cross the floodplain to reach the piezometer location, but instead traveled down the overflow channel (personal observation, October 2000).

Variance was also relatively high in P5 and P6, closer to the river than any other piezometer except P1a. P5, as noted above, is situated on a high sand terrace near the diversion split. The airphotos show that this terrace was farmed until sometime between 1965 and 1974.

Although it is no longer evident, an irrigation ditch ran between the field and the base of the hills to the east until at least 1965. The ditch carried water from a diversion point about ½ mile upstream. Here the possibility exists that subsurface flow is traveling downstream through relatively permeable substrate in the abandoned ditch, which follows a much straighter, and therefore shorter, course than the river itself. Variance at P5 between river and groundwater elevations is greater during periods of increasing river stage than during those of decreasing stage because the water elevations within the piezometer tend to rise more rapidly than those in the river channel. P6, across the river, is situated in what was in 1965 the river bed. The river today meanders sharply toward its old bed before turning back to the east, perhaps delivering some seepage flow into the abandoned channel to elevate groundwater levels there. Water levels inside P6 fluctuate more slowly during changes in river stage than those in P5.

P3, which showed the least variation from river surface elevation, was placed on a sand terrace only 20 feet east of an overflow channel that was once the upstream end of the ditch near P5. Water was present in this channel during every site visit, and it hosts a luxuriant growth of reed, forbs, and young cottonwood (see Figure 62). The piezometer site is very close to the old diversion point, and this may be reflected in the lack of variance between river stage and groundwater elevation within the piezometer. Water entering the abandoned ditch flows about the same distance downstream to P3 as it does to the river staff gage where measurements were taken.

With distance effects removed (Figure 61), water elevations inside P1a, nearest the river, showed the greatest variance from surface water elevation for all piezometers except P5. P1a is located in sand adjacent to an overflow channel. Although the channel was dry during every visit, it lies at the downstream end of a backwater pond created by flood debris. Sand is highly permeable. It seems quite likely that water trapped in the pond during higher river stages travels through the sand bed of the overflow channel and reaches the piezometer sooner than water from the active channel, which must travel through a silt bank before reaching the overflow channel. After river stage drops during drier periods, the pond evaporates. Water elevations within the piezometers drop even as river stage remains constant.

P1b is about 80 feet shoreward of P1a. If subsurface movement of water from the river were traveling through the river banks in a direction perpendicular to the channel, one would expect water elevations in P1b to respond to stage changes in the river more slowly than in P1a.

**Figure 62. Overflow channel occupying irrigation ditch abandoned ca. 1965, near piezometer 3. May 2000.**

Water elevations inside P1b were always slightly lower than those in P1a, but change in the water levels in P1b exactly follows the pattern of those in P1a. It could be that subsurface flow from the elevated backwater pond that appears to supply water to P1a is also reaching P1b, which is only a short distance farther downstream from the backwater. Like P2a and P2b across the river, water levels inside P1a and P1b rose sharply after the small flood in October, 2000. Flood water reached the piezometers through the abandoned channel, not by traveling across the floodpla in from the active channel.

Two conclusions seem evident. In the reach upstream of the diversions, seepage is generally from the river toward its floodplains, and therefore, streamflow is important in maintaining groundwater levels. Movement of groundwater, however, is far from uniformly perpendicular to the river. Rates and paths of groundwater movement through the floodplains around the Gila River are controlled by a combination of factors including varying substrate permeability. Not least among these factors is the network of abandoned channels and ditches that crosses the floodplains and probably exerts a strong influence on groundwater flow paths and transmissivity.

***Estimates of diversion effects***. To evaluate the usefulness of discharge–groundwater elevation regressions, third-order polynomial equations were constructed in JMP (1997). Data from one randomly selected piezometer at each of the three sites were used. For the upstream-most site, P2b data were run against lagged Gila gagesite discharge, as described in the Methods section. P4 and P6 data were used from the middle and downstream-most sites, respectively. For these sites, the constructed regression used *Qxs2* as discharge. Third-order polynomial equations resulted in the best fits, since they accommodated change in the slope of the regression at lowest and highest discharge levels. Regression results are shown in Table 9.

**Table 9. Regression results, piezometer water surface level fit by lagged gagesite discharge or calculated discharge at cross-section 2.**

| Piezo. | Equation | $R^2$ | F ratio | Prob > F |
|---|---|---|---|---|
| 2b | WS = 86.394 + (0.0198gage Q) – (5e-4 gage Q)$^2$ + (4.68e-8 gage Q)$^3$ | 0.65 | 18.2 | <0.0001 |
| 4 | WS = 90.736 + (0.00585Qxs2) – (6.81e-6 Qxs2)$^2$ + (4.66e-9 Qxs2)$^3$ | 0.94 | 153.6 | <0.0001 |
| 6 | WS = 90.045 + (0.00601Qxs2) – (1e-4 Qxs2)$^2$ + (9.1e-9 Qxs2)$^3$ | 0.68 | 21.6 | <0.0001 |

WS, piezometer water elevation relative to 100.0 ft. arbitrary datum; gage Q = 6-hr lagged Gila gagesite discharge; Qxs2 = calculated discharge at cross-section 2.

Predicted values from the regressions were saved for construction of a time series that used *Qnet* discharge calculated from daily means for the same days as those on which piezometer measurements were made. Predicted groundwater elevations at *gage Q* or *Qxs2* (full flow) conditions and at *Qnet* (diverted) flow conditions are plotted with actual groundwater elevations in Figure 63. The predictions fail to model the likely groundwater impacts of extended near-zero streamflow. For example, actual groundwater elevations at full flow of about 40 cfs experienced the greatest decline at piezometer 6 in October 2000. Predicted values, based on discharge of less than 10 cfs, overstated groundwater elevation by more than 0.5 feet. Nor did any model tested predict continued decline in groundwater elevations at zero streamflow.

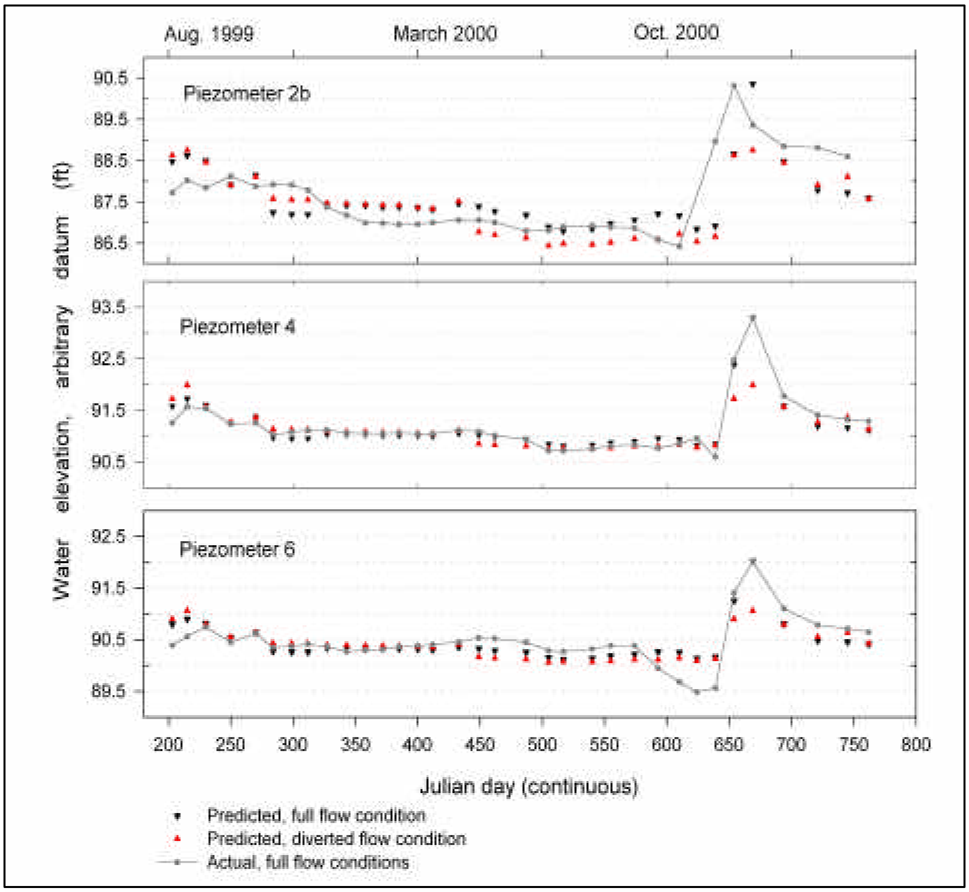



**Figure 63. Predicted piezometer water elevations under undiverted (*Qgm*) and diverted (*Qnet*) discharge and actual measured water elevations. Predictions were calculated for one piezometer selected from each of three sites.**

Jacobson (personal communication, 2001) installed a piezometer on a sand terrace just downstream of the Fort West and Upper Gila diversions in August 2001. He monitored a 1.5-foot decrease in the piezometer water level during September, 2001. Groundwater elevation in early

September was about six feet lower than by early November. He also noted that a dense stand of mid-aged cottonwood trees at the site were "looking quite stressed and there are many trees showing signs of cavitation and dieback" (personal communication, September 2001). Both observations suggest that the lack of appreciable decline in groundwater elevations under diverted conditions that is predicted by the models reflects not reality, but the models' predictive shortcomings.

***Groundwater impacts: summary.*** Irrigation diversions create significant impacts to the Gila River's baseflow regime, especially near diversion points. They probably decrease streambank water storage as well, since typically, though not always, groundwater moves from the Gila stream channel into floodplains during periods of low flow. However, groundwater movement through floodplains is not necessarily perpendicular to the stream channel; variances between ground-and surface water elevations are not dependent on distance from the active channel. Rather, shallow groundwater flow paths seem to be strongly influenced by the paths of abandoned channels across floodplains and varying substrate permeability rates.

## DISCUSSION

The discussion that follows synthesizes results obtained from the study and described in the previous section. Evidence from each aspect of the research is evaluated in conjunction with other results to account for the changes documented in the river corridor, their relationship to flood events and anthropogenic activities, and their likely potential for future condition of the stream channel and riparian corridor. A final section evaluates the implications and validity of this study approach for the interpretation of the river's past, current, and future condition.

### Flood effects

The geomorphic effects of large floods in semi-arid alluvial valleys are extremely complex. Among other factors, duration of flooding, relative magnitudes of mainstem and tributary flooding, and patterns of existing vegetation can strongly influence patterns of erosion and deposition within the mainstem channel (Bourke & Pickup, 1999; Graf, 1988a; Kennedy, 1999; Simon & Darby, 1999). Baker (1988; see also Baker & Costa, 1987; and Beven, 1981) depicts a sequence of channel narrowing and widening over time, dependent on flood magnitudes and timing. Bull (1988) described general long-term processes of aggradation and eventual erosion in arid land rivers. Nanson (1986) studied floodplain development and erosion along a confined river in southern Australia and found that cyclic but infrequent floods scoured floodplain vegetation and fine-grained sediments from across the valley floor. Kochel (1988) noted that the magnitude of geomorphic change within the river corridor is less closely related to the absolute magnitude of a particular flood than to the relationship between mean annual discharge and maximum peak discharge for a given watershed. The Gila River's flood regime is extremely variable, as evidenced by the 20 years from 1978 to 1997. Although the Gila Valley experienced a closely-spaced series of major floods during this period, each was, statistically speaking, a relatively rare event. As a consequence, the ratios of peak discharge to mean annual discharge during these floods were much more extreme than they would be in a less variable system.

In the 40 years prior to 1930, one or more large floods appear to have straightened the Gila River channel and removed floodplain vegetation along some reaches within the Gila Valley.

These events occurred prior to channelization and other river construction activities within the valley. The evidence suggests that, at least under the watershed conditions existing at the time, floods alone were capable of creating conditions in the riparian corridor similar to those that existed in 1999. However, only relatively small areas across the river floodplain were scoured during these floods. Channel incision was also limited; the most noticeable result of early floods was probably extensive braiding of the river channel documented on the aerial photographs from 1935. Channel braiding is a function of particle size, flood discharge, and valley slope. Sand channels generally braid during smaller floods than gravel-bed channels (Carson, 1984). Interview and archival data suggested that bed material in the Gila River channel near the downstream end of the study reach, and perhaps farther upstream as well, was composed of fine-grained material during the first part of the 20$^{th}$ century. During the pre-1935 period, relatively moderate flood conditions may have created braiding of the stream channel.

Alternatively, Lane (1957; cited in Carson, 1984) documents a mechanism wherein a surplus of sediment is delivered from tributary streams into a "low gradient main valley" (325), increasing the potential for braiding. Water surface slope in the Gila River channel is generally less than 0.5% (Table 8), and significant quantities of sediment may have reached the main river from tributary drainages within the valley during one or more floods between 1918 and 1935 to create the braided pattern visible in 1935. This was not, however, the mechanism underlying the second instance of braiding that occurred in the valley after 1974, because sediment inflow from tributaries had been halted by construction of check dams before 1964.

All evidence indicates that mostly moderate floods between 1930 and 1972 deposited fine sediments on river banks and floodplains throughout the valley. Floods were "trained" onto fields by residents in order to build soils. Vegetation on river banks and floodplains through most of the river corridor was intact in 1935, and by 1950, was reestablished on previously bare floodplains in the upstream end of the study reach and around the Bear Creek confluence. Deposition and vegetation regeneration by 1950 "reattached" many of the islands that created the braided channel of 1935 to river banks, reestablishing the general single, meandering thread of the Gila River channel.

Levee construction began in the late 1940s and by 1965 levees lined long reaches of both sides of the river, tightly confining the river in some areas. The largest flood measured at the Gila gagesite between 1950 and 1972 occurred in 1965 when discharge reached just over 6200 cfs. For the next few years, the river, although straightened and channelized, mostly maintained its course within a single channel. Levee construction had cleared vegetation from floodplains in a long, narrow strip that extended from cross-section 3 downstream through the study reach.

**Levee implications**

The evidence of major lateral and vertical erosion and loss of riparian vegetation during the period between 1972 and 1996 throughout the valley is unmistakable. A question central to this study concerned the relative roles played by channelization efforts and the series of major floods experienced in the valley from 1978 through 1996 on resulting river condition. The results of levee construction and the relative resistance of the valley's levees and riparian vegetation to flood effects are examined below.

A drawing prepared by the Army COE during planning for levee reconstruction work in 1979 depicts the floodplain as the source for borrow material (Figure 64). Borrowing levee material from the floodplain left a strip of disturbed, churned up floodplain, highly susceptible to erosion, that extended nearly to the base, or toe, of the levee. In some areas, if not all, it actually

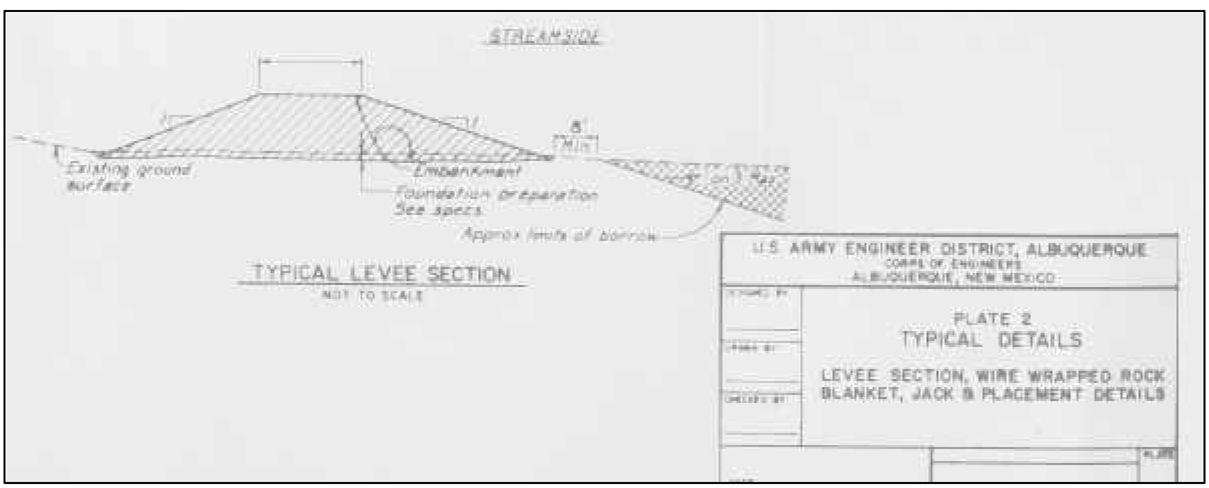



**Figure 64. Army Corps of Engineers drawing, March 1979, for levee construction on Gila River May 1979. Note "Approx limits of borrow" area and 1:3 slope specification. Courtesy Jon Souder.**

created a new channel in the floodplain for floodwaters, as one resident (interview, February 2001) noted. Although the COE diagrammed an "8' Min" (8-foot minimum) strip between borrow area and levee, the practical realities of bulldozing the quantities of material required for levee construction would have left precious little floodplain intact between borrow strip and levee in the event of the sort of flooding experienced in the Gila Valley after 1970. This fact appears to have played a role in early damage to the levee structures and in the eventual condition of the river channel and floodplains after 1980.

Levee damage apparently began during a 12,500 cfs flood in October of 1972. By 1974, shifts in the river channel toward the base of levees were evident in many spots. At many or perhaps all of these, the river occupied the "channel" that had been excavated there during construction. Some cultivated field areas were expanded into floodplains between 1935 and 1974, as shown on Figure 32. Many made contact with the shoreward sides of levees by 1974. The levees are locally known as “sugar rock,” for the ease with which they melt (interviews, April 2000 and February 2001). They were constructed of gravel and cobble in a matrix of sand; remnants are typically composed of cobble and coarse gravel (personal observation, 1999-2000). It seems likely that during the 1972 flood, as flood waters rose against the levees, finer material within them was carried downstream while coarser fragments slumped into the channel. This process would have continued during the greater 1978 event, when flood waters completely covered the valley. After this flood, the river channel was again braided among high bars and islands. The cross-sections show it occupying not only the same channel as in 1974 but also the channels excavated streamward of the levees for borrow materials in many locations. Braiding in some cases appears controlled by floodplain vegetation, as streamflow preferentially cut channels through bare floodplain sediments (for example, just upstream of cross-section 2).

***Sequence of erosion.*** Within some cutbanks along the river today a layer of coarser, cobble-sized material, deposited from the many steep local tributaries to the Gila prior to construction of the check dams, lies beneath a deep layer of generally fine sediment (personal observation, 1999-2000). A probable series of events during the floods of 1972 through 1984 follows. The first of these floods induced incision for limited distances upstream of the artificial channels created by levee construction when they were occupied by the active channel. For example, just below cross-section 2, after the 1972 flood the river flowed in a straight line toward the upstream end of the short levee section in that reach. Farther downstream, one river channel in

1974 follows a straight line from its contact with the bluff just above cross-section 3 past the upstream end of the levee on river right (Figure 39).

The high-magnitude flood of 1978 may then have scoured some of the fine material deposited in the previous decades from the Gila River floodplain, along with much of the sparse vegetation remaining between levees. In general, the effect was to lower the entire floodplain relative to fields. Braiding of the river through a complex network of channels (Figures 35 and 40), rather than deep erosion within a single active channel, was another consequence of the 1978 flood. Sand and other fines within levees were transported downstream during floods, while some coarse levee materials were deposited in the river channel as bedload. Flooding may have preferentially eroded sand, silt, and fine gravels from the floodplain to leave a system of braided channels where earlier deposits of cobble and coarse gravels formed islands and bars between active channel areas. Erosion of finer sediments from river bar surfaces (as occurred at cross-section 3 during the moderate flood in August 1999 described above), can result in "chute cutoff," one form of incipient channel braiding (Ashmore, 1991). Creation of mid-channel bars and islands was aided by the collapse of coarse levee material into the channel. A typical mechanism for building mid-channel bars involves bedload movement of very coarse sediments during floods until the sediment conveyance capacity of discharge decreases during the receding limb of a flood. Coarse sediment is then deposited mid-channel, where additional bedload gathers around the upstream and downstream ends of this "cluster nucleus" (Ferguson, 1993: 77).

Levee reconstruction projects in 1979 were designed to protect against a 15-year flood (US Army COE, April 1979), equivalent to discharge of about 15,000 cfs (USGS, 2003). Reconstruction required excavation of new borrow "channels," perhaps even more extensive than earlier ones. For example, re-channelization work and repair of the right side levee at cross-section 3 would have required finding material not only to reconstruct the levee, but to fill the channel scoured shoreward of it during the 1978 flood. Some of the braiding that appears in 1980 may simply represent borrow areas excavated from more than one location across the floodplain.

Donegon, in his 1997 review of the projects, notes repeatedly that the levees were "effectively destroyed" for the second time by floods in 1983 and 1984. However, many of the levees were also damaged during a flood in February 1980 in which combined streamflow in the Gila River and Mogollon Creek was no greater than 4400 cfs (Donegon, 1997: 4, 5, 10). By comparison with the statements made about the minimal effects of the much larger floods of 1941 and 1949, this suggests that smaller floods after about 1972 were more erosive than earlier floods. One irrigator who was interviewed said as much, pointing out that it is these smaller floods from which he and others hope the levees will provide protection to fields (interview, February 2001). The levees were not reconstructed after 1984 and were further damaged by continued flooding through 1997.

Damage to most levees is now so extensive that identification of levee remnants can be very difficult. Most remain only as large ridges of cobble and gravel across floodpla ins (this is the case at most cross-section locations); others are nonexistent. Much of the coarser material from slumping of the levees was probably deposited in channels active during the floods. Flood-induced channel widening increases the stream's capacity to move coarse bedload, probably resulting in deposition of bedload across broader areas in the valley (Baker & Ritter, 1975). In many reaches throughout the study area today, coarse gravel and small cobbles armor the active channel (personal observation, 1999-2000). Greater stream energy is required to transport these coarse materials than the finer mixture of sand and silt found in the fields just beyond the floodplain.

The extent of vertical and lateral erosion within short reaches of the river corridor is controlled by varied local conditions. Loss of shoreward vegetation may have increased the erosional susceptibility of fields adjacent to levees. At sites where the river breached the upstream end of a levee to flow between its coarse remains and a field, stream power during floods is preferentially utilized to transport fine field sediments rather than coarse bed and floodplain material. Most lateral erosion prior to the 1990s floods (on the USGS, 1987 color infrared airphoto) seems to have occurred under these conditions. At other locations, vertical erosion may have predominated during each flood event until the layer of coarser bed material was reached. Incision within the river channel seems to have reached its deepest extent, exposing the longest reaches of armored bed material, during flooding in the 1990s. Depending on flood magnitude, extent of braiding in the reach, and remaining vegetation, subsequent lateral erosion acted against levee remnants or against fine field sediments.

The cross-section data generally show early (1965 and 1974) channels at the highest elevations, 1980 channels lower, and an active channel incised five to eight feet below. Some of the fine deposits found within the abandoned channels and on their banks have been deposited by floods that occurred between 1980 and 1996. Because of the temporal gap in aerial photography coverage between those years, the exact date the river occupied the currently active channel is unknown. Flood waters of large enough magnitude branch into the abandoned channels, and dense vegetation along some of these old channels traps fine sediments. Excavation of the channels to determine the composition of underlying bed material was not possible for this study.

In an earlier study of erosion on the Salt River in Arizona, Graf (1983) documented virtually no change in bed elevation between the late 1880s and 1965, in spite of a number of major flood events. Between 1965 and 1983, however, the Salt River's bed elevation dropped about 20 feet. Graf also noted that sediments deposited prior to 1965 were generally composed of coarse sand and that vertical erosion proceeded through this layer—especially during a flood in 1978—into a resistant cobble layer. Unlike the Gila River, however, a 1980 flood also eroded through the cobble layer into an underlying layer of sand (Graf, 1983). Lateral channel movement within much of the reach that Graf studied was constrained by "near-channel construction" associated with "urban development," and gravel mining activities were ongoing within the main channel (131). Both circumstances may account for the continued incision and lack of lateral channel movement that appears to differentiate the erosional patterns on the Salt River from erosion observed on the Gila River.

***Vegetated floodplain area.*** Four years after the last major flood event in the Gila Valley, most river banks and much of the river floodplain area remained devoid of new riparian growth. Maximum vegetation loss from floodplains probably occurred by 1984. By 1996, riparian vegetation extent in most of the study reach, measured from the 1996 airphotos, was generally the same as in 1980 (downstream of the Bear Creek confluence) or somewhat greater (upstream of cross-section 5 (Figure 38; cf. Figures 19 through 21). The major exceptions were at the Highway 211 bridge and around the Gila Farms diversion area downstream of cross-section 5. Unvegetated extent in each of these areas increased by 20 to 25% between 1980 and 1996 (Figure 20).

Further examination of Figures 19 through 21, the graphs of change in unvegetated surface area, suggests that levee construction—especially the second bout of work, in 1979—may be at least partly implicated in current condition of the river and floodplains. Figure 19 graphs changes in unvegetated floodplain surface in the upstream third of the study reach. No levees were constructed between the gagesite and cross-section 2, a constricted segment that is prone to scour during large floods. There was virtually no change in unvegetated floodplain surface in this segment between 1935 and 1950. No regeneration of vegetation that was removed by flooding prior to 1935 occurred, but almost no existing vegetation was removed. As shown in Figures 20 and 21, vegetation downstream of cross-section 5 increased except at the Bear Creek confluence during the same period. Little or no vegetation was scoured by the 12,000 cfs flood in 1949. Only between cross-sections 2 and 5, where a majority of the earliest levee construction in the valley took place, did vegetated surface area decrease between 1935 and 1950. This vegetation was almost certainly removed during levee construction, or by a combination of construction and the 1949 flood, rather than by floods alone.

Despite the period of extensive levee building throughout the valley between 1950 and 1965, unvegetated surface decreased between every cross-section in the study reach. It *increased* in every reach—even the unleveed reach above cross-section 2—after the 1972 flood, another 12,000-cfs event. The comparatively greater loss of floodplain vegetation after the 1972 flood, nearly identical in magnitude to the 1949 flood, could reflect the combined effects of both levee and check dam construction. Floodwaters in 1949 transported both existing sediment in the main channel and any that were delivered by incoming drainages in the valley during the flood, but only bed and floodplain materials along the main channel (and those arriving from Spar Canyon) were available for transport in 1972. Channel straightening and meander cutoff during the 1972 flood caused loss of vegetation.

Other variables may have contributed to the relative effects of the two floods, and they require more study—prior climatic and soil moisture conditions, for instance, may have influenced the resulting impacts to vegetation. However, it is noteworthy that the 1949 flood was bracketed by two others, all three occurring within four months, and that all three were "winter" floods. In the valley, these floods are generally considered more erosive than so-called "summer" floods. The idea behind this, as noted by Baker (1988), and Stromberg (1993a), is that winter runoff, of either snowmelt or "rain on snow," carries less overland sediment to the river channel. Since less energy is used in conveyance of sediment within the channel, more energy is therefore available to erode channel banks and floodplains. Based on climate records from three high elevation weather stations in the Gila watershed (Adobe Ranch, at 7400 feet; Hood, at 7000 feet, and Beaverhead, at 6700 feet) snow was present in the headwaters in January 1949 (Western Regional Climate Center, 2003). If the "winter flood" theory is correct, this would suggest that the 1948–1949 floods would have *greater* erosive effect than the October 1972 flood—but the reverse seems to have been true.

In 1980, following the huge flood of December 1978, and levee reconstruction in 1979, unvegetated area decreased in the unleveed reach above cross-section 2, and increased only slightly between cross-sections 2 and 3, where the only levee rebuilt was at the downstream end of the reach. Large increases in unvegetated surface coincided with areas of major reconstruction, from cross-section 3 to cross-section 9, and from cross-section 10 to the downstream end of the study reach. Greater variances between unleveed and leveed reaches become evident by 1996, 17 years after final reconstruction of the levees. Vegetation regeneration is far more pronounced in the reach from the gagesite to cross-section 3, at the upstream end of levees reconstructed in 1979, than downstream. Moreover, six of the "top ten" floods of the 1970–1997 period occurred between 1980 and 1996, including the flood of record in 1984. A flood of nearly 17,000 cfs came through the valley less than two years before the 1996 airphotos were taken. Nonetheless, by 1996 new vegetation emerged throughout the river corridor above Bear Creek, except in the reach between cross-sections 5 and 10. This indicates that the impact of construction activities on riparian area was more substantial than the levees themselves. Their effect on regeneration potential probably decreases farther as the levees continue to deteriorate.

Cross-sections 9 and 10 are at the downstream end of this reach. At the first site visit in January 1999, no appreciable difference in riparian extent existed between these two cross-sections, which bracket the Highway 211 bridge. It should be noted that cattle have been grazed on an annual November through April rotation since 1992 downstream of the bridge; no cattle have grazed the floodplains upstream of it since about 1998 (interview, February 2001). It seems likely that floodplain constriction caused by the Highway 211 bridge, and the presence of high cobble berms—remnant levee—on river left between cross-sections 9 and 10 were major factors inhibiting vegetation regrowth in this area before 1996.

Farther upstream toward cross-section 5, barren floodplains are most notable in the westward meander just downstream of cross-section 5, and around the Gila Farms ditch diversion (see Figure 5). An odd, dark semi-circle within the meander marks some sort of reconstruction or restoration effort that may be connected with the presence of a line of stream jacks (bank protection devices reminiscent of the metal anti-tank contraptions used in World War II) in that area today (personal observation, 1999). Unlike the Fort West diversion point, the Gila Farms diversion has not been moved upstream in response to incision after the 1980s–1990s floods (interview, April 2000). However, the 1974, 1980, and 1996 airphotos show that it was reworked many times within the same general area. Today, the volumes of earth that must be moved to maintain it are evidenced by multiple channels, barren bars and floodplains and high, gravelly berms throughout the reach around the diversion. Seedling survival in this reach is doubtful.

The regeneration of vegetation above cross-section 5, and lack of it downstream, suggest two things. One, the riparian corridor, or most of it, is capable of "recovery" in the absence of restoration efforts. Two, channel construction activities—reconstruction of levees and diversion maintenance—probably inhibit riparian regeneration more than the levees themselves.

## Riparian potential

***Diversion effects.*** An emphatic "however" must be interjected here. Although riparian regeneration between 1980 and 1996 took place through the entire reach upstream of cross-section five, the location of regrowth relative to the active channel varies in important ways. Regeneration that occurred between cross-sections 3 and 4 is not indicative of recovery along the active channel, for example, where virtually no vegetation existed even in 2000. Because of the diversions just upstream of cross-section 3, the stream channel in this reach was frequently dry during site visits. In the upper end of this reach, the river travels along the base of fields on the west edge of the floodplain. Near the eastern floodplain edge, where the river channel was extensively braided in 1980 (Figure 40), a very dense band of small (less than 12 feet high) willow and cottonwood grows. The upstream end of the Fort West ditch is only a few hundred feet farther east. About midway down the ditch between its Spar Canyon diversion point and cross-section 4, excess water from the ditch is shunted to the west, where it probably travels in one of the overflow channels that appear in the 1980 airphotos. The excess flow carried by this channel during site visits appeared to be around one cfs. Beavers had built three dams down the length of the channel by 1999. The resulting ponds and groundwater infiltration are extensive enough to support the nearly impenetrable band of vegetation and to allow a steady seepage to reenter the river channel immediately upstream of cross-section 4. For revegetation work, more than 1000 willow and cottonwood cuttings were taken from this riparian band in 2000; the cuttings "hardly made a dent in it" (interview, February 2001).

Upstream of the diversions, young stands of riparian vegetation along the active channel were already well-established when the study began in January 1999 (Figure 7 is a photograph of cross-section 2), in strong contrast to most areas downstream. The contrast suggested that water availability in the active channel exercised major control over seedling survival on nearby banks. The low flow and IHA analyses confirmed that alterations to the river's base flow regime imposed by the diversions during the months of April–October had a significant impact on streamflow. Only during two years, 1991 and 1993, did diverted flow conditions reach the targeted 30-day minimum discharge (the 25$^{th}$ percentile of full streamflow). Streamflow under undiverted conditions was greater than 20 cfs during 100 times as many days as under diverted conditions.

***Spatial distribution of vegetation.*** Field observations in March and September 2000 downstream of cross-section 4 located many stringers of young cottonwood (generally about 30 feet tall, with diameters of 4 to 8 inches) growing within or next to overflow channels within 300 feet of the active channel. Most were growing on loam or sand surfaces six to eight feet above the active channel thalweg. The trees are of similar size. Root collars were frequently buried beneath one to four inches of soil or sand, indicating deposition since tree establishment. These strands of vegetation began growing sometime after 1980 and are visible in Figure 37 as sporadic, uncolored dark gray bands near the 1980 and 1996 channels. Abandoned channels can provide ideal "nursery sites" for riparian reestablishment (Asplund & Gooch, 1988; Braatne, Rood, & Heilman, 1996; Brady, Patton, & Paxson, 1985). Where seedlings occupy the lower elevation surface of an abandoned channel, potential root contact with groundwater is increased. The location of these stands also removes them from the potential scouring effects of moderate floods within incised sections of the active channel and increases the possibility of their benefiting from local groundwater recharge after floods in which discharge is partly captured by the overflow channels.

Abandoned ditches on the floodplain sometimes act as overflow channels, or possibly, as paths for groundwater movement parallel with, rather than perpendicular to, the active channel. Currently inactive ditches that were mapped during the SGO and 1918 surveys may indicate likely areas of regeneration. For example, one now-abandoned ditch mapped in 1918 travels within 300 feet of the active river channel down the west side of the floodplain between cross-section 3 and cross-section 5. Stringers of young cottonwoods appear along overflow channels west of the river through the reach, and a dense stand was present next to the active channel just upstream of cross-section 5 in January 1999. Water availability for these trees was probably good; they grew from a height of about 10 feet to over 20 feet during the course of site visits.

Permeability of substrate and subsurface flow movement in abandoned, buried channels can strongly influence the rates of groundwater movement (Poole, et al et al., 2002). Evaluation of groundwater elevations relative to the active channel surface upstream of the diversions suggests that movement of subsurface flows is highly variable, even absent the additional influence of the active irrigation network in use farther downstream. All of the ditches in the valley are unlined, and at some areas below the diversion points seepage from the ditches also influences patterns of vegetation survival on the river floodplains. During the driest months, the river bed is frequently dry from Spar Canyon to the west-to-east meander section just upstream of cross-section 4. As noted previously, almost no riparian trees of any age are present near the channel here. Approximately one cfs is returned to the channel at cross-section 4 from Fort West ditch overflow. Downstream of the cross-section, seepage from irrigated fields probably elevates groundwater levels and infiltrates the floodplain; water was always present at cross-section 5.

More water reaches the river channel downstream of ditch "turnouts," where irrigation water is returned to the river channel. Two of these are located at Winn and Bell canyons, roughly ½ mile and one mile downstream of cross-section 5 (interviews, February 2001). Although much of the active channel is incised, many stands of moderately sized cottonwood and willow are established in low-elevation areas on the floodplain through the reach downstream of the turnouts.

The patterns of vegetation regrowth downstream of the diversion points for the Upper Gila and Fort West ditches strongly indicate their dependence on water availability, either as the presence of streamflow in the active channel, as groundwater infiltration from field and ditch seep back toward the river channel, or as recharge carried by abandoned channels and ditches during flood events. It is probably most useful to think of riparian potential on floodplains in the valley in terms of probability. The patterns of earlier regeneration described above, and the locations where seedlings survived after the August 1999 flood, showed that seedlings were most likely to become established in certain overflow channels or in backwater areas; some survived on relatively flat surfaces next to the active channel where soil or sand and vegetation was already present. These surfaces were typically about one foot above water surface at base flow.

Ultimately, the spatial distribution of seedling recruitment and survival on banks and floodplains will depend on the timing and magnitude of floods and local precipitation. Small floods (around 500 cfs) occurring in the late spring or summer months will likely result in the greatest establishment of vegetation on low bars and horizontal floodplain surfaces near the active channel. The presence of such emergent vegetation on these surfaces would enhance the probability of additional recruitment in the same areas over the near term. On the other hand, higher-magnitude floods (e.g., 5000 cfs) will more likely facilitate establishment along abandoned channels, where survival may be inhibited by distance from the base flow channel, or enhanced by ditch proximity and field seep.

On the active channel, potential regeneration in the cross-section 3 to 4 reach is lowest. Much of the reach is incised between steep banks, and these are often composed of extremely coarse materials. The lack of low, horizontal bar surfaces, soil, and existing vegetation decreases the chance that riparian seeds will lodge in a spot where they are both relatively safe from being removed by the force of the stream current and able to reach groundwater during the seedling stage. Only a series of very low-magnitude flow events will facilitate seedling recruitment in this reach. In addition, the elevations of overflow channels on the floodplain in this segment are relatively high compared to the active channel thalweg. This decreases the possibility that discharge during moderate flood events will enter the overflow channels, an otherwise likely spot for regeneration, and that groundwater recharge from the active channel will be elevated enough to remain available for seedling growth. The last factor is made even less likely by the area's proximity to the diversion points; streamflow within the channel here during dry months is probably less than anywhere else within the study area.

In this reach, and those downstream, other sources of water increase the chances for seedling establishment and survival off the active channel. As the volumes of ditch and field seep—dependent on ditch proximity, on irrigation schedules, and on constructed modifications to the ditch systems—increase, so will the *chances* for seedling survival. Substrate availability and channel morphology also influence survival rates (Stromberg, 1993b). Near-term regeneration will likely occur along lower-elevation floodplain surfaces within abandoned channels. However, as Lewin (1996) notes, abandoned channels are liable to be "ephemeral," as sedimentation may fill them in "over a period of years" (208). The density of vegetation available within the channel to trap sediment exercises some control over the rate of deposition; again, timing and magnitude of future floods are the major controls.

Long-term survival of riparian trees is also dependent on all of the factors noted above. Well-established cottonwoods in one of the abandoned channels at cross-section 4, for example, may be at risk due to the combination of nearly total diversion of streamflow during an extended drought in 2000 and 2001 (Jacobson, personal communication, 2001) and channel incision at the cross-section. Conversely, during these same years, established vegetation along the active channel near the P1a–P2b sites, and at the diversion split downstream, demonstrated rates of growth that could be described as astounding (Figures 65 to 67). Full streamflow occupies the channel at both sites year-round. The emergence of near-channel vegetation at the diversion split also provided good evidence of its potential influence on channel pattern. In early 1999, rushes and other vegetation grew densely on a low island immediately upstream of the view shown in Figures 66 and 67, and in the shallow channel shoreward of it. Sediment trapped by the vegetation during moderate flow events before mid-2001 reconnected the island and floodplain, effectively "unbraiding" the river at this location.

**Figure 65. Looking downstream toward location of piezometers P1a and P1b, September 2000. Staff gage visible on left.**

**Figure 66. Looking downstream toward bar forming diversion split (center of photo), May 1999.**

**Figure 67. Same view as Figure 6 6, October 2001.**

It is important to note here again that the examination above of the controls exerted on patterns of vegetation establishment excludes what is likely a major factor in the Gila Valley: livestock grazing within the riparian zone. Extensive grazing on the river's floodplains continues in the downstream-most end of the study reach, particularly below cross-section 12. Field observation strongly suggests that this grazing may be the most significant variable affecting seedling survival in this reach. Emergent vegetation on the floodplains in this segment was almost nonexistent when the study began in 1999, and remained so in 2001.

***Channel pattern and vegetation flood resistance.*** The classic case for floodplain formation is based on lateral deposition on and subsequent erosion of point bars, creating a situation in which meanders "travel" downstream (Lewin, 1996). But Nanson (1986), studying an alternative formation mechanism called "vertical accretion," reviewed a number of studies documenting the process. In some confined, low-gradient river valleys,

> wandering channels…alternate from valley side to side but not in a truly meandering fashion. The channel hugs the bedrock valley wall before switching valley sides at river bends that also abut bedrock. This pattern precludes channel migration, but, despite this, alternating strips of disjunct floodplain form between the channel and the farthest side of the valley. Paired flood plains are uncommon (1469).

This does not quite describe the situation in the Gila Valley itself, where the river would encounter not bedrock, but high gravel terraces—whose bases are approximately outlined by the irrigation ditches—were it to meander fully across the width of the valley bottom. However, the river does function under conditions of bedrock control that extend for miles upstream of Spar Canyon; near the downstream end of the study reach, geologic controls also form the narrow constriction at the Duck Creek confluence. In vertically accreting floodplains, overbank deposition of fine-grained material occurs on available floodplain areas during moderate flood events, and is periodically "stripped" by catastrophic floods. On one of the rivers that Nanson studied, two to four meters (about 6 to 13 feet) of fine sediments were removed during a "series of major floods in close succession" between 1968 and 1978 (Nanson, 1986: 1470). Geomorphic controls imposed at both ends of the Gila Valley may *somewhat* confine its meander pattern within the valley. The river channel demonstrated a marked propensity to return to earlier meanders during the 1980s–1990s floods. Whether the main control on this pattern is vegetation, bedrock geomorphology, coarse alluvium deposits remaining at the base of tributary canyons, or something else altogether is worthy of additional study.

The river's reoccupation of previous meanders occurred under conditions in which most of the floodplain vegetation had been removed, and this may or may not have occurred had floodplain vegetation been intact. However, the evidence does suggest that the absence of floodplain vegetation and the extent of field area lost between 1978 and 1996 may be related. This thesis provides only a preliminary evaluation of the resistance of vegetation in the valley to flood scour and can provide no definitive conclusion, but other studies show that vegetation can be highly flow resistant (Baker, 1988). One study, cited by Johnson et al. (1995), found that streambanks with vegetation were 20,000 times as resistant to erosion as comparable unvegetated banks.

The preponderance of meander cuts along non- or sparsely vegetated areas noted previously provides one indication of the potential resistance of floodplain vegetation to flood scour, at least during the majority of flood events in the Gila Valley—perhaps those of recurrence intervals of up to 20 years or more. Another site which has proven extremely resistant to flood scour occurs just upstream of Spar Canyon. The area, depicted as a large green patch, is circled in Figures 39 through 41. Groundwater in this area has long been elevated by the proximity of the small reservoir for the Upper Gila ditch diversion (Figure 68), and all aerial photographs after 1950 show dense riparian growth there. Massive piles of woody flood debris are strewn throughout this area today. Vegetation just upstream, around the short levee constructed at the P5 location and within the constricted reach downstream of it, was almost completely cleared by 1980—either by the 1978 flood, bulldozer work, or both. Yet vegetation between the reservoir area and river channel remained intact during the 1978 flood—and all later floods. In fact, the area's resistance to floods is at least partly responsible for the river's lateral erosion toward the east, through part of the Spar Canyon alluvial fan and into the mouth of the canyon. Although coarse materials at the base of Spar Canyon maintained the river's meander to the west between 1917 and at least 1974, the high-magnitude 1978 flood marked the beginning of eastward lateral erosion through these deposits. Lateral movement proceeded in later floods and became responsible for much of the present-day downcutting in Spar Canyon. Figure 69 documents the resulting eight-foot cutbank at the base of the canyon.

**Figure 68. Upper Gila diversion berm in foreground, and reservoir. Berm is approximately 10 feet high. May 1999.**

**Figure 69. Looking upstream past eight-foot cutbank at mouth of Spar Canyon, on right of photo. January 1999.**

Many valley residents believe that riparian vegetation on river floodplains and in-channel flood debris are responsible for the meanders that have cut farm fields since 1965. For example, one resident told me that he holds Phelps Dodge partly responsible for damage caused by moderate floods, because the company discontinued channel clearing work around the Highway 211 bridge after it acquired property there. He believes this induced the reappearance of channel meanders at the bridge (interview, April 2000). A commonly held belief is that the river "cuts around" vegetation and that levees are necessary to constrain it (interviews, April 2000 and February 2001). One irrigator noted that "most" farmers in the valley share his support of levee reconstruction (interview, February 2001).

This is not universally true. At least one local farmer blames the levees themselves for field damage, noting that his grandfather had impressed upon him the importance of "never" digging in the riverbed, because "then the water would just go there." In addition to the problem of creating new channels for the river in flood, he opposes losing the river's deposits of new soil on the fields (interview, February 2001). One rancher who was interviewed supports active efforts to reestablish riparian vegetation on streambanks, believing it "the only way" to stabilize eroding banks (interview, February 2001). One measure of the breadth of views within the valley on the value of levees, vegetation, and major restoration efforts was provided by a controversial proposed stabilization project at the Highway 211 bridge. The project envisioned bulldozing a trench into the floodplain in order to "uncover the water table" (as one person interviewed, February 2001, put it) before planting willow and cottonwood along the river's right bank. Local residents debated the pros and cons of the project for months. (Permits required for the work were eventually denied by the federal agency that reviewed the proposal.)

**Implications of the study approach**

Results from this work led me to a number of conclusions about the likely history of erosional and depositional phases over the past 120 years, resistance of levees and vegetation to removal by flooding, and the complexity of factors contributing to the abundance and distribution of emergent riparian growth in the Gila Valley. These are summarized in the Conclusions section that follows. First, however, I return to some of the philosophical research issues that were mentioned in the Introduction. These issues arise because of the variety of data used for this study, including interpretive, anecdotal accounts and unquantified information collected during field observation. Synthesizing this variety of data into a single, coherent whole was an intrinsic component of the work. But the subjective nature of some of these data and their interpretation raises the specter of bias and its potential impact on the study conclusions. These issues are discussed below.

***Subjectivity.*** John Steinbeck (1984) quite clearly defined the trouble with subjectivity in *Travels with Charley*. Describing his and Joseph Alsop's simultaneous visits to Prague, he observes that Alsop

> …talked to informed people, officials, ambassadors; he read reports…while I in my slipshod manner roved about with actors, gypsies, vagabonds. Joe and I flew home to America in the same plane, and on the way he told me about Prague, and his Prague had no relation to the city I had seen and heard. It just wasn't the same place, and yet each of us was honest, neither one a liar, both pretty good observers by any standard, and we brought home two cities, two truths. [77]

The problem of subjectivity is central to an ongoing debate among the various social sciences, including geography—or at least the subset of the field labeled "cultural geography." Establishing the relative validity of quantitative ("testable") research versus work that relies on qualitative ("interpretive") methods is fundamental to the debate. Historically, the natural sciences laid claim to the former, on which the principles of hypothesis testing, replicability, and generalizability depend. The social sciences have meanwhile vacillated along a sort of continuum between positivist and interpretive approaches. Debate among proponents of each, or of some combination of them, is voluminous (for a small sampling, refer to Bernstein, 1983; Howe, 1988; Huberman, 1987; Jacob, 1988). Geographers, to varying degrees over the decades, have vociferously participated (Martin & James, 1993; especially 374–381; 431). Glesne and Peshkin (1992) summarize the general terms of the debate:

> Quantitative methods are, in general, supported by the positivist or scientific paradigm, which leads us to regard the world as made up of observable, measurable facts. Quantitative researchers seek explanations and predictions that will generalize to other persons and places. Careful sampling strategies and experimental designs are aspects of quantitative methods aimed at producing generalizable results. Meanwhile … qualitative researchers deal with multiple … "qualities" that are complex and indivisible into discrete variables…Hard-to-answer, context-bound questions emerge along with unexpected patterns and new understandings through the evolutionary nature of qualitative inquiry (5–6).

It is not surprising that a question preoccupying social scientists should also occur to anyone studying rivers. River systems are much like human societies in their diversity and in the complexity of variables and interactions of which each is composed. It is not too farfetched to liken any human culture to the floodplain and channel within which the modern river flows. Floodplain and channel both shape, and are shaped by, the river itself over time. Humans act upon each other and upon their local culture, society, and physical environment in much the same way as the river's internal, hydraulic forces act upon each other and on its channel and floodplains. Understanding—much less predicting—the behavior of complex human or riverine systems is hardly possible via individual study of each variable within them. As Putnam remarks of scientific reductionism: "If you want to know why a square peg doesn't fit into a round hole, you had better *not* describe the peg in terms of its constituent elementary particles" (cited in Rorty, 1982: 201).

***Reductionism and overgeneralization.*** Yet quantitative research provides such crucial cornerstones in our knowledge of how river systems function that it seems nearly inane to point it out. Without such work, interpretive studies like this one would be impossible. Classic work by Leopold, Wolman, and Miller (1964) and others (e.g., Leopold & Maddock, 1953; Schumm, 1960) are among the foundations for later research into factors influencing channel geometry. Flood-frequency studies like Waltermeyer's (1986) enable reasonable estimates of hydrographs for ungaged streams. Researchers like Hey (1979), Andrews (1983), and Baker and Costa (1987) contributed to the large literature on hydraulic transport of bed material and sediment. Stromberg's work (e.g., 1993a; Stromberg & Patten, 1990, 1991, 1996) is fundamental to current conceptualization of southwestern riparian seedling recruitment.

On the other hand, the problem of overgeneralizing from results obtained in the study of one river system to another has been and remains a pitfall for hydrologic research. This may be especially true in studies of semi-arid land rivers: classic bankfull theory, mostly derived from empirical studies of rivers in humid regions, suggests that a river will experience floods that just overtop its floodplain ("bankfull") on average once every 1.5 to 2 years. The theory also suggests that a relationship between drainage area and bankfull discharge exists for all "unimpacted" rivers in a given climatic and topographic region (Leopold, Wolman, & Miller, 1964). Furthermore, the general theory holds that a river's channel form is shaped and maintained by these moderate floods, the "channel-forming discharge" (Leopold, Wolman, & Miller, 1964: 81). Some researchers interpret bankfull theory to be valid for all unimpacted rivers. Rosgen (1996), for example, bases his stream classification system on proper identification of bankfull stage and claims that

> Natural stream channel stability is achieved by allowing the river to develop a *stable* dimension, pattern, and profile such that, over time, channel features are maintained and the stream system *neither aggrades nor degrades* (1-3). [emphasis mine]

The concept of a channel-forming discharge, occurring on average about once per 1.5 years, is often cited as a foundation for stream channel assessment and management (e.g., USDI Bureau of Land Management, 1998). Yet some researchers note a distinction between the geomorphic *work* accomplished by frequent, moderate flood events, and geomorphic *effectiveness*, a combined measure of total erosion and the time required for landforms to return to the condition prevailing between major flood events (Rountree, Heritage, & Rogers, 2000). A number have documented the pitfalls of over-generalizing from bankfull theory to semi-arid and arid land rivers, where the rare, major flood event may control channel form long after the event itself—even in the absence of significant anthropogenic impacts (e.g., Baker, 1977; Graf, 1983, 1988b; Heritage et al., 1999; Nanson, 1986). Furthermore, Leopold, Wolman, and Miller (1964) themselves describe a number of potential *limiting conditions* to the bankfull theory.

***Consilience, or just soft science?*** Limiting conditions establish the boundaries for the applicability of results from one study to another. In his evaluation of a qualitative hydrologic model for analyzing quantitative data, Osterkamp (1979) observes that researchers frequently work within limiting factors—not all of them testable—generate and test new theories based on results within those conditions, and then broadcast those ideas for further testing. This process is something that Wilson (1998) readily concedes is necessary along the path toward scientific "truth." For example, the steel lab flume may allow for repeatable results from hydraulic analyses. The river's cobble and sand bed almost surely will not. This fact does not suggest that basic hydraulic theory is flawed. It does remind us of "the turbulence of the real world" (Wilson, 1998: 202). This "turbulence" is created by the same complex, sometimes indivisible variables within any system that Glesne and Peshkin (1992) described previously.

Studies that combine statistically testable data with information gathered by observation and inference, like Everitt's classic (1968) work on cottonwood regeneration patterns, are actually not uncommon. In fact, close reading of even the most heavily equation-laden paper usually reveals at least a few qualitative assumptions intermingled with "hard" data. It appears, therefore, that some researchers resolve the quantitative/qualitative conundrum by adopting what Howe (1988) calls the "compatibility thesis," in which the two methods become "inseparable" (10). Howe clears the epistemological impasse by noting that

> One gets to the point of employing statistical tests [i.e., quantitative analysis] only by first making numerous judgments about what counts as a valid measure of the variables of interest, what variables threaten to confound comparisons, and what statistical tests are appropriate. Accordingly, the results of a given statistical analysis are only as credible as their background assumptions and arguments (12).

Howe's (1988) compatibility thesis closely resembles Wilson's (1998) idea for what he terms *consilience*: "the linking of facts and fact-based theory across disciplines" (8). The effort to answer questions stemming from interactions between the natural world and humanity places this work in what could be called "environmental geography," an area of study that may bring methods and theory from many disciplines to bear on the question at hand (Howe & Eisenhart, 1990). Work that is based on such a variety of methods may adopt a somewhat "metaphysical world view" (Wilson, 1998), but it avoids classification as so-called soft science when its validity is tested "by methods developed in the natural sciences" (9).

***Synthesis and testing of "mixed" data types.*** Wilson's advice makes sense, but how to test interpretive data, which—as in this study—are frequently comprised of information obtained through observation and inference? In this case, qualitative data were tested less against themselves than against each other and against the "hard" data collected during the project. The process of creating a viable framework for understanding the relation between past events and current condition of the riparian corridor evolved through an iterative process, in which numerous theories were mentally proposed and discarded when one or another piece of the available evidence seemed to contradict them. No data were excluded from this process. What is presented in this work is only the last "story" that I devised, the one that best fits all of the data available. Howe (1988) and others (e.g., Jacob, 1988) observe that interpretation of qualitative data must incorporate openness to alternative inferences. Where reasonable alternative explanations for events or outcomes suggested themselves in this work, they have been included.

***Value and costs of the study approach.*** The information needed to complete this work was surprisingly abundant. Locating the data and assembling them into a coherent form, however, was an arduous and time-intensive process. Quantifiable data like the hydrographic records, cross-section maps, and groundwater elevations were relatively easy to acquire. Reconstructing the entire "story" told by these data in order to understand their implications for current and future condition would not have been possible without the more subjective evidence provided by interviews, historic descriptions, and intensive field observation. These data were more difficult to find and were "testable" only in the sense described above.

The approach adopted for the study allowed the flexibility to construct, and to modify, a logical sequence of events and their probable effects on the riparian corridor during the past century or so. It avoided the "snapshot" pitfall of examining only present channel and riparian condition. Based on existing condition, one might well target remnant levee material as an obstacle to all riparian regeneration, or support selective levee reconstruction to protect the most vulnerable field areas from further lateral erosion. Field observation and the historic evidence suggest that efforts to "correct" either of these situations may have undesirable consequences, and no part of the quantifiable data collected for the study contradict this. On the other hand, these conclusions cannot be tested in the scientific sense, except by additional research that targets a more narrowly defined range of variables. These areas of possible study and a number of questions left unanswered by the thesis are addressed in the Conclusions that follow.

## CONCLUSIONS

The bifaceted theory on which this study was based proposed that 1) current condition of the Gila River results from a combination of anthropogenic modification and natural processes; and that 2) probable future condition will primarily depend on patterns of riparian regeneration. In order to differentiate between human- and flood-related impacts in the riparian corridor, one objective of the study was to describe, as completely as possible, the geomorphic, hydrographic, and anthropogenic environments within which the river has functioned during the past 100 years or so.

This study documented the chronology of flood events, major construction activities likely to have impacted the Gila River corridor, and changes to the stream channel and floodplains subsequent to flood or anthropogenic impacts between the 1880s and 1997. Change in amount of unvegetated floodplain surface was quantified for six periods between 1935 and 1996, allowing comparison of the relative change between unmodified and channelized, diverted reaches. Existing channel and floodplain morphology at ten locations were documented and tied to historic river channel locations. Impacts to the river's natural base flow from irrigation diversions were analyzed. Current relationships between groundwater and river surface elevations under the river's undiverted flow regime were identified and evaluated.

The results of the study suggest the following conclusions:

- The effects of channelization or other modifications to the stream channel and floodplains are unpredictable. Groundwater proximity, presence and age of floodplain vegetation, substrate composition, and the relative discharge carried by the main channel and tributaries during flood events are all important variables influencing conditions in the riparian corridor. Many of these variables are dependent on one another. Some are impossible to predict or model. As a consequence, attempting major channel modifications, whether to aid in vegetation restoration or to protect farm fields, may be more likely to have undesirable consequences than those hoped for.
- Flood energy, especially during floods after 1983, appears to have been expended vertically until coarse materials within the channel and floodplains were exposed, and

laterally, against vulnerable fine-grained soils in fields. Dense bands of multi-aged vegetation probably serve to absorb flood energy and appear more resistant to scouring effects than do levees constructed from floodplain material. It is worth noting that construction of stronger levees to stop lateral erosion would likely result in greater channel incision during floods and eventual loss of upstream diversion points for the gravity-fed irrigation ditches.

- Excavation of floodplain material for levee construction created depressions along the Gila River's floodplain and exacerbated channel incision during floods between 1972 and 1997. Coarse substrate buried beneath several feet of fine sediments was exposed during levee construction and repair efforts and floods; cobble and coarse gravel now form the surface along much of the streambank and on floodplains in the study reach. Incision of the main river channel retards reestablishment of bank-side vegetation that would serve to trap fine sediments during floods.
- Variability in substrate density and the complexity of the hydrologic system created by the network of abandoned and overflow channels across the floodplain, points of irrigation diversion and return, and seepage from fields and ditches results in uneven return of riparian vegetation. Most seedling establishment since 1984 has occurred along the banks of abandoned channels after floods overtopped those channels. Flood waters that overtopped the overflow channels deposited fine sediment along their banks and provided conditions of soil moisture that facilitated seedling survival. In 2001, most younger stands of riparian vegetation were found along overflow channels.
- Vegetation reestablishment does occur along the active channel in some reaches. Upstream of the first two irrigation diversion points, vegetation along river banks is nearly unbroken, especially since a moderate flood in August 1999 which deposited silt and sand on floodplains and recharged groundwater levels. Irrigation diversions significantly reduce natural base flow, and observations of comparative seedling survival upstream of the diversions and downstream of irrigation tailwater returned to the channel suggest that near-complete diversion of water from the river channel during the driest months reduces the probability of riparian reestablishment on river banks. Lack of vegetation may, in turn, exacerbate incision and lateral erosion within this reach.

- The combined natural and human-built hydrology created by the Gila River, its riparian corridor, and irrigation works within the valley form a dynamic and complex system. One mark of ecosystem health within a river corridor is its resiliency: its ability to return to a previous functioning condition after major perturbation (Society of Wetland Scientists, 2000). In the case of the Gila Valley, both channelization works and flood events from 1972 through 1997 were major perturbations to the system. In general, the resiliency of the Gila River system in the valley seems to have been dampened to varying degrees by anthropogenic impacts including levee construction and irrigation diversions. Return to pre-1972 conditions of riparian density is occurring rapidly in the least modified reach upstream of Spar Canyon, and patchily, but floodplain-wide, throughout the downstream reach—except where cattle grazing within the riparian zone may be the determinative factor precluding seedling survival.

**Additional research needs**

This study generated a host of unanswered questions. One of the more valuable aspects of the thesis may be to provide a data set useful for future research. The maps that were constructed to quantify unvegetated floodplain surfaces also depict patterns of riparian regeneration over time that should be examined for additional insight into the sets of conditions most likely to sustain vegetation reestablishment. In addition, the maps may prove useful in examining one of the most potentially significant factors influencing return of riparian vegetation to the valley's floodplains: the presence or absence of intensive cattle grazing within the riparian corridor. Varying rates of riparian seedling survival between cross-section sites that were observed during field work strongly supported the conclusion that grazing intensity and, perhaps its seasonality were major controls on riparian regeneration. Work to differentiate between grazing impacts and the effects of changing floodplain geomorphology on riparian reestablishment is needed.

Filling in some of the temporal gaps between the multidate aerial photographs used in this study—particularly the 1980 and 1996 coverages—would be especially valuable for understanding the relative roles and relationship of incision and lateral erosion within the river corridor. It was clear from this study that meander cuts tended to occur more frequently along the western floodplain of the river than on the east; topographic survey to establish the general relative elevations of floodplains east and west of the river would help to clarify whether levee construction or the valley's general topography is most likely responsible for this. Monitoring changes in channel and floodplain morphology and sediment size distributions at the cross-section survey sites could provide continued insight into the effects of levee remnants and varying flood magnitudes on riparian establishment and survival. Collection of piezometer and river surface elevation data downstream of the diversion points would enhance understanding of the effects of irrigation withdrawals on groundwater elevations.

Watershed-scale perturbations like grazing or logging were not examined for the thesis, but the periods of most significant change in the river corridor that were identified suggest particular time frames for further study. Additional knowledge of the climate and watershed conditions prevalent within these periods could clarify the individual and combined effects of watershed-scale factors on the riparian corridor. For example, the most intensive upland grazing within the watershed seems to have occurred during the decades immediately before and after 1900. Removal of grass cover from the watershed, in combination with the conditions of drought or moderate precipitation that prevailed during the 1930–1970 period, may largely account for the river's depositional tendency during these decades. Work to validate this possibility may extend the applicability of the present research to other river systems in the southwestern U.S. that experienced similar phases of deposition and erosion during the 20th century.

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**Gila Valley Interview with ________________________________________**

**Date_____________________ Phone _______ In person at ___________**

1. How long have you or your family lived in the Cliff/Gila Valley?

2. What sorts of work have supported you or your family during residence here? Have you held a position on one of the committees overseeing ditch operations in the valley?

3. What types of change have you observed in the population of the valley? What economic changes have you seen (e.g., in employment, production, or ownership)?

4. What is your impression of the presence of these organizations in the valley?:

   Phelps-Dodge

   The Nature Conservancy

   Army Corps of Engineers

5. Do you have opinions about the activities of other agencies or organizations in the valley or in the region?

6. What physical changes have you observed on the Gila River and its riparian area?

7. Have you noticed any changes to the Gila River's flow regime (i.e., timing of floods or levels of discharge) over time?

10. If you have noticed changes to the river, what do you think has caused them?

11. What changes do you think are likely to occur in the valley over the next 50 years?