Available online at www.sciencedirect.com

SCIENCE DIRECT®

Journal of Hydrology 320 (2006) 302–323

Journal of Hydrology

www.elsevier.com/locate/jhydrol

Ground-water surface-water interactions and long-term change in riverine riparian vegetation in the southwestern United States

Robert H. Webb*, Stanley A. Leake

U.S. Geological Survey, 520 N. Park Avenue, Tucson, AZ 85745, USA

Received 10 May 2005; revised 23 May 2005

Abstract

Riverine riparian vegetation has changed throughout the southwestern United States, prompting concern about losses of habitat and biodiversity. Woody riparian vegetation grows in a variety of geomorphic settings ranging from bedrock-lined channels to perennial streams crossing deep alluvium and is dependent on interaction between ground-water and surface-water resources. Historically, few reaches in Arizona, southern Utah, or eastern California below 1530 m elevation had closed gallery forests of cottonwood and willow; instead, many alluvial reaches that now support riparian gallery forests once had marshy grasslands and most bedrock canyons were essentially barren. Repeat photography using more than 3000 historical images of rivers indicates that riparian vegetation has increased over much of the region. These increases appear to be related to several factors, notably the reduction in beaver populations by trappers in the 19th century, downcutting of arroyos that drained alluvial aquifers between 1880 and 1910, the frequent recurrence of winter floods during discrete periods of the 20th century, an increased growing season, and stable ground-water levels. Reductions in riparian vegetation result from agricultural clearing, excessive ground-water use, complete flow diversion, and impoundment of reservoirs. Elimination of riparian vegetation occurs either where high ground-water use lowers the water table below the rooting depth of riparian species, where base flow is completely diverted, or both. We illustrate regional changes using case histories of the San Pedro and Santa Cruz Rivers, which are adjacent watersheds in southern Arizona with long histories of water development and different trajectories of change in riparian vegetation.

Published by Elsevier B.V.

Keywords: Floods; Riparian vegetation; Surface water; Ground water; Geomorphology; Channel change

1. Introduction

Riparian ecosystems are highly valued resources in the southwestern United States owing to their high use by neotropical migratory animals, their high productivity and biodiversity, and their function in stabilizing riverine environments (Ohmart and Anderson, 1982). Riparian vegetation may occur in settings ranging from isolated springs, to swampy areas with poor drainage (locally known as ciénegas; Hendrickson and Minckley, 1985), to drainages with shallow ground water but no year-round flow, and finally to perennial rivers

---

* Corresponding author. Tel.: +1 520 670 6671x238; fax: +1 520 670 5592.

E-mail address: rhwebb@usgs.gov (R.H. Webb).

0022-1694/$ - see front matter Published by Elsevier B.V.
doi:10.1016/j.jhydrol.2005.07.022

(Cowardin et al., 1979; Brown, 1985). These habitats accommodate a wide variety of organisms, ranging from annual plants to algae and insects to native and non-native fish to migratory birds and resident animals. Native fish populations, in particular, are severely threatened by the combination of flow regulation and non-native predators (Minckley and Deacon, 1991). Similarly, changes in aquatic food bases, particularly downstream of dams, are dramatic and reflect complex changes in flow, sediment concentrations, and temperature (Blinn and Cole, 1991; Shannon and Benenati, 2002). In contrast, long-term change in woody vegetation, the most visible part of riverine environment, is perhaps the least understood part of riparian ecosystems.

Riparian ecosystems serve as the primary link between upland terrestrial and aquatic ecosystems (Gregory et al., 1991) and are, in many respects, symbolic of larger-scale landscape change because of their responsiveness to fluvial disturbances. They also are the ultimate expression of ground-water and surface-water interactions. Although many have looked at riparian vegetation primarily because of the value of its components, notably bird populations (Carothers et al., 1974), riparian ecosystems can be viewed as a scale phenomenon from minute details to largest scale (Gregory et al., 1991). Essentially all riparian ecosystems in the Southwest are considered to be at risk for decline, and the perception of historical region-wide loss prevails (Dobyns, 1981; Tellman et al., 1997). In addition, the large influx of non-native species, most notably tamarisk (*Tamarix ramosissima*), has raised concerns about the long-term ecological health of these ecosystems.

Here, we briefly review riparian resources and evaluate historical changes in the southwestern United States, addressing the overall question of the reach-scale changes in riparian ecosystems and their cause. We use the subset of rivers in southern Utah, eastern California, and Arizona (Fig. 1) below 1524 m elevation to demonstrate regional changes. We use repeat photography to evaluate change in woody species throughout the region, which provides a record from the late 19th century to the present. Finally, we use the adjacent San Pedro and Santa Cruz Rivers as case histories to illustrate the extent and cause for long-term change in riparian vegetation. In particular, the interactions of surface water and ground water are discussed in terms of their effects on this valued biological resource.

2. Background

2.1. Climatic setting

Riparian vegetation in the Southwest is dependent upon the climatic regime. This region is either arid or semiarid with the three hydroclimatic seasons of winter (November–March), summer (July–September), and fall (September–October), when most precipitation and runoff occurs. Winter storms are either regional-scale frontal systems or cutoff low-pressure systems, and fall storms generally are related to dissipating tropical cyclones in the Pacific Ocean; airmass thunderstorms advected in the North American monsoon generate summer rainfall. Winter cold temperatures increase both in elevation and northward, and this affects the types of species that are present. This climatic regime affects germination and establishment of riparian vegetation, but growth and potential lifespan is a function of the stability of surface–water and ground–water systems.

2.2. Types of woody riparian vegetation

In this paper, we focus on change in woody riparian vegetation and do not evaluate changes in herbaceous species, because change in herbaceous species is difficult to evaluate in repeat photography. Two classes of the woody plants inhabit wetlands. Obligate riparian species require a year-round dependable water supply, while facultative riparian species can live in both riparian settings and the more xeric uplands. In the Southwest, the cottonwood tree (*Populus fremontii*) is the iconic obligate riparian species, while the mesquites (*Prosopis velutina*, *P. pubescens*, or *P. glandulosa*) are facultative riparian species. Phreatophytes use ground water; therefore, both obligate and facultative riparian species can be phreatophytes; for physiological reasons, the line between obligate and facultative can be blurred. Other native, obligate trees include black willow (*Salix gooddingii*),

Fig. 1. Map of the southwestern United States showing river reaches used to analyze regional change in riparian vegetation.

Arizona ash (*Fraxinus velutina*), sycamore (*Platanus wrightii*), and netleaf hackberry (*Celtis reticulata*). Several shrubs contribute significant coverage in riparian areas, including arrowweed (*Tessaria sericea*), seep willow (*Baccharis salicifolia*), and coyote willow (*Salix exigua*).

‘Tamarisk,’ also known as saltcedar, refers to a complex suite of species native to a large area extending from North Africa through Eurasia to China (Gaskin and Schaal, 2002). Tamarisk is considered a severe threat to riparian ecosystems. Deltas of small or large reservoirs provide large areas for colonization of tamarisk (Harris, 1966); consequently, the spread to free-flowing reaches frequently begins from colonizers in deltas. The spread of tamarisk was rapid: in 1920, it covered more than 4000 ha in the western United States; by 1961, tamarisk covered 364,000 ha and was projected to cover 526,000 ha by 1970 (Christensen, 1962; Robinson, 1965). The current spatial extent of tamarisk is unknown but is probably only slightly higher than the 1970 area.

2.3. Extent of riparian ecosystems in the southwest

Riparian ecosystems are an extremely small component of the landscape. In California, riparian areas cover 138,000 ha or less than 0.5% of the state's area (Sands and Howe, 1977). Similarly, in the arid Southwest, riparian vegetation constitutes 0.5% of the landscape or less (Strong and Bock, 1990). Because they cover such a small area and have high biological value, the goal of protection of riparian ecosystems has a higher management priority than nearly any other habitat type in the region that does not contain endangered species.

2.4. Ground-water and surface-water interactions and riparian vegetation

In intermediate-sized drainages, and particularly those with relatively low-elevation headwaters, channels typically have an alternating pattern of perennial and ephemeral reaches. Moving downstream, effluent reaches increase in flow owing to ground-water additions, transitioning to influent reaches where flow infiltrates into the aquifer. Influent and effluent sections are associated with geologic structures, including faults and shallowly buried bedrock. The thriving riparian ecosystems of the San Pedro River (Fig. 1) depend on the influent–effluent nature of this stream. Other rivers, such as the Santa Cruz River, had this hydrologic characteristic eliminated by ground-water overdraft, but the influent–effluent setting that creates alternating perennial–ephemeral reaches has been artificially restored owing to irrigation returns and waste-water effluent discharge.

Riparian ecosystems occur over a variety of geomorphic configurations in the Southwest. These settings determine how ground water and surface water interact and, largely, what species of woody vegetation can grow in a given reach. Bedrock canyons comprise a complex suite of geomorphic configurations, ranging from a thin veneer of alluvium over bedrock to a relatively thick alluvial fill that has both coarse-grained and fine-grained terraces. Considerable variation in canyon width and bedrock types create mappable geomorphic settings that provide a large range in potential for riparian vegetation. Alluvial channels flow over deep alluvial fills with little or no bedrock constraints on lateral channel migration. This general class of channels has more variation in potential riparian habitat than bedrock canyons owing to the complex interactions among surface water, ground water, geologic framework, and subsurface geology.

2.5. Controls on the stability of riparian vegetation

2.5.1. Livestock grazing

Grazing by domestic animals has direct and indirect effects on riparian ecosystems (Ohmart, 1996). Livestock were introduced to the Southwest over a broad time-period, beginning around 1700 in southern Arizona and as late as the 1880 s in parts of southern Utah. Livestock heavily use riparian areas because of their high productivity—particularly of herbaceous species—and the readily available water and shade. Effects that are considered negative include consumption and trampling of native-plant seedlings, soil compaction, destabilization of channel banks, increase in streamflow sediment concentrations, and displacement of wildlife (Lusby et al., 1971; Ohmart, 1996). Unless riparian areas are fenced, livestock will use riparian areas, including those with tamarisk (Gary, 1960), disproportionately to other parts of the landscape (Platts and Nelson, 1985; Ohmart, 1996).

2.5.2. Floods

Floods, whether natural or the result of dam operations, have a major role in shaping the species composition and productivity of riverine riparian vegetation (Junk et al., 1989; Ohmart, 1996). In alluvial reaches, major floods cause bank scour and remove at least some of the riparian vegetation (Stromberg et al., 1993). Plants may be uprooted individually in response to detrital loading on their upstream sides, or whole terraces may be removed during lateral avulsions, channel widening, or meander propagation. In particular, mesquite bosques developed on terraces may be removed during flood-induced channel meandering (Minckley and Clark, 1984). On the other hand, floods create openings in typically dense riparian assemblages, transport seeds and vegetative propagules, saturate flood plains to encourage seedling growth, and deposit nutrient-rich sediments that promote germination and recruitment, particularly of cottonwood (Stromberg et al., 1993). Long-term directional changes may occur as well: on the Gila River in central Arizona, a 1905 flood removed much of the original cottonwood and seepwillow stands (Turner, 1974); they recolonized by the mid-1930 s, but between the 1930 s and 1960 s tamarisk thickets had replaced the native species.

2.5.3. Arroyo cutting

Beginning about the mid-1880 s, and extending through the 1920 s to the 1940 s, the frequency and severity of floods increased owing to unusually frequent storms of regional extent (Turner et al., 2003). These floods, combined with the effects of livestock grazing, induced historical arroyo downcutting (Cooke and Reeves, 1976; Graf, 1983; Turner et al., 2003). The result was incision of narrow channels through flood plain alluvium during an extremely large flood, followed by channel widening during a series of events (Fig. 2). Downcutting quickly dropped the alluvial water table, with die back or death occurring in woody riparian vegetation on high terraces. Channel widening would have removed some of the plants that survived the water-level decline. After channel widening, a period of mostly denuded riverine conditions, development of low terraces above the saturated zone would have encouraged establishment of woody riparian species.

2.5.4. Beaver depredations

One of the most intriguing hypotheses concerning the cause of arroyo cutting is the 19th century decimation of beaver populations by trappers (Parker et al., 1985), which might have allowed floods to more readily cut through the channel bottoms (Dobyns, 1981). Beaver dams served as local base levels, mitigating the tendency for downcutting during floods. Beavers culled woody riparian vegetation, particularly cottonwood and willow, and thereby could have served to limit the density of native species. These animals once were numerous and widespread throughout the Southwest and doubtless had profound effects on prehistoric distributions of riparian vegetation (Ohmart, 1996).

2.5.5. Fire

Before fire suppression began in the early 20th century, wildfires—either set deliberately by aboriginals or by lightning strikes—were common in the upper elevations of the Southwest (Turner et al., 2003). Fires could be generated in riparian ecosystems or could sweep out of adjacent grasslands or shrublands into the riparian zone. Although little evidence exists to suggest that prehistoric stands of woody riparian vegetation were suppressed by frequent fires, the possibility remains. With widespread development adjacent to riparian ecosystems of the Southwest, human-caused fires are now common in riparian zones throughout the Southwest; along the lower Colorado River, fires in one reach burned more than one third of the area occupied by riparian vegetation (Busch, 1995). Although non-native tamarisk responds positively to fire, native species also can resprout.

2.5.6. Growing season and favorable climatic conditions

Twentieth century climate in the Southwest has fluctuated between wet periods and drought on a decadal scale (Webb and Betancourt, 1992; Hereford and Webb, 1992; Hereford et al., 2002, 2004; Turner et al., 2003). The period of 1880–1891 was generally wet, with numerous regional-scale storms that caused channel downcutting. The most severe drought, and the one that affected the largest amount of the region, began in the summer of 1891 and ended in 1904. The wettest period in the region's history began in 1909 and extended through about 1920. Annual temperatures generally were low from 1900–1930, creating a high precipitation—low temperature combination (Turner et al., 2003).

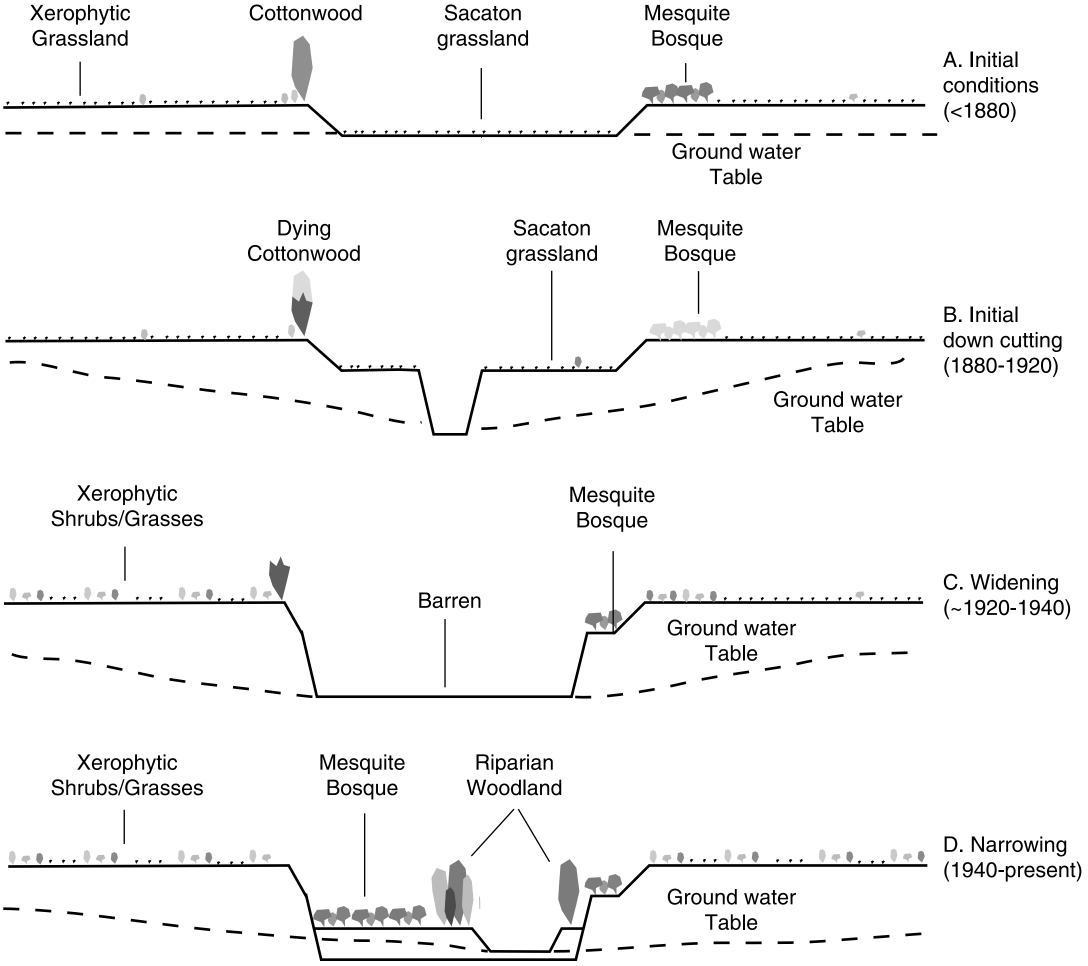

Fig. 2. Diagram showing a generalized response of riparian vegetation to the process of arroyo downcutting and widening of alluvial channels from about 1880 to the present.

Climate was regionally variable between 1920 and the early 1940 s; in southern Arizona, conditions were relatively dry with few significant winter storms, but conditions were generally wet in the northern part of the region. Between the mid-1940 s and the early 1960 s, drought conditions prevailed with strong regional variation in intensity, creating a warm-dry period. Beginning in the early 1960 s, the climate of the region became significantly wetter and warmer. Numerous strong storms in fall and winter occurred between 1970 and 1995, leading to significant floods in central and southern Arizona and above-average precipitation in the Mojave Desert and the Colorado Plateau. Temperatures steadily rose during the 1980 s and 1990 s, creating ideal climatic conditions for germination and establishment of riparian vegetation. Drought generally prevailed at the end of the 20th century and the beginning of the 21st century.

2.5.7. Declines in ground-water levels

In the arid and semiarid southwestern United States, ground water has been an important source of water for agriculture, industry, and public supply. Ground-water use in Arizona escalated rapidly in the middle part of the 20th century (Fig. 3), slowing with the importation of Colorado River water in the mid-1980 s. Many aquifer systems in the area are characterized by a large volume of water in storage

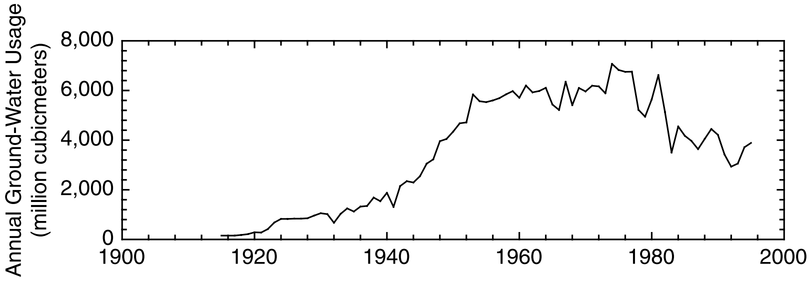

Fig. 3. Total ground-water withdrawals in Arizona, 1915–1995. (Data for 1915–1990 from Anning and Duet, (1994); data for 1991–1995 from M.T. Anderson, unpublished data, 2003).

but a relatively small rate of natural recharge and discharge. The recharge to the aquifers commonly comes from precipitation at higher elevations in mountains adjacent to the aquifers. The effects of ground-water withdrawals can be local or on a reach scale; a deep cone of depression that rapidly develops around a pumping well on a floodplain could kill nearby trees in a matter of days. The more typical situation is many wells in an aquifer that are pumped for an extended period.

Riparian trees are profoundly sensitive to changes in ground-water levels. Cottonwood provides one example: if lowering occurs slowly enough, in response to drought or to steady pumping, roots may be able to elongate quickly enough to keep pace and allow the tree to survive (Scott et al., 1999). Established plants may be able to survive rapid drawdown for short periods, but mortality in saplings may be as high as 100% (Shafroth et al., 2000). Rapid drawdown may be as little as 1 m in a matter of weeks (Scott et al., 1999), and the rate of change, not the absolute depth to water, is the most important factor in plant survival (Shafroth et al., 2000). While mesquite can withstand relatively large fluctuations in ground-water level, trees in bosques are known to become stressed when ground-water levels decline to 13.7–15.2 m below land surface (Stromberg et al., 1992). Mesquite along the middle Gila River could not survive a water-table decline of about 30 m in the 1940 s and 1950 s (Judd et al., 1971).

As illustrated in Fig. 4, the effects of ground-water pumping of an alluvial aquifer on a riparian system can be categorized into three stages. Stage I begins with the cone of depression that develops at the onset of pumping, locally affecting water stored around the well and not significantly impacting the reach-scale stream/aquifer system. Stage II begins after a substantial withdrawal draws down the aquifer sufficiently to create a water-level gradient away from the stream and floodplain; water availability to riparian plants may be unaffected but streamflow may be reduced. Finally, after a substantial period of pumping in excess of rate of ground-water flow from up-gradient areas, surface-water and ground-water systems may become disconnected if streamflow cannot provide enough recharge to maintain water levels in the alluvial aquifer. In Stage III, riparian vegetation can be strongly affected.

The traditional wisdom was that ground water could be withdrawn at rates less than or equal to the amount of recharge to an aquifer without any serious consequences. Theis (1940), however, pointed out that ground-water withdrawals can potentially affect the amount of water entering as well as leaving aquifers. Bredehoeft et al. (1982) indicated that the amount of ground-water withdrawal that can be sustained is dependent on the amount of discharge from the aquifer that can be captured. Removal of water by sustained pumping less than the basin recharge will eventually be balanced by an increased inflow and (or) decreased outflow. In the alluvial aquifers of the Southwest, almost all of the water removed will be accommodated by decreased outflow to springs, streams, riparian areas, or playas. If ground-water pumpage were to stop after a period of time, outflow still would be reduced as cones of depression are refilled. The overall reduction in the cumulative volume of outflow (assuming no increased inflow) would equal the total quantity pumped over the period of active pumping.

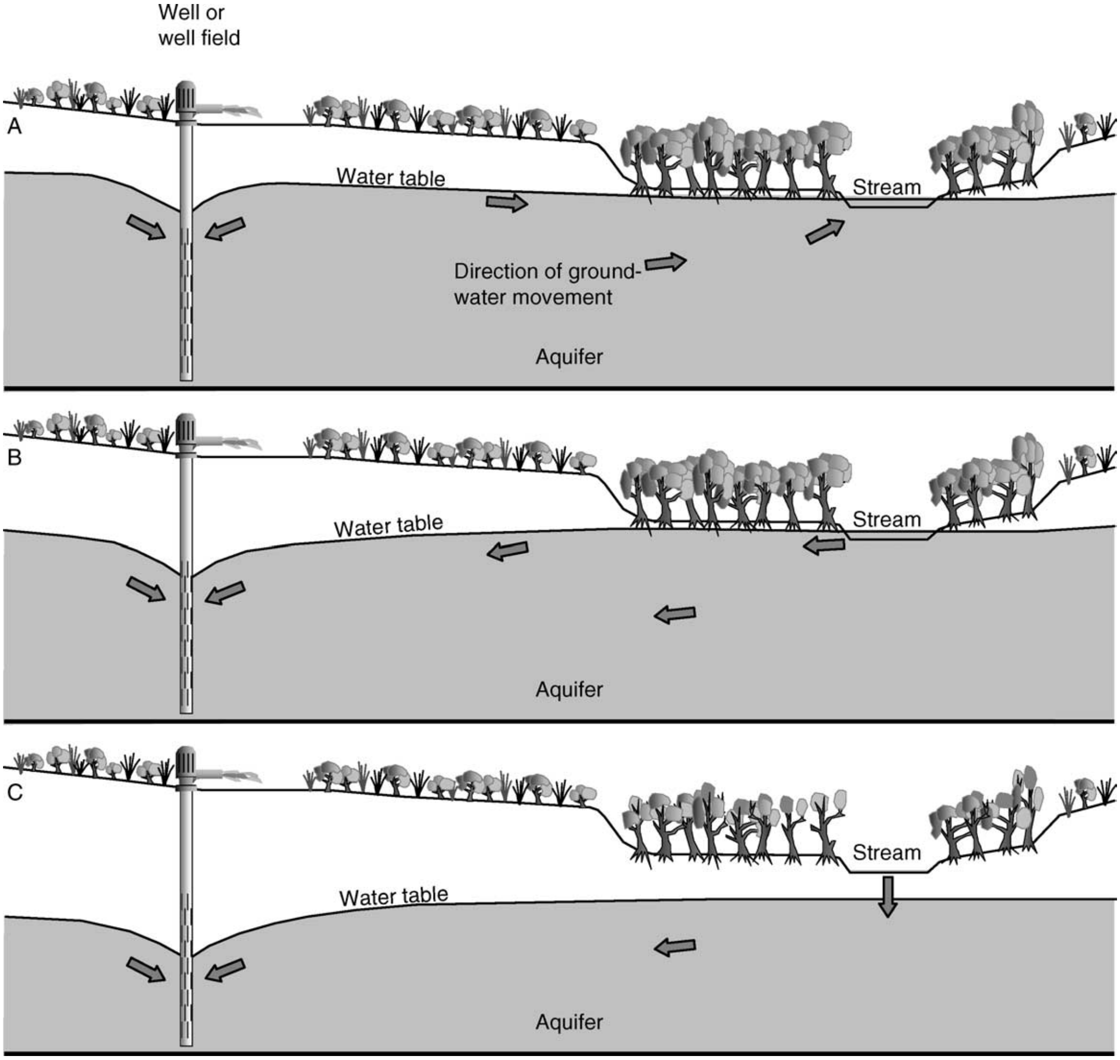

Fig. 4. Expected stages of capture of ground-water outflow to a riparian area and stream. (A) Stage I—near the onset of pumping, water pumped comes from storage around the well and the stream/aquifer system functions as it did prior to pumping. Ground water from upgradient areas supplies riparian vegetation in the floodplain as well as base flow to the gaining stream. Periodic stream runoff events also may supply water to the near-stream aquifer. (B) Stage II—drawdown from well has caused movement of water away from the stream and floodplain after a substantial period of pumping. Availability of water for riparian phreatophytes may not be diminished because of increased inflow from the stream, but the stream has become losing or possibly intermittent. (C) Stage III—after a substantial period of pumping in excess of rate of ground-water flow from upgradient areas, the stream and aquifer may be disconnected if streamflow cannot provide enough recharge to maintain the water table. The stream has become ephemeral.

2.5.8. Regulation of surface water

The response of riparian vegetation to flow regulation depends upon the wide spectrum of possible water use and amount of flood control, which ranges from complete diversion of surface flow for irrigation to dam releases with flood control. After construction of dams, a period of geomorphic adjustment to the changed flow and sediment-transport regimes is expected, followed by an adjustment in riparian vegetation (Johnson, 1998). Flow diversions, whether partial or total, strongly affect riverine riparian ecosystems by reducing recharge to shallow aquifer systems. Water use for agriculture can also lower river flows, particularly during summer months, and thereby stress riparian plants in the season when they need water most.

Flood control, a common justification for dams, reduces peak discharges and the amount of water available to riparian systems on floodplains as well as potentially changing the seasonality of flooding. Species dependent on flooding for germination and establishment can only rarely reproduce, and low interannual variability with no seasonal peak may retard establishment of some species owing to periodic inundation of seedlings (Fenner et al., 1985). Long-term flood control may cause conversion of formerly mesic floodplains to xeric shrublands (Stromberg et al., 1996; Merritt and Cooper, 2000). Conversely, reduced flooding, coupled with lowered variability in daily discharge, greatly benefits established riparian species on the streamward side of floodplains because formerly scoured channel margins become stable habitat for new plant establishment.

3. Methods of repeat photography

Repeat photography has been used to document landscape change, including change in riparian vegetation, in the southwestern United States (Turner and Karpiscak, 1980; Webb, 1996; Turner et al., 2003; Webb et al., 2004). This technique complements other techniques, such as analysis of aerial photography and remote sensing, and provides the unique benefits of identification of species-specific change and a longer record. Aerial photography, which has been used to study landscape changes since it first became available in the late 1920 s or 1930 s, provides reach-scale assessments of change (Stromberg et al., 2004) but does not cover earlier times when many of the changes began, and its resolution allows only limited assessment of changes in species composition. Multispectral satellite imagery provides an excellent technique for monitoring and evaluating ecosystem changes after 1974, and although satellite imagery provides large spatial coverage and collects visible and non-visible spectral data (Kepner et al., 2000), it provides limited information concerning species-composition changes.

Extensive photography at gaging stations documents long-term changes in the riverine environments of Arizona. The Desert Laboratory Repeat Photography Collection, the largest collection of repeat photography in the world, contains imagery representing a total of 5954 camera stations in the southwestern United States and northern Mexico and 7964 matches. Of the total number of reoccupied camera stations, 3222 show riparian vegetation in the Southwest (Table 1). The geographic region with the most repeat photography is Grand Canyon, with 1362 camera stations showing riparian vegetation (Webb, 1996). Although the earliest matched photograph is an 1863 view of the Colorado River at Fort Mojave, Arizona, the number of original views that show riparian vegetation is highest in the 1890 s, when 18% of the original photographs were taken (Fig. 5). A second peak period of historical photography, in the 1920 s, resulted from the establishment and photography of gaging stations within Arizona as well as large-scale expeditions conducted by the US Geological Survey.

Historical photographs were first matched in the period of 1959–1962, mostly in southern Arizona (Turner et al., 2003). Replication of historical photographs of the Colorado River—particularly in Grand Canyon—began in 1968 and continued from 1974–1983 and 1989–1995. Many additional images, notably views at U.S. Geological Survey gaging stations, were replicated between 1999 and 2003 (Fig. 5). As a result, time series of change can be evaluated in a variety of hydrologic settings. Change in woody vegetation, both in terms of all species present and selected riparian species, was interpreted from the imagery, but only the general trends in all woody riparian vegetation are presented here.

4. Results

4.1. Regional changes in riparian vegetation

The repeat photography (Table 1) shows that virtually all riparian areas in the Southwest have changed owing to natural and human causes (Fig. 6). All free-flowing river reaches documented in southern Utah and northern Arizona have had increases in riparian vegetation in the 20th century, most notably

Table 1
Historical photographs that were matched or analyzed for change in riparian vegetation

River	Region	Number of matched photographs	Earliest photograph date
Agua Fria River	Central Arizona	9	1940
Aravaipa Creek	Southern Arizona	24	1867
Bill Williams River	Western Arizona	58	1923
Canada del Oro	Southern Arizona	10	1912
Colorado River	Professor Valley	38	1905
Colorado River	Meander Canyon	9	1914
Colorado River	Cataract Canyon	217	1871
Colorado River	Glen Canyon	24	1871
Colorado River	Grand Canyon and tributaries	1362	1871
Colorado River	Black Canyon	29	1871
Colorado River	Lower River	86	1863
Chinle Wash	Northern Arizona	7	1935
Green River	Desolation Canyon	49	1871
Green River	Gray Canyon	19	1871
Green River	Labyrinth Canyon	23	1871
Green River	Stillwater Canyon	29	1871
Escalante River	Southern Utah	17	1872
Gila River	Central Arizona	171	1910
Hassayampa River	Central Arizona	26	1933
Havasu Creek	Grand Canyon	95	1885
Kanab Creek system	Utah, Arizona	73	1872
Little Colorado River	Northern Arizona	1	1923
Moenkopi Wash	Northern Arizona	11	1932
Mojave River	California	32	1863
Paria River	Northern Arizona	21	1872
Pima Canyon	Southern Arizona	14	1910
Rillito Creek system	Southern Arizona	24	1939
Sabino Creek	Southern Arizona	34	1890
Salt River and tributaries	Central Arizona	34	1917
San Carlos River	Central Arizona	15	1935
San Francisco River	Southern Arizona	15	1891
San Juan River	Southern Utah	132	1875
San Pedro River and tributaries	Southern Arizona	93	1883
San Simon Creek	Southern Arizona	15	1931
Santa Cruz River	Southern Arizona	150	1880
Sonoita Creek	Southern Arizona	23	1895
Verde River and tributaries	Central Arizona	59	1917
Virgin River	Southern Utah	109	1873
Whitewater Draw	Southern Arizona	17	1930
Miscellaneous reaches	Throughout region	70	1891

the San Juan River (Webb et al., 2001a), where 19th century floods and an extremely large flood in October 1911 created a barren flood plain as much as a half kilometer wide that subsequently became vegetated with both native and non-native species. Other large increases occurred along the alluvial reaches of Kanab Creek (Webb et al., 1991), Havasu Creek (Melis et al., 1996), and the Escalante River (Webb and Baker, 1987). Much of the regional increase is attributable to tamarisk, particularly along the Green River (Graf, 1978), although native species in general have increased. One exception is cottonwoods along the lower Green and Colorado Rivers, where an unexplained decrease has occurred despite large increases on smaller rivers in the region (Webb et al., 2004).

Beginning at the delta of Lake Powell in Cataract Canyon, the Colorado River represents a mosaic of changing riparian vegetation to the United States—Mexican border (Fig. 6). Bedrock-controlled reaches where stage-discharge relations show a wide range in pre-dam inundation had little riparian vegetation. Locally, terraces in Glen Canyon, wide reaches of Grand Canyon, in the wider reaches now covered by Lake Mead, in Cottonwood Canyon, and near present-day Lake Havasu City supported riparian stands that ranged from mesquite thickets to open cottonwood

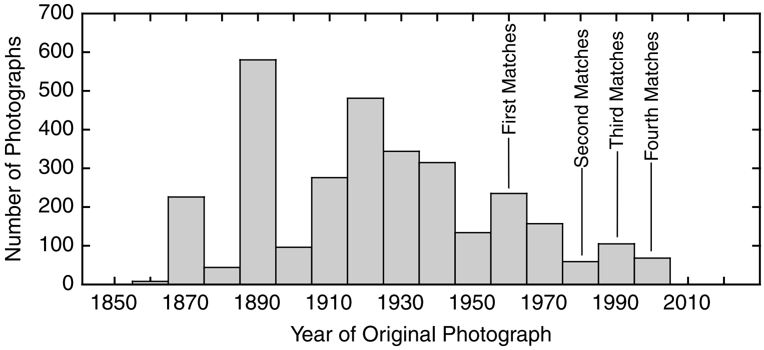

Fig. 5. Histogram showing the temporal distribution of the original dates of historical photography used to document long-term change in riparian vegetation in the Southwest.

galleries. Losses of the original riverine habitat occurred under the now-present reservoirs of Lakes Mead, Powell, Mojave, and Havasu. Arguably, these losses in riparian habitat may be offset by vegetation established along shorelines or in deltas, but most of this vegetation typically is dense tamarisk, is unstable owing to fluctuating reservoir levels, and is not comparable with the pre-dam vegetation, either in location, function, or species composition. In the regulated reaches through Grand Canyon, between Lakes Mojave and Havasu, and for most of the distance between Lake Havasu and Yuma, Arizona, riparian vegetation has generally increased, although much of the increase is non-native tamarisk. Some protected riparian areas, such as the Topock Marsh, now contain cottonwood trees and other native and non-native species where mudflats once existed.

The upper Gila River in Arizona, as well as its major tributaries, has had large increases in native and non-native riparian vegetation despite extremely large floods between 1983 and 1995 (Minckley and Clark, 1984). Although some reaches support mostly tamarisk—notably the reach immediately upstream from San Carlos Reservoir (Turner, 1974)—other reaches upstream from Safford, Arizona, and downstream from Coolidge Dam now have cottonwood and mesquite stands. Tributaries such as San Simon Creek, the San Carlos River, and the lower San Pedro River (and tributaries) have increased riparian vegetation, in some cases all of which are native species. Despite repeated large floods between 1978 and 1995, the Salt River upstream from Roosevelt Dam (Fig. 1) also has increased riparian vegetation, mostly mesquite, willows, and tamarisk. With the exception of reaches under reservoirs, riparian vegetation has increased dramatically along the Verde River, with the increases on the upstream reaches mostly occurring in a large suite of native species.

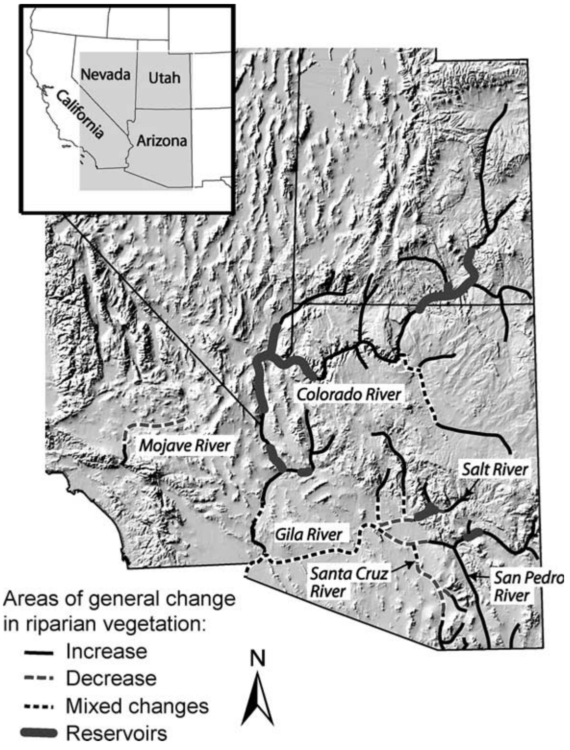

Fig. 6. Digital-elevation topographic map of the southwestern United States showing principal watercourses and reach-averaged change in riparian vegetation.

Just upstream of Florence, Arizona, the entire surface flow of the Gila River, except during periods of flooding, is diverted at the Ashhurst—Hayden Dam for irrigation. With those diversions and extensive ground-water pumping, a once thriving riparian community between Maricopa, Arizona, and the confluence with the Salt River has been lost (Rea, 1983). Photography shows that the Salt River through Phoenix supported sparse riparian vegetation, and channelization and surface-water diversions have eliminated most riparian vegetation in this reach despite continued high water levels in the alluvial aquifer. Owing to waste-water discharge and irrigation returns, the Gila River has riparian vegetation in the reach between the Salt-Gila confluence and Gila Bend, Arizona; tamarisk dominates the vegetation, although locally dense stands of cottonwood and mesquite are also present. Tributaries of the Salt and Gila entering from north of Phoenix, such as the Hassayampa, Agua Fria, and New Rivers, generally have increases in both native and non-native vegetation. Finally, downstream from Gila Bend, the Gila River sustains little beyond tamarisk owing to the combination of ground-water pumping, channelization, and reduction in surface-water flow.

The Mojave River offers a study in change of riparian vegetation owing to the combination of flow regulation and ground-water pumping (Lines, 1999; Webb et al., 2001b). A thriving riparian ecosystem consisting mostly of cottonwood and black willow has developed upstream and downstream from Victorville; this reach once supported scattered stands of black willows but now has large areas of closed gallery forests of Frémont cottonwood. Downstream from the Narrows north of Victorville, increased ground-water pumping associated with agricultural development gradually reduces density of riparian trees, which had increased historically before ground-water development. From just upstream of Barstow to Camp Cady, California, a riparian ecosystem that once consisted of sections with mesquite and black willow has been largely eliminated owing to excessive ground-water pumping, and scattered tamarisk in xerophytic settings now is common in this reach. Subsurface geologic structure forces ground water to the surface near Camp Cady, and a closed gallery forest of cottonwood, flanked with mesquite, has developed where riparian trees were once sparse (Webb et al., 2001b). Finally, perennial flow in Afton Canyon supports scattered cottonwood among dense tamarisk thickets where scattered black willow once grew. Tamarisk eradication is a management priority in this reach.

The Owens River in eastern California has no repeat photography at present but is included because of its documented history of water development that affected riparian vegetation. Diversions currently affect 88% of the channel distance in this watershed, making it one of the most regulated river systems in the United States (Hill et al., 2002). Channel widths of some regulated streams have decreased as riparian vegetation has increased. Riparian vegetation along the river downstream from the main diversion point has changed from native species to a non-native assemblage dominated by tamarisk and Russian olive (Brothers, 1981). Owens Lake, the terminus of the Owens River, dried in the early 1900 s following a nearly full diversion of streamflow. Some recovery of saline, lacustrine wetlands flanking the playa occurred between 1977 and 1992, following above-average runoff that was not diverted (Schultz, 2001).

4.2. Case study: The San Pedro River

The San Pedro River enters the United States from its headwaters in Sonora, Mexico (Fig. 7). Beginning upstream from Palominas, Arizona, the river is effluent and supports a closed gallery forest of cottonwood flanked with mesquite on the distal margins of flood plains. Ground-water levels in the alluvial aquifer are high and fluctuate, probably in response to recharge from floods (Fig. 8A). At Charleston, annual flow is 1.59 m^3/s (Table 2) and the annual flood series consists of an extremely large flood in 1926 (2780 m^3/s) followed by a series of relatively small floods extending to 2001; at Palominas (Fig. 8B), annual flow is 0.86 m^3/s, and the flood record is similar although streamflow gaging began after the 1926 event. Ground-water development near the river has not significantly reduced levels in the alluvial aquifer (Fig. 8A), although ground-water development in and adjacent to Sierra Vista, Arizona (Fig. 7), is thought to pose a severe future threat to the riparian ecosystem (Pool and Coes, 1999). A total of 59 historical

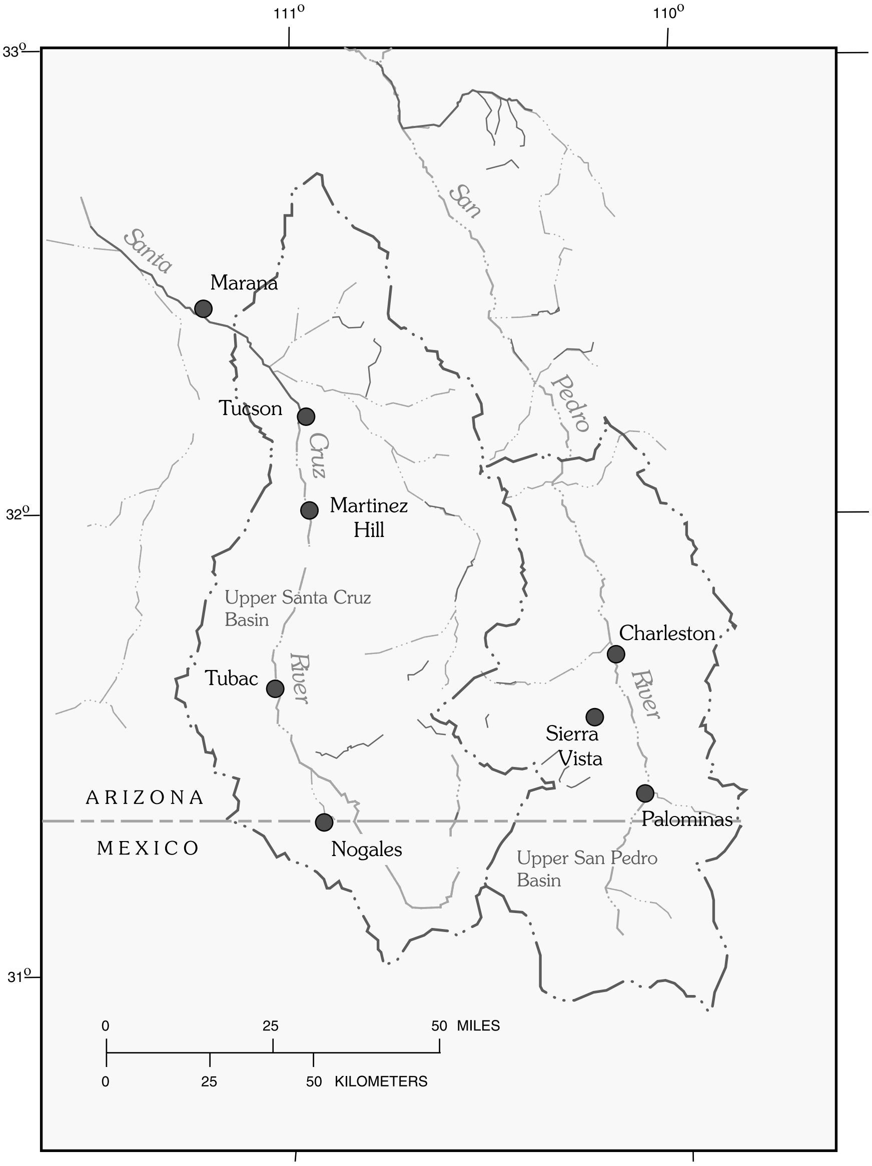

Fig. 7. Map of the San Pedro and Santa Cruz watersheds in southern Arizona and Sonora, Mexico.

photograph pairs document changes in this reach from 1880 to the present.

Photographs taken in the 19th century, combined with historical accounts, indicate a complete change in hydrologic and ecological conditions along this river. Despite descriptions of low streamflow, fish—probably Colorado River pikeminnow—were abundant (Davis, 1986). Flood plains were saturated, and the marshy conditions led to mosquito-borne malaria in settlements and army encampments (Hastings, 1959). Part of the reason for high water tables in the alluvial aquifers might have been the abundant beaver populations, which attracted 19th century trappers (Davis, 1986). The floodplains supported alkali sacaton (*Sporobolus airiodes*) grasslands with scattered stands of woody vegetation,

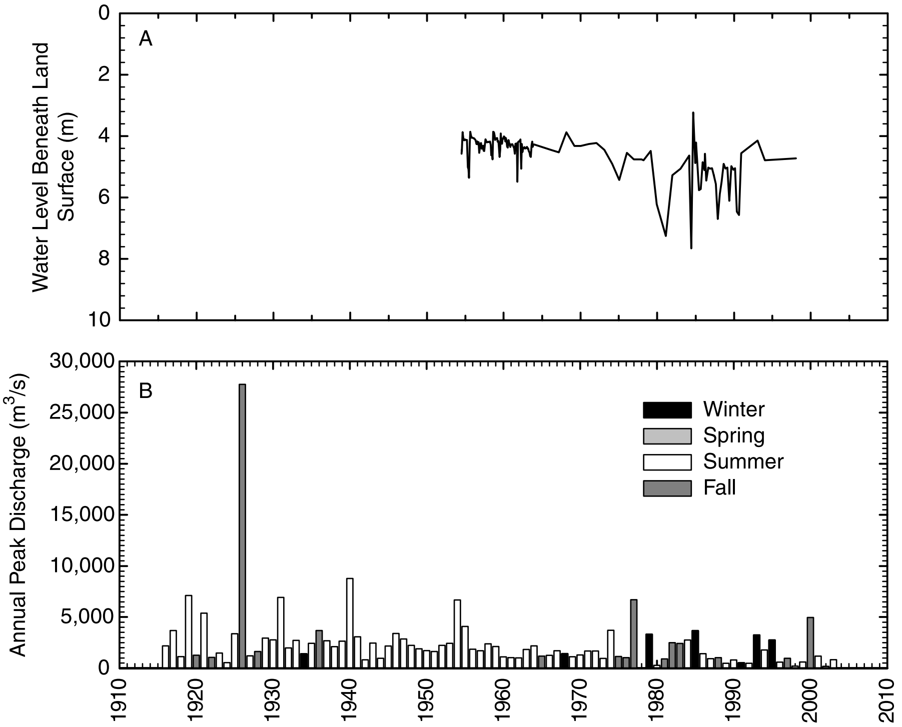

Fig. 8. Annual flood series and ground-water levels for the upper San Pedro River. (A) Ground-water levels for well D-23-22 33DCD2 adjacent to the San Pedro River near Palominas, Arizona. (B) Annual flood series for the San Pedro River at Palominas, Arizona (09470500). These two graphs show stationary records of surface water and ground water, which indicates riparian vegetation should benefit from the stable hydrologic conditions along this river.

including isolated cottonwood trees (Turner et al., 2003), although gallery forests were present downstream near the confluence with the Gila River (Davis, 1986).

Channel changes on the San Pedro River closely follow the conceptual model of arroyo downcutting depicted in Fig. 2. Beginning in the late 1870 s, floods in the San Pedro River began downcutting, creating a well-developed arroyo near the confluence with the Gila River by 1883. This headcut had extended 200 km upstream into the upper San Pedro River by 1892 (Bryan, 1925). Widening ensued, with the overall geometry of the arroyo stabilizing by 1941 (Hereford, 1993). The first photographs, taken in the 1930 s, show a barren channel with no stable flood plains within the arroyo walls (Fig. 9A). After 1941, low flood plains developed (Hereford, 1993) owing to a summer-dominated flood regime (Fig. 8B), allowing establishment of mostly native woody species (Fig. 9B). Beginning in the mid-1960 s, the seasonality of flooding shifted to a fall- and winter-dominated pattern (Fig. 8B). Woody riparian

Table 2
Comparison of drainage areas for principal gaging stations on the Santa Cruz and San Pedro Rivers, southern Arizona (from Pope et al., 1998)

River	Gaging Station	Drainage area (km^2)	Mean annual discharge (m^3/s)	Mean basin elevation (m)	Mean annual precipitation (mm)
San Pedro	Charleston	770	1.59	1475	419
Santa Cruz	Tucson	855	0.65	1234	429

Fig. 9. Repeat photography showing changes in riparian vegetation along the San Pedro River at Palominas, Arizona. (A) (April 17, 1930). This upstream view on the San Pedro River shows a wide arroyo system without flow terraces. An extremely large flood occurred in 1926, only four years before this photograph was taken. The mountains in the distance are in Sonora, Mexico. The terraces support desert scrub, although they once likely supported alkali sacaton grassland on marshy flood plains (Turner et al., 2003). A single juniper at left is the only significant woody species present (photographer unknown, courtesy of the U.S. Geological Survey). (B) (January 23, 1981). The channel had widened further in the mid-20th century, followed by the deposition of low terraces within the arroyo. A young cottonwood grove is shown in the background along the perennial stream (R.M. Turner). (C) (February 7, 1995). The cottonwoods have grown, and more have become established in the intervening 14 years. The low terrace, now a flood plain within the larger channel, has become more prominent. (D. Oldershaw). (D) (October 8, 2000). Cottonwood establishment and growth continued in the intervening 5 years, forming a closed canopy forest obscuring the background. Another photograph taken 6 weeks later shows little change despite the occurrence of the largest flood since 1978 and the third largest in the 65-year gaging record (Fig. 8B). (D. Oldershaw, Stake 1007).

vegetation increased despite periodic, sizeable floods (Fig. 9B–D). Tamarisk is present in this reach but is diminutive and sparse under the closed canopy of native species.

Ground-water levels remain high near Palominas despite fluctuations (Fig. 8A) that may be attributable to agricultural operations, which increased in the 1970 s and 1980 s. Base-flow decreases in this period (Pool and Coes, 1999) could be explained individually or collectively by a variety of factors. Ground-water and surface-water development associated with mining operations in Mexico and agricultural and urban development in the United States could be affecting the overall aquifer system that creates effluent conditions in this reach, as suggested in Fig. 4. The large increase in riparian vegetation could, through evapotranspiration, be reducing surface flows. Finally, seasonal shifts in regional climate (Turner et al., 2003), combined with increased woody vegetation on uplands, could be reducing recharge to the alluvial aquifer.

4.3. Case study: The Santa Cruz River

The drainage basin of the Santa Cruz River at Tucson has similar characteristics to the San Pedro River near Charleston (Table 2), but the history of water developments and riparian vegetation along the two rivers is completely different. The two drainage basins have adjacent headwaters in southern Arizona and northern Sonora, Mexico (Fig. 7). Like the San Pedro River, the Santa Cruz River was a discontinuous ephemeral stream in the 1800 s with effluent-influent reaches that supported dense riparian vegetation. A total of 150 historical photographs document changes in riparian vegetation along the entire Santa Cruz River (Table 1), and 114 photographs document changes in the vicinity of Tucson. Near Tucson, historical photographs document an open gallery forest of cottonwood trees with scattered shrubs and herbaceous vegetation. Mesquite bosques were locally dense along the flood plain.

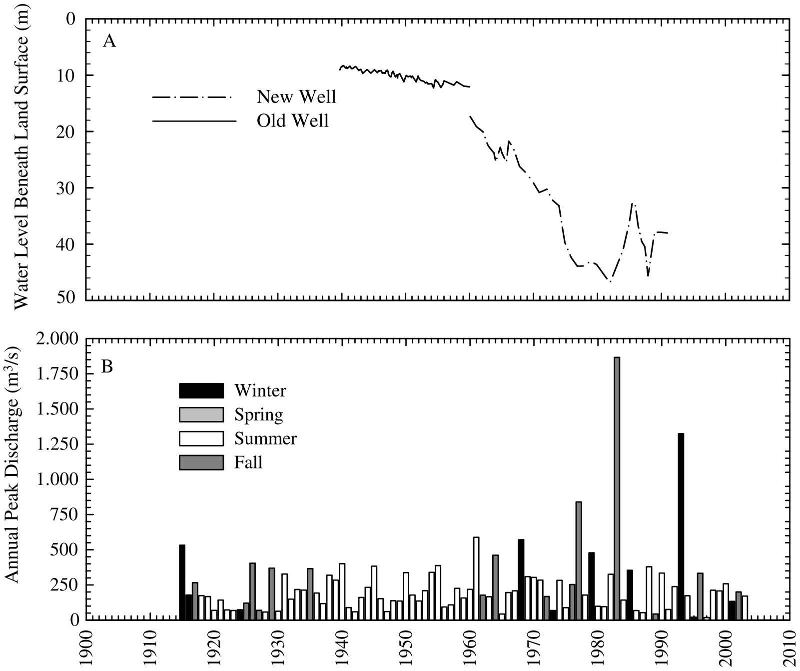

Fig. 10. Ground-water levels and annual flood series for the Santa Cruz River. (A) Ground-water levels for two wells—D-15-13 22DCC2 (old well) and D-15-13 23CCB2 (new well)—along the Santa Cruz River north of Martinez Hill near Tucson, Arizona. Excessive withdrawals are responsible for water-level declines after about 1950, and rises in the early 1980 s and early 1990 s reflect recharge during large floods. (B) Annual flood series of the Santa Cruz River at Tucson, Arizona (09482500).

As with the San Pedro River, channel change along the Santa Cruz River follows the conceptual model depicted in Fig. 2. Beginning about 1878, the Santa Cruz River downcut into its flood plain in the vicinity of Tucson, and the headcut propagated upstream (Betancourt, 1990). The downcutting and subsequent widening occurred during a series of floods, with substantial erosion occurring between 1878 and 1891. A large flood in 1916, at the start of the gaging record (Fig. 10B), widened the channel, destroying bridges in the City of Tucson. Photographs taken during the period of arroyo entrenchment document recovery of riparian vegetation, with new cottonwood stands and mesquite bosques forming adjacent to the active channel.

At some unknown time, but probably extending through the 1930 s, the arroyo coalesced into a continuously incised channel from Tucson to the headwaters. Photographs of the river taken in 1942 from Martinez Hill, upstream of Tucson (Fig. 7), show a shallowly incised channel through a corridor of cottonwood trees in a wide mesquite bosque (Fig. 11A). At that time, the bosque was highly valued as White-wing Dove habitat by the Arizona Game and Fish Department, and ground-water development was believed to threaten this habitat. Floods in the middle part of the 20th century were generally small and caused by summer thunderstorms (Webb and Betancourt, 1992). Nineteenth century agricultural activities near Tucson were sustained by surface-water diversion (Betancourt, 1990), which ceased owing to the combination of arroyo downcutting and the mid-century drought. Ground-water development accelerated in the 1950 s, leading to significant lowering of the water table in the alluvial aquifer by the 1970 s (Fig. 10A). By the 1970 s, the riparian vegetation and mesquite bosques had been eliminated, which deviates from the conceptual model depicted in Fig. 2.

Beginning with the 1977 event, and extending through 1993, a series of fall and winter floods widened the channel to its current extent (Fig. 11B). As shown in Fig. 10B and discussed by Webb and Betancourt (1992), these events represent a change in seasonality of flooding as well as suggest that the flood history is non-stationary. The San Pedro River also had seasonality change but did not have the increased flood frequency (Fig. 8B). These floods also temporarily recharged the aquifer immediately underneath the river (Fig. 10A), as depicted by a 12.2 m rise in water level following the 1983 flood. This increase was temporary and not sufficient to sustain growth of new riparian vegetation.

Flood damages prompted flood-plain managers to enact channel stabilization with ‘soil cement,’ a weak cementation process that created an engineered, trapezoidal channel with grade-control structures and designed to transport flood waters without storing sediment. A secondary effect of the channelization is that established riverine vegetation was destroyed and the soil-cemented banks retarded re-establishment. Despite the river engineering, the Santa Cruz River since the 1993 flood (Fig. 10B) has begun to deposit new, low floodplains within its artificial banks. Riparian vegetation, including black willow, mesquite, and non-native species, are becoming established on these flood plains. Effluent from wastewater-treatment facilities is sustaining a significant, new riparian area downstream from the locations of the historical ones and north of Tucson. These new riparian areas appear to be trapping sediments during summer thunderstorm runoff, leading to deposition of low, in-channel flood plains.

5. Discussion and conclusions

An historical photographic record has shown that riverine riparian vegetation has changed along virtually every river reach below 1530 m elevation in the southwestern United States. Using repeat photography, we document a mosaic of directional change in riparian vegetation on a reach-scale basis (Fig. 6). This approach is unique to this region and has not been attempted elsewhere in the world, even though many of the issues related to long-term change and potential loss of biodiversity are common.

While most observers focus on loss of riparian vegetation in the Southwest, our work suggests that total elimination of obligate riparian vegetation has only occurred in three river reaches: the Santa Cruz River through Tucson, Arizona; the Gila River in central Arizona; and the Mojave River in the vicinity of Barstow, California (Fig. 6). Losses also have been documented for the Owens River in eastern California

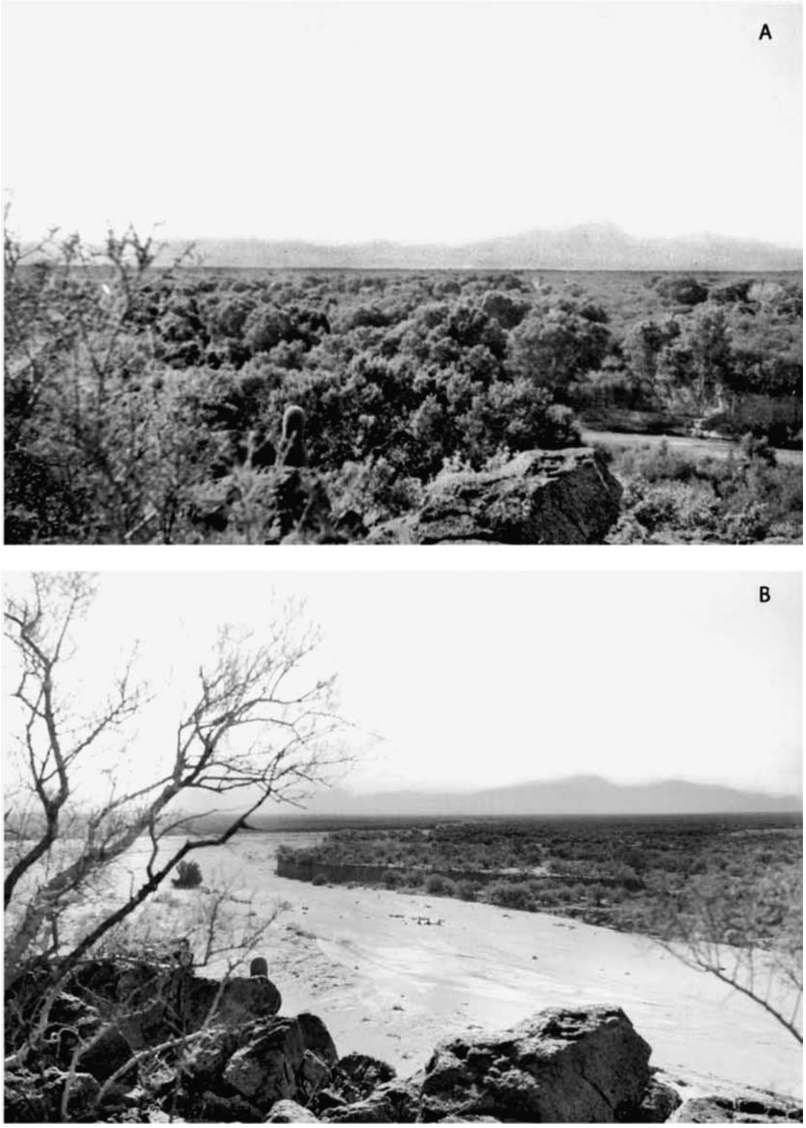

Fig. 11. Repeat photography showing changes in riparian vegetation along the Santa Cruz River south of Martinez Hill. (A) (June 1942). Perennial flow in the Santa Cruz River in the vicinity of Martinez Hill prompted Spanish missionaries to establish the Mission San Xavier del Bac near this site in the early 1700 s. By 1940, a narrow arroyo had formed here, but the riparian ecosystem continued to thrive. Cottonwoods line the channel, visible at lower right, with an extensive mesquite bosque in the background. (photographer unknown, courtesy of the Arizona Game and Fish Department). (B) (November 25, 2002). By the time of the first repeat photograph from this camera station in 1981, the cottonwoods had disappeared and the mesquite bosque was dying. The 1977, 1983, and 1993 floods (Fig. 10B) widened the channel significantly, removing low floodplains. Ground-water overdraft had dropped water levels in the alluvial aquifer well beyond the roots of riparian species (R.M. Turner, Stake 937).

and are likely to have occurred along the Salt River through Phoenix, although the latter is attributable more to bank protection than ground-water development and sparse photographic evidence suggests little historical riparian vegetation. Losses have also occurred where large reservoirs, particularly on the Colorado River, inundated long free-flowing reaches that once supported riparian vegetation.

Except in the case of reservoirs, losses in riparian vegetation are strongly associated with extensive ground-water usage and, in the case of the middle Gila River, total diversion of surface water. Some land uses commonly implicated in the decline of riparian vegetation appear to be either unimportant or have had the opposite effect. Despite claims that livestock grazing diminishes riparian vegetation, numerous reaches that sustained livestock had increases in riparian vegetation of about the same magnitude as ungrazed reaches. Flow regulation, such as on the Colorado River, creates a less-variable hydrologic environment that encourages growth of established vegetation; future problems in these reaches are expected owing to low disturbance of flood plains, the lack of potential for germination and establishment of new individuals, and increasing occurrence of fire.

More commonly, woody riparian vegetation has increased in the Southwest. Although much of the increase is attributable to non-native tamarisk and other invasive species, many reaches—notably the upper San Pedro River in southern Arizona—have had large increases in native species. Other reaches, typically those with ephemeral flow regimes, have had less change. Increases are associated with arroyo downcutting, which drained saturated flood plains and allowed woody vegetation to become established; high ground-water levels in alluvial aquifers that stabilized following arroyo downcutting; and the occurrence of winter floods in the late 20th century, which encouraged germination and establishment of native species where ground-water levels remained high.

Four atmospherically driven factors that favored establishment and growth of riparian vegetation—winter flooding, increased precipitation, longer growing season, and higher carbon dioxide content of the atmosphere—coincided in the period from the mid-1960 s through the mid-1990 s (Turner et al., 2003). Owing primarily to increases in nighttime temperatures and winter temperatures overall, the growing season has increased by as much as 60 days in the Southwest. Most woody riparian plants use the C3 photosynthetic pathway and are expected to benefit from increased atmospheric carbon dioxide, although the relatively modest increases as of 2000 are unlikely to have had much of an effect in spurring growth (Turner et al., 2003).

The long-term trajectories of change in riparian vegetation have management implications for riverine ecosystems with ground-water and surface-water interactions. In one sense, most riparian areas in the southwestern United States are vulnerable because additional water-resources development or modification in any reach that currently sustains this type of ecosystem potentially could decimate or eliminate obligate riparian species; the only question would be the amount of time before the reduction occurs. If the current robust status of some riparian ecosystems, such as the San Pedro River, are attributable to the extremely favorable conditions for growth from the 1970 s through the mid-1990 s, then extended drought could affect the beginning of the effluent reach and the end of the influent reach over and beyond the effects of existing and future water developments.

The explicit linkage of fate of riparian vegetation and conjunctive use of ground water and surface water needs to be more thoroughly understood if protection of this type of ecosystem is a future management priority. Climatically driven hydrologic processes, particularly the occurrence of winter floods, favors germination and establishment of native riparian vegetation, and maintenance of high ground-water levels in alluvial aquifers adjacent to river channels is necessary to sustain that growth. Although flow regulation can favor growth of riparian vegetation, future management should emphasize the necessity of periodic winter floods to introduce disturbance and initiate germination and recruitment of native species.

Acknowledgements

Our work was funded by the Ground Water Resources Program of the US Geological Survey. Mark Anderson of the US Geological Survey supplied data for Fig. 3, and Diane Boyer and Peter Griffiths of the US Geological Survey helped with the illustrations. We thank R.M. Turner, D. Goodrich, E. Weeks, T.C. Winter, P. Schot, and other reviewers for their critical and thoughtful reviews.

References

Anning, D.W., Duet, N.R., 1994. Summary of ground-water conditions in Arizona, 1987–1990, US Geological Survey Open-file Report 94-476, 2 sheets.

Betancourt, J.B., 1990. Tucson's Santa Cruz River and the arroyo legacy. PhD dissertation, Tucson, University of Arizona, 232 p.

Blinn, D.W., Cole, G.A., 1991. Algal and invertebrate biota in the Colorado river: comparison of pre- and post-dam conditions, in: Colorado River Ecology and Dam Management. National Academy Press, Washington, DC p. 102–123.

Bredehoeft, J.D., Papadopulus, S.S., Cooper Jr.., H.H., 1982. Scientific Basis of Water-Resource Management. National Academy Press, Washington, DC. 127 p.

Brothers, T.S., 1981. Historical vegetation change in the Owens River riparian woodland, in: Proceedings of the California Riparian Systems Conference, Davis, CA, September 17–19 1981 pp. 75–84.

Brown, D.E., 1985. Arizona Wetlands and Waterfowl. University of Arizona Press, Tucson. 169 p.

Bryan, K., 1925. Date of channel trenching (arroyo cutting) in the arid southwest. Science 62, 338–344.

Busch, D.E., 1995. Effects of fire on southwestern riparian plant community structure. Southwestern Naturalist 40, 259–267.

Carothers, S.W., Johnson, R.R., Aitchison, S.W., 1974. Population structure and social organization of southwestern riparian birds. American Zoology 14, 97–108.

Christensen, E.M., 1962. The rate of naturalization of tamarisk in Utah. American Midland Naturalist 68, 51–57.

Cooke, R.U., Reeves, R.W., 1976. Arroyos and Environmental Change in the American Southwest. Oxford University Press, London, England. 213 p.

Cowardin, L.M., Carter, V., Golet, F.C., LaRoe, E.T., 1979. Classification of wetlands and deepwater habitats of the United States, Washington, DC. US Department of the Interior, Fish and Wildlife Service, Office of Biological Services Report FWS/OBS-79/31, 131 p.

Davis Jr.., G.P., 1986. In: Carmony, N.B., Brown, D.E. (Eds.), Man and Wildlife in Arizona, The American Exploration Period, 1824–1865. Arizona Game and Fish Department, Phoenix, p. 231.

Dobyns, H.F., 1981. From Fire to Flood, Historic Human Destruction of Sonoran Desert Riverine Oases. Ballena Press, Socorro, NM. 222 p.

Fenner, P., Brady, W.W., Patton, D.R., 1985. Effects of regulated water flows on regeneration of fremont cottonwood. Journal of Range Management 38, 135–138.

Gary, H.L., 1960. Utilization of fire-stamen tamarisk by cattle, US Department of Agriculture, Forest Service Research Note 51 1960. 4 p.

Gaskin, J.F., Schaal, B.A., 2002. Hybrid *Tamarix* widespread in US invasion and undetected in native Asian range. Proceedings of the National Academy of Science 99, 11256–11259.

Graf, W.L., 1978. Fluvial adjustments to the spread of tamarisk in the Colorado plateau region. Geological Society of America Bulletin 89, 1491–1501.

Graf, W.L., 1983. The arroyo problem—paleohydrology and paleohydraulics in the short term. In: Gregory, K.J. (Ed.), Background to Paleohydrology. Wiley, New York, pp. 279–302.

Gregory, S.V., Swanson, F.J., McKee, W.A., Cummins, K.W., 1991. An ecosystem perspective of riparian zones: focus on links between land and water. Bioscience 41, 540–551.

Harris, D.R., 1966. Recent plant invasions in the arid and semi-arid Southwest of the United States. Annals of the Association of American Geographers 65, 408–422.

Hastings, J.R., 1959. Vegetation change and arroyo cutting in southeastern Arizona. Journal of the Arizona Academy of Science 1, 60–67.

Hendrickson, D.A., Minckley, D.A., 1985. Ciénegas—Vanishing climax communities of the American Southwest. Desert Plants 6, 131–175.

Hereford, R., 1993. Entrenchment and Widening of the Upper San Pedro River, AZ Geological Society of America Special Paper, vol. 282 1993. 46 p.

Hereford, Richard, Webb, R.H., 1992. Historic variation in warm-season rainfall on the Colorado Plateau, USA. Climatic Change 22, 239–256.

Hereford, R., Webb, R.H., Graham, S., 2002. Precipitation history of the Colorado Plateau region, 1900–2000, US Geological Survey Fact Sheet 119-02 2002. 4 p.

Hereford, R., Webb, R.H., Longpré, C.I., 2004. Precipitation history and ecosystem response to multidecadal precipitation variability in the Mojave Desert region, 1893–2001. Journal of Arid Environments, in press.

Hill, M., Tillemans, B., Martin, D.W., Platts, W., 2002. Recovery of riparian ecosystems in the upper Owens River watershed, American Water Resources Association, Summer Specialty Conference, Ground Water/Surface Water Interactions, July 1–3 2002 pp. 161–166.

Johnson, W.C., 1998. Adjustment of riparian vegetation to river regulation in the Great Plains, USA. Wetlands 18, 608–618.

Judd, B.I., Laughlin, J.M., Guenther, H.R., Handegarde, R., 1971. The lethal decline of mesquite on the casa grande national monument. Great Basin Naturalist 31, 153–159.

Junk, W.J., Bayley, P.B., Sparks, R.E., 1989. The flood pulse concept in river-floodplain systems. In: Dodge, D.P. (Ed.), Proceedings of the International Large River Symposium: Canadian Special Publication in Fisheries and Aquatic Sciences, vol. 106, pp. 110–127.

Kepner, W.G., Watts, C.J., Edmonds, C.M., Maingi, J.K., Marsh, S.E., 2000. A landscape approach for detecting and evaluating change in a semi-arid environment. Journal of Environmental Monitoring and Assessment 64, 179–195.

Lines, G.C., 1999. Health of native riparian vegetation and its relation to hydrologic conditions along the Mojave River, southern California. US Geological Survey Water-Resources Investigations Report 99-4112, 28 p.

Lusby, G.C., Reid, V.H., Knipe, O.D., 1971. Effects of grazing on the hydrology and biology of the Badger Wash Basin in western Colorado, 1953–66, US Geological Survey Water-Supply Paper 1532-D 1971. 90 p.

Melis, T.S., Phillips, W.M., Webb, R.H., Bills, D.J., 1996. When the blue-green waters turn red: historical flooding in Havasu Creek, AZ. US Geological Survey Water-Resources Investigations Report 96-4059, 136 p.

Merritt, D.M., Cooper, D.J., 2000. Riparian vegetation and channel change in response to river regulation: a comparative study of regulated and unregulated streams in the Green River basin, USA. Regulated Rivers: Research and Management 16, 543–564.

Minckley, W.L., Clark, T.O., 1984. Formation and destruction of a Gila River mesquite bosque community. Desert Plants 6, 23–30.

Minckley, W.L., Deacon, J.E. (Eds.), 1991. Battle Against Extinction: Native Fish Management in the American West. University of Arizona Press, Tucson. 517 p.

Ohmart, R.D., 1996. Historical and present impacts of livestock grazing on fish and wildlife resources in western riparian habitats. In: Krauseman, P.R. (Ed.), Rangeland Wildlife. Society of Range Management, Denver, CO, pp. 245–279.

Ohmart, R.D., Anderson, B.W., 1982. North American desert riparian ecosystems. In: Bender, G.L. (Ed.), Reference Handbook on the Deserts of North America. Greenwood Press, Westport, CT, pp. 433–466.

Parker, M., Wood, F.J., Smith, B.H., Elder, R.G., 1985. Erosional downcutting in lower order riparian ecosystems: Have historical changes been caused by removal of beaver? In: Johnson, R.R., Ziebell, C.D., Patton, D.R., Ffolliott, P.F., Hamre, R.H. (Eds.), Riparian Ecosystems and their Management: Reconciling Conflicting Uses, Tucson, AZ, First North American Riparian Conference, US Department of Agriculture, Forest Service General Technical Report RM-120, pp. 35–38.

Platts, W.S., Nelson, R.L., 1985. Will the riparian pasture build good streams? Rangelands 7, 7–10.

Pool, D.R., Coes, A.L., 1999. Hydrogeologic investigations of the Sierra Vista subwatershed of the Upper San Pedro Basin, Cochise County, Southeast AZ. Water-Resources Investigations Report 99-4197, 41 p.

Pope, G.L., Rigas, P.D., Smith, C.F., 1998, Statistical summaries of streamflow data and characteristics of drainage basins for selected streamflow-gaging stations in Arizona through Water Year 1996. US Geological Survey Water-Resources Investigations Report 98-4225, 907 p.

Rea, A.M., 1983. Once a River: Bird Life and Habitat Changes on the Middle Gila. University of Arizona Press, Tucson. 284 p.

Robinson, T.W., 1965. Introduction, spread, and areal extent of saltcedar (*Tamarix*) in the western states, US Geological Survey Professional Paper 491-A 1965. 12 p.

Sands, A., Howe, G., 1977. An overview of riparian forests in California: their ecology and conservation. In: Johnson, R.R., Jones, D.A. (Eds.), (technical coordinators), Importance, Preservation, and Management of Riparian Habitat, A symposium. US Department of Agriculture, Forest Service General Technical Report RM-43, pp. 98–115.

Schultz, B.W., 2001. Extent of vegetated wetlands at Owens Dry Lake, CA, USA, between 1977 and 1992. Journal of Arid Environments 48, 69–87.

Scott, M.L., Shafroth, P.B., Auble, G.T., 1999. Responses of riparian cottonwoods to alluvial water table declines. Environmental Management 23, 347–358.

Shafroth, P.B., Stromberg, J.C., Patten, D.T., 2000. Woody riparian vegetation response to different alluvial water table regimes. Western North American Naturalist 60, 66–76.

Shannon, J.P., Benenati, E.P., 2002. Essentials of aquatic ecology in the Colorado River. Flagstaff, Northern Arizona University, Creative Communications Report G46703/500/02-02, 73 p.

Stromberg, J.C., Tress, J.A., Wilkins, S.D., Clark, S.D., 1992. Response of velvet mesquite to ground water decline. Journal of Arid Environments 23, 45–58.

Stromberg, J.C., Wilkins, S.D., Tress, J.A., 1993. Vegetation-hydrology models: implications for management of *Prosopis velutina* (velvet mesquite) riparian ecosystems. Ecological Applications 3, 307–314.

Stromberg, J.C., Tiller, R., Richter, B., 1996. Effects of ground water decline on riparian vegetation of semi-arid regions: the San Pedro, AZ. Ecological Applications 6 (1), 113–131.

Stromberg, J.C., Briggs, M., Gourley, C., Scott, M., Shafroth, P., Stevens, L., 2004. Human alterations of riparian ecosystems. In: Baker Jr.., M.B., Ffolliott, P.F., DeBano, L.F., Neary, D.G. (Eds.), Riparian Areas of the Southwestern United States, Hydrology, Ecology, and Management. Lewis Publishers, New York, pp. 99–126.

Strong, T.R., Bock, C.E., 1990. Bird species distribution patterns in riparian habitats in southeastern Arizona. The Condor 92, 866–885.

Tellman, B., Yarde, R., Wallace, M.G., 1997. Arizona's changing rivers: how people have affected the rivers, University of Arizona, Water Resources Research Center Issue Paper No. 19 1997. 198 p.

Theis, C.V., 1940. The source of water derived from wells: essential factors controlling the response of an aquifer to development. Civil Engineer 10, 277–280.

Turner, R.M., 1974. Quantitative and historical evidence of vegetation changes along the upper Gila River, AZ, U.S. Geological Survey Professional Paper 655-H 1974. 20 p.

Turner, R.M., Karpiscak, M.M., 1980. Recent vegetation changes along the Colorado River between Glen Canyon Dam and Lake Mead, AZ, US Geological Survey Professional Paper 1132 1980. 125 p.

Turner, R.M., Webb, R.H., Bowers, J.E., 2003. The Changing Mile Revisited. University of Arizona Press, Tucson. 334 p.

Webb, R.H., 1996. Grand Canyon, a Century of Change. University of Arizona Press, Tucson. 290 p.

Webb, R.H., Baker, V.R., 1987. Changes in hydrologic conditions related to large floods on the Escalante River, south-central Utah. In: Singh, V. (Ed.), Regional Flood-Frequency Analysis. D. Reidel Publishers, Dordrect, The Netherlands, pp. 306–320.

Webb, R.H., Betancourt, J.L., 1992. Climatic variability and flood frequency of the Santa Cruz River, Pima County, AZ, US Geological Survey Water-Supply Paper 2379 1992. 40 p.

Webb, R.H., Smith, S.S., McCord, V.A.S., 1991. Historic channel change of Kanab Creek, Southern Utah and Northern Arizona, Grand Canyon, AZ, Grand Canyon Natural History Association Monograph Number 9 1991. 91 p.

Webb, R.H., Boyer, D.E., Orchard, K.L, Baker, V.R., 2001. Changes in riparian vegetation in the southwestern United States. Floods and Riparian Vegetation on the San Juan River, southeastern Utah. US Geological Survey Open-File Report OF 01-314, 1 sheet.

Webb, R.H., Boyer, D.E., Berry, K.H., 2001. Changes in riparian vegetation in the southwestern United States. Historical Changes along the Mojave River, CA. US Geological Survey Open-File Report OF 01-245, 1 sheet.

Webb, R.H., Belnap, J., Weisheit, J., 2004. Cataract Canyon, A Human and Environmental History of the Colorado River in Canyonlands. University of Utah Press, Salt Lake City. 268 p.