

Chapter 9. Evaluating Riparian Vegetation Change in Canyon-Bound Reaches of the Colorado River Using Spatially Extensive Matched Photo Sets

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Introduction

Much of what we know about the functional ecology of aquatic and riparian ecosystems comes from work on regulated rivers (Johnson et al. 2012). What little we know about unregulated conditions on many of our larger rivers is often inferred from recollections of individuals, personal diaries, notes, maps, and collections from early scientific surveys (Webb et al. 2007) and from repeat photography (Turner and Karpiscak 1980; Webb 1996). Later surveys often included photographs typically taken at specific and relatively few locations. Because rivers and their related riparian ecosystems vary in both longitudinal and lateral dimensions, such records provide relatively general and incomplete information about historical resource conditions, especially at large spatial scales and over long spans of time.

Pre-development conditions have been more extensively documented along the canyon-bound sections of the Colorado River than along any other river in the western United States (Powell 1961; Smith and Crampton 1987; Wheeler 1872). Unique to this reach of the Colorado River are the existence of photographs taken systematically by the Stanton expedition of 1889-1890 as part of a survey for the route of a railway through the canyons of the Colorado and matched originally in the 1990s (Webb 1996). This work includes a total of 445 photographs, which were taken between what is now Glen Canyon Dam and the upper end of Lake Mead, a distance of 485 river kilometers (rkms). The unparalleled spatial coverage of these photos provides a broad-scale and comprehensive visual record of pre-development conditions along this reach of the Colorado River. As such, this photographic record has and may continue to serve as a basis for monitoring change in the condition of desert and riparian resources in these remote canyons (Webb et al. 2011).

In this investigation, based on both original matches made in the 1990s and a second set taken between 2010 and 2012, repeat photography in Grand Canyon was used to detect and evaluate changes in riparian vegetation over time, relative to distinct changes in flow regime downstream of Glen Canyon Dam in Glen, Marble, and Grand Canyons (fig. 26). All Stanton original photographs are from the National Archives and are public domain. All the matches were done by USGS and are public domain. Our analyses are compatible with evaluations based on aerial imagery (Sankey et al. 2015) with the additional benefit of species-specific assessments. We evaluated change in riparian vegetation relative to earlier descriptions of change and predictions of future condition following completion of Glen Canyon Dam (Johnson 1991; Turner and Karpiscak 1980; Webb 1996). Finally, we examine on-the-ground response of riparian vegetation in

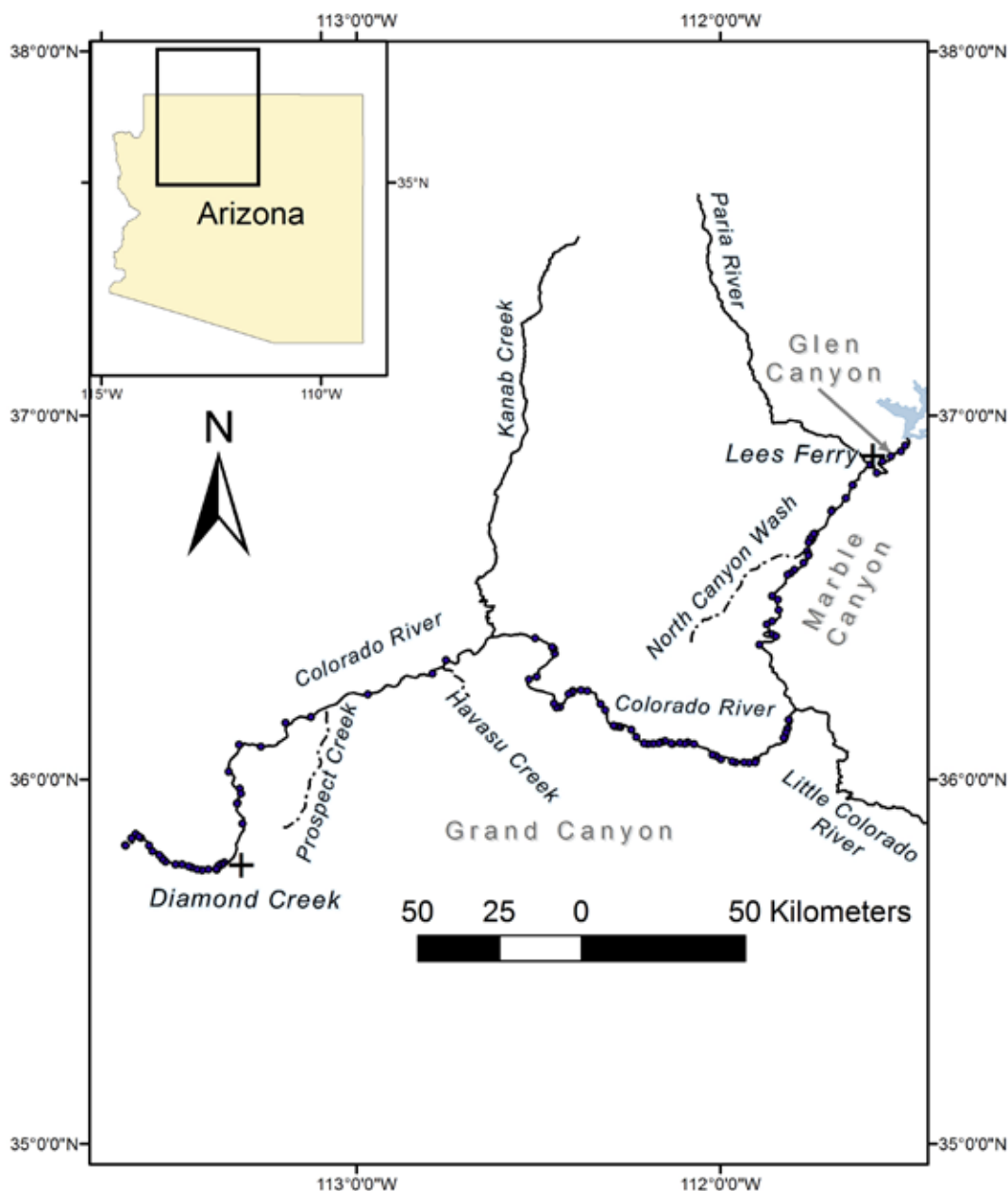


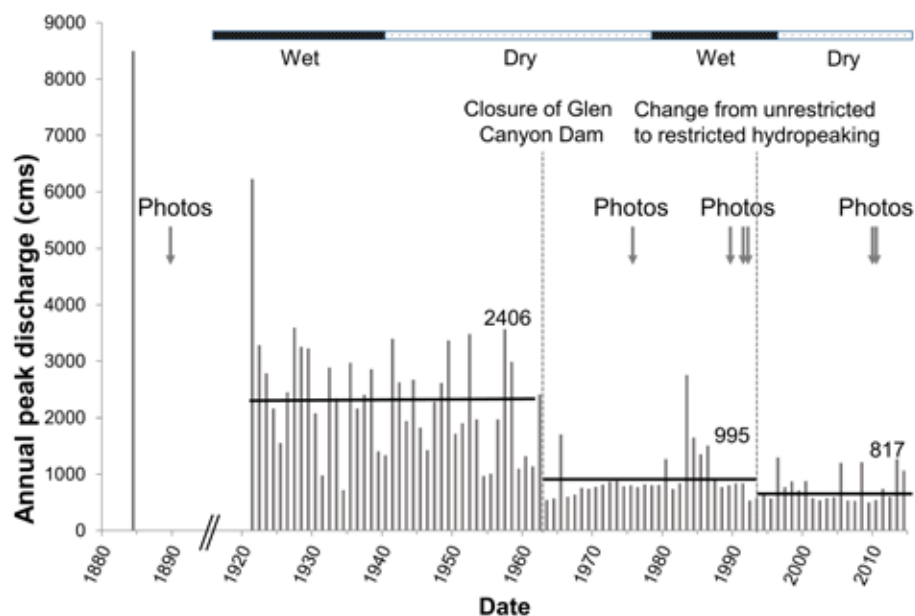
Figure 26—Study area map, including 25 river kilometers of Glen Canyon between Glen Canyon Dam and Lees Ferry (cross). Marble Canyon extends from the Paria River to the Little Colorado River and Grand Canyon, from the Little Colorado River to approximately 50 river kilometers below Diamond Creek (cross). The solid circles are locations of the 160 original Stanton Expedition photos matched and analyzed for this study (figure by M.L. Scott).

relation to recent work that explicitly links flow and climate variables to riparian vegetation change at a broader scale in the post-dam era (Sankey et al. 2015).

Hydrologic and Climatic Context

Pattern in the occurrence, composition, and productivity of riparian vegetation is structured by transverse (lateral) and longitudinal physical gradients related to the river. Transverse gradients, particularly in arid regions and along physically constrained channels, change sharply over relatively short distances, and riparian vegetation is

Figure 27—Annual peak discharge, in cubic meters per second, for the period of record at the Lees Ferry gage (U.S. Geological Survey gage 09380000). Horizontal lines and associated values indicate the average 2-year return peak flow for the pre-dam and two post-dam periods. Discharge of the 1884 flood was estimated. Relatively wet or dry periods, based on regional precipitation, are indicated.



primarily arrayed along a hydrologic gradient (Friedman et al. 2006). Variation in riparian vegetation away from the channel correlates with several interrelated factors that include decreasing fluvial disturbance and inundation (Auble et al. 1994, 2005), change in fluvial landforms (Hupp and Osterkamp 1985), groundwater availability (Webb and Leake 2006), and increasing drought stress (Zimmerman 1969). Longitudinal gradients range from the scale of local hydrologic controls like debris fans to the watershed, where along most western rivers, factors such as temperature, discharge, and floodplain area tend to increase predictably in the downstream direction (Ward et al. 2002).

Streamflow and sediment transport in the Grand Canyon were completely altered by construction of Glen Canyon Dam. Paleoflood records near Lees Ferry, spanning the past 4,500 years, indicate that prior to the dam, the long-term discharge of a common flood (2-year recurrence interval) was 2,133 cubic meters per second (cms) or 75,326 cubic feet per second (cfs) (O'Connor et al. 1994). More recent estimates give a revised value of 2,406 cms (85,000 cfs) for the 2-year return flood (Topping et al. 2003; fig. 27). The post-dam period includes two contrasting periods of stream discharge, primarily the result of changing reservoir operations. From 1963 to 1993, Glen Canyon Dam released water in response to power demands (hydropeaking) with daily highs as high as 878 cms (31,005 cfs) and lows averaging 140 cms (4,944 cfs). This period also featured three large, long-duration floods in 1983, 1984, and 1986 (fig. 28). From 1993 to the present, hydropeaking releases were limited to a narrower range of high and low flows (US DOI 1996) and six, short duration, high-flow experiments occurred in 1996 (Collier et al. 1997; Webb et al. 1999), 2004, 2008, 2012, 2013, and 2014 (Grams et al. 2015; fig. 28).

Riparian Vegetation in the Grand Canyon

Understanding riparian vegetation in the canyons of the Colorado River begins with the dynamics and distribution of fine-grained sediment. The most conspicuous pre-dam riparian vegetation, termed the old high-water zone (Johnson 1991), consisted of discontinuous bands of woody plants associated with alluvial deposits emplaced by

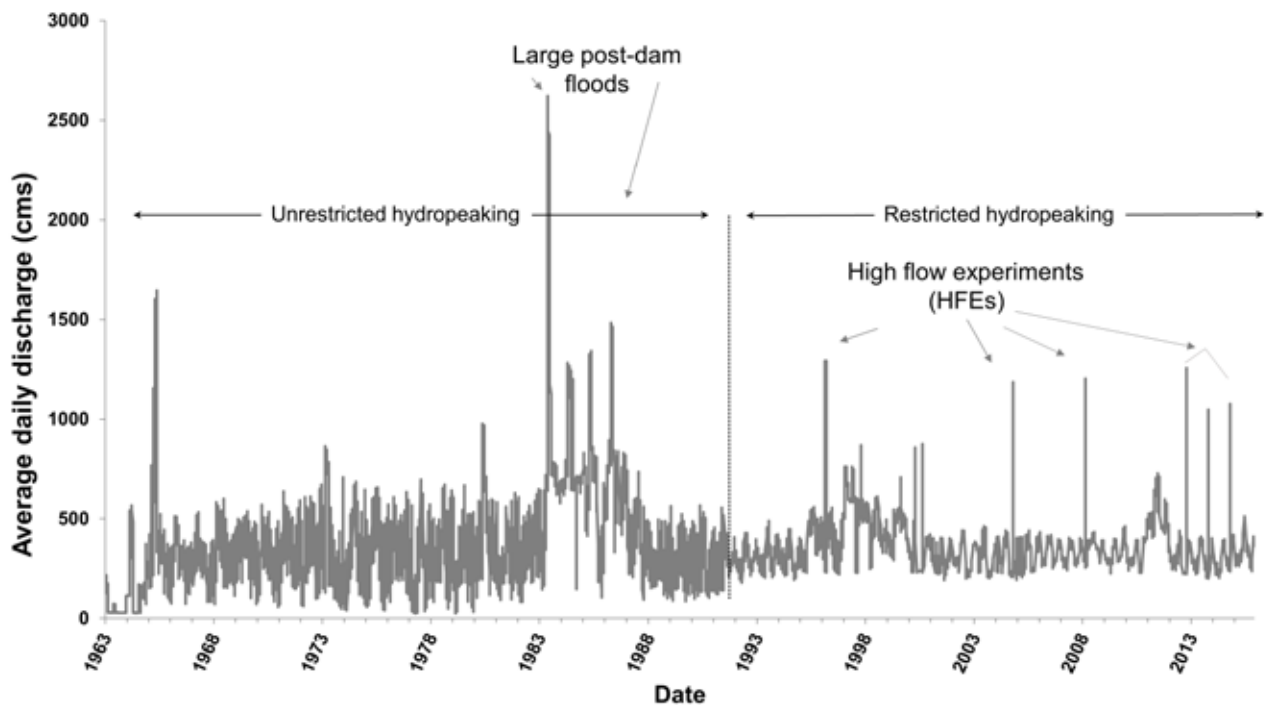


Figure 28—Average daily discharge at Lees Ferry for the post-dam period. The effects of two different hydropower peaking release patterns on peak and base flows are evident, as are the series of large, long-duration floods in the mid-1980s. Three short duration, high flow experiments occurred in 1996, 2004, and 2008, followed by three high flow experiments in 2012, 2013, and 2014.

relatively common pre-dam floods up to 2,800 cms. The vegetation in this zone consists of an ensemble of species whose composition shifts upstream to downstream. Netleaf hackberry (*Celtis reticulata*) is a common tree of this zone through Cataract, Glen, and Marble Canyons. The old high-water zone in Marble Canyon (fig. 26) includes Redbud (*Cercis orbiculata*) and Apache plume (*Fallugia paradoxa*), a shrub, present to about river kilometer (rkm) 65. Below rkm 65 and where the canyon widens, catclaw acacia (*Acacia greggii*) and honey mesquite (*Prosopis glandulosa*) dominate this zone. Throughout most of their range, neither of these warm desert species is restricted to riparian habitats, but in the Grand Canyon, mesquite is an obligate riparian species and is limited to alluvial terraces and talus slopes adjacent to the river (Warren et al. 1982). Honey mesquite is largely absent in the narrow inner gorges (~rkm 120-270) where alluvial terraces are rare and the old high-water zone is absent or discontinuous. Here, catclaw grows along the canyon walls and on talus slopes. Below rkm 270, mesquite reappears and becomes abundant on alluvial deposits (Anderson and Ruffner 1987).

The species in the old high-water zone are largely native and have been termed facultative riparian species (Johnson and Lowe 1985) and with the exception of honey mesquite, they do not strictly require riverine disturbance or moisture subsidies to establish and persist. However, species like catclaw reach their greatest densities and sizes along tributaries or in the main canyons, within influence of the river (Anderson and Ruffner 1987). In the case of honey mesquite in Grand Canyon, and other riparian settings, flooding likely serves as an important agent in seed dispersal and germination (Stromberg 1993).

To establish and persist, early successional, woody riparian plants require bare, moist, and typically fine-grained alluvium that remains relatively safe from subsequent fluvial disturbance (McBride and Strahan 1984; Scott et al. 1997). Pre-dam photographs (Turner and Karpiscak 1980; Webb 1996) and systematic plant collections (Clover and Jotter 1944) in the canyons of the Colorado River suggest that these conditions were infrequently met. Canyon width and the occurrence of debris fans provide the primary structural controls on fine sediment deposition in these canyons (Howard and Dolan 1981; Schmidt 1990). Most fine-grained alluvial surfaces below the high flood line occurred as eddy sand bars and discontinuous channel margin deposits associated with debris-fan channel constrictions. These surfaces, particularly in narrow canyon settings, were apparently reworked frequently enough by pre-dam flows that they were largely devoid of vegetation.

Species, including sandbar willow (*Salix exigua*), seep-willows (*Baccharis emoryi* and *B. salicifolia*), Fremont cottonwood (*Populus fremontii*), and arrow-weed (*Pluchea sericea*), are riparian obligates, requiring connection with the river for moisture throughout the growing season. These and other obligate riparian species were found at the mouths of or upstream on some of the perennial tributaries or in wider canyon reaches like Lees Ferry (Clover and Jotter 1944). In western Grand Canyon, where wider canyon reaches allow for reduced flood power and more extensive deposition of fine sediment (Schmidt and Grams 2011), riparian trees survived in some locations. A Fremont cottonwood tree can be seen below the high-water line at rkm 313.6 in a 1923 photo (Turner and Karpiscak 1980). Clover and Jotter (1944) note the occurrence of large tree willows (*Salix gooddingii*), which also can be seen in pre-dam photos from Granite Park (Turner and Karpiscak 1980) and other locations in western Grand Canyon as documented in written records (Webb 2005) and photos. As with species in the old high-water zone, some obligate riparian species show longitudinal trends in occurrence. For example, desert broom (*Baccharis sarothroides*) first appears around rkm 200 and becomes very common below National Canyon. In the late 1930s, the nonnative riparian tree tamarisk (*Tamarix ramosissima*) was reported to be relatively common from Green River, Utah, to the confluence of the Colorado River. It also was common in the approaches to Cataract Canyon, in wide reaches of Glen Canyon, and downstream from Grand Canyon. It was found above and at Lees Ferry but reported only below Vaseys Paradise and at the mouth of Saddle Canyon in Marble Canyon. In lower Grand Canyon, it was found above Lava Falls, near the mouth of Spring Canyon and at Separation Rapid (Clover and Jotter 1944; Webb 2005).

The closing of Glen Canyon Dam in March 1963 fundamentally altered the downstream aquatic and riparian ecosystems in Glen, Marble, and Grand Canyons (Dolan et al. 1974; Johnson et al. 1977; Johnson 1987). The pre-dam floods that reworked alluvial sediments were abruptly reduced (fig. 27), as was the annual pulse of fine sediment, by approximately 80 percent, which came from the Colorado River watershed upstream of Lees Ferry (Topping et al. 2000; Rubin et al. 2002). Riparian vegetation along the former high flood line was disconnected from the river and formerly active channel bedforms suddenly became ideal sites for successful establishment of riparian vegetation, both native and nonnative.

Accounts in the late 1960s by P.S. Martin (as cited in Johnson 1991 and Webb 1996) attest to the “explosive spread” of tamarisk through Grand Canyon. No doubt there was competition among tamarisk and various native riparian species including sandbar willow, Goodding’s willow, Fremont cottonwood, and several shrub species that rapidly colonized newly available establishment sites (Webb 1996). Photos from the mid-1970s show the encroachment of dense stands of riparian vegetation onto formerly scoured alluvial surfaces (Turner and Karpiscak 1980; Webb 1996). Although many newly established stands of riparian vegetation were dominated by tamarisk, mixed stands of tamarisk, sandbar willow, and seep-willow also were present. In certain settings, riverine marsh vegetation became established (Stevens et al. 1995). As has been documented downstream of dams on other rivers (Williams and Wolman 1984), the channel of the Colorado River canyons below Glen Canyon Dam narrowed. The rapid establishment of riparian vegetation created new habitat for a variety of wildlife species, including birds (Willson and Carothers 1979). These dramatic transformations in downstream aquatic and riparian ecosystems, coupled with rapidly escalating human use of the river corridor, raised concerns (Dolan et al. 1974). Efforts were soon underway to understand the nature of these changes with the hope that improved understanding would lead to anticipation of future change and improved resource management in Grand Canyon National Park immediately downstream of Glen Canyon Dam (Johnson 1991; Schmidt et al. 1998).

First Predictions of Change

After completion of Glen Canyon Dam, Turner and Karpiscak (1980) matched photos taken before the dam with those taken in the early to mid-1970s. The most striking change was the widespread and rapid establishment of new riparian plant assemblages. Dense stands were often dominated by tamarisk but included many native riparian and riverine marsh species. They speculated that the new riparian community was still assembling and, based on the recent spread of camelthorn (*Alhagi maurorum*) from the Little Colorado River and observed occurrences of both Russian olive (*Elaeagnus angustifolia*) and Siberian elm (*Ulmus pumila*), predicted an increased importance for these nonnative species in the riparian vegetation community.

Turner and Karpiscak (1980) observed local declines in the density of plants in the old high-water zone. Based on the fact that flooding would no longer directly inundate these zones, they predicted a more generalized decline of species from the old high-water zone. At the same time, they noted species like catclaw and honey mesquite establishing with tamarisk and sandbar willow in the newly established riparian communities and predicted that they would become a minor but important component of the post-dam riparian community known as the “new high-water zone.” Finally, they concluded that prediction of future conditions was not possible given the apparent rapid flux in the new riparian communities and key unknowns like streamflow, which was now determined by power and water-supply demands, as well as water availability. Acknowledging the unpredictability of regional climate, they pointed to the possible effects of drought and excess moisture on release patterns from the dam and the effects of prolonged low flows or inundation on the newly formed communities. Only the passage of time would refine our understanding of these relationships.

Following the largest post-dam floods on record in the mid-1980s (figs. 27 and 28), Stevens and Waring (1985) recorded high mortality in the new high-water zone riparian vegetation. They also noted significant differences in post-flood establishment. Tamarisk was five times more abundant than any other species on reworked flood surfaces, and clonal species like arrow-weed, sandbar willow, and common reed (*Phragmites australis*) rapidly colonized disturbed surfaces. They suggested that given different mortality rates and colonization patterns across species, longer-term compositional shifts in riparian vegetation were likely to result from large, long-duration post-dam floods. These results illustrate the points made earlier by Turner and Karpiscak (1980) that only by understanding the response of the new riparian ecosystem to the range of possible post-dam flows over time can we begin to predict future conditions.

From 1989-1992, Webb (1996) matched all of the 445 original Stanton expedition photos from 1889-1890 in what remained of Glen Canyon as well as Marble and Grand Canyons. Among other things, Webb's work with his colleagues provides a spatially comprehensive and quantitative assessment of change in riparian vegetation against pre-dam conditions and serves to evaluate trends detected by Turner and Karpiscak (1980) 20 years earlier. Despite high mortality recorded for riparian vegetation in 1983-1984 below the 1,400 cms (49,440 cfs) stage, these photos document the pervasive presence of post-dam riparian vegetation assemblages in the new high-water zone, including stands of riverine marsh habitat in wider canyon settings (Stevens et al. 1995). Vegetation was sparse only in settings where currents were swift and there was limited availability of fine sediment (Webb 1996). He argues that the rapid spread of tamarisk following dam closure was facilitated by source populations in major tributaries where it had long been established (Clover and Jotter 1944; Dodge 1936). However, Stevens (1989) observed that sandbar willow's ability to spread from root sprouts could ultimately lead to a gradual replacement of tamarisk by willow in the post-dam setting.

Establishment of old high-water zone species like honey mesquite and catclaw in the new high-water zone, noted by Turner and Karpiscak (1980), was confirmed by Webb (1996). He also documented the loss of desert broom from the old high-water community and new occurrences in the new high-water zone in the lower canyon. Because of relatively slow establishment and growth rates of species like honey mesquite and catclaw, mature stands of these trees in the new riparian assemblage could take decades to develop (Webb 1996). Finally, Webb found no clear evidence suggesting a decrease in honey mesquite densities in the old high-water zone over the preceding century but noted crown dieback in many individuals.

Methods

Repeat photography is the art and science of using ground-based photography to match historical images of landscapes. This approach has long been used to qualitatively and quantitatively assess landscape change (Webb et al. 2010), including in Grand Canyon (Turner and Karpiscak 1980; Webb 1996). Repeat photographs where views are a century or even a few decades apart are not suitable for resolving features or processes that respond on shorter time steps. However, the intervals of our photos are appropriate for examining increases in the number or size of long-lived individual plants in the riparian zone like catclaw acacia or changes in the distribution and size of riparian species

that tend to grow in dense clumps like sandbar willow where individuals are difficult to identify. Our goal was to quantify change in the abundance of key riparian species and the overall cover or biomass of riparian vegetation resulting from long-term, non-periodic change in streamflow and precipitation.

Photographs produced by the Stanton railroad survey expeditions of 1889 and 1890 through Marble and Grand Canyons were matched in 1989-1992 (Webb 1996). In 2010-2012, all photographs were again matched approximately 20 years following the first match using the same cameras and techniques described in Boyer et al. (2010). At each camera station, plants were identified and changes in riparian vegetation between the original and first matched photos, compared to the present, were interpreted in the field and recorded as annotations on hard copies of those images. High-resolution digital scans of these images were used in conjunction with field annotations to quantify changes in riparian vegetation.

We examined in detail 160 sets of matches for a total of 492 individual photos (an online Appendix table and all photos are available at: <http://dx.doi.org/10.5066/F76W988R>). These included eight matched photo sets with additional dates (e.g., 1975 and 1989) that bracketed the high, post-dam flows (1983 to 1986), allowing us to make inferences about riparian vegetation dynamics over shorter time steps and in response to relatively large post-dam flows. We selected this subset of matched photos to analyze because the images generally featured clear views of riparian vegetation along canyon-bound portions of the Colorado River through Glen, Marble, and Grand Canyons. Our selected photo points provide a broad representation of physical settings in the canyons examined (fig. 26). We focused our analysis on changes in the number of individuals and cover of key riparian species, which could be reliably identified in the imagery as well as general changes in the cover or biomass of riparian vegetation in the field of view. Change in number of individuals and biomass were assessed visually as a categorical increase, no change, or a decrease. Because the photo match comparisons between 1989-1992 and 2010-2012 were made between leaf-off and leaf-on conditions, changes in state had to be unambiguous and typically involved the loss or addition of individual plants or groups of plants. We include photo matches as figures that illustrate changes in riparian vegetation across a wide range of fluvial geomorphic settings.

Results and Discussion

Our photographic images fall within three distinct regimes relative to flow regulation in Grand Canyon (fig. 28). The original Stanton photos were from the period of largely unregulated flow prior to construction of Glen Canyon Dam. Photos from the 1970s and 1980s and the first full set of repeat photos (Webb 1996) were taken during the period of unrestricted hydropеaking (figs. 27 and 28). The second set of repeat photos was taken during the period of restricted hydropеaking and prescribed experimental floods (fig. 28). Of note is the fact that the original Stanton photos were taken 5 to 6 years following the occurrence in 1884 of the largest historical flood known on the Colorado River, with an estimated discharge of about $5,946 \pm 850$ cms ($210,000 \pm 30,000$ cfs) at Lees Ferry (Topping et al. 2003). The views in 1990 occurred at the end of a regionally wet period and the 1983 flood with a peak discharge of 2,621 cms (92,560 cfs), whereas the views in 2010-2012 followed a period referred

Table 8—The percentage and number of photos, for the periods 1989–1992 and 2010–2012, in which tamarisk was present in the matched view. A total of 160 original photos were examined. Categorical state changes in cover (percentage increase, decrease, no change) for all woody riparian vegetation; all native woody riparian species; and all old high water-zone (OHWZ) species, are compared over the period 1989–1992 to 2010–2012, based on the number of views in which the vegetation category occurred (n).

	Tamarisk presence in 1989–1992 views (n = 160)	Tamarisk presence in 2010–2012 views (n = 160)	Changes in matched views for the interval: 1989–1992 to 2010–2012 (number of views in which the vegetation category occurred)					Decrease in OHWZ species (n = 48)
			Increase in woody riparian vegetation (n = 159)	No change in woody riparian vegetation (n = 159)	Increase in woody riparian natives (n = 157)	No change in woody riparian natives (n = 157)	No change in OHWZ species (n = 48)	
%	79.5	96.9	89.3	9.4	87.3	11.5	43.8 ^a	18.8 ^a
n	128	156	142	15	137	18	21	9

^a State change for OHWZ species could not be determined in 38% of the views in which they occurred (n = 18).

Table 9—The number and percentage of views in which key riparian species increased in cover during the interval: 1989–1992 to 2010–2012. A total of 160 original photos were examined.

	Increases in riparian species during the interval: 1989–1992 to 2010–2012				
	<i>Baccharis</i> spp.	<i>Salix exigua</i>	<i>Pluchea sericea</i>	<i>Acacia gregii</i>	<i>Prosopis glandulosa</i>
%	53.4	1.9	13	10.6	6.8
n	86	3	21	17	11

to as the early 21st century drought (Woodhouse et al. 2010). Finally, the 2010–2012 views were taken following a controlled flood with a discharge of 1,175 cms (41,500 cfs). Results of our photo matches summarizing overall change in riparian vegetation over the past 20 years are presented in table 8. Corresponding changes for key riparian species are included in table 9. An online Appendix (<http://dx.doi.org/10.5066/F76W988R>) provides a table listing information and the interpretation results for each photo station along with all the photos examined.

Turner and Karpiscak (1980) predicted increases in the invasive species Russian olive and Siberian elm along the Lower Colorado River. Such increases have been large elsewhere, and Russian olive is now the fourth-most frequently occurring woody riparian species in the western United States (Friedman et al. 2005). However, neither of these species appeared in our photo matches and only a few Russian olive stems were observed upstream of Lees Ferry in 2011. These species do not appear to have spread. In the case of Russian olive, the National Park Service (NPS) in Grand Canyon began removing Russian olive in the 1990s and continues to remove them when observed (Hahn 2011). The removal efforts by NPS appear to have been successful given the rapid spread of Russian olive along smaller, regional streams like the Escalante River and at Canyon de Chelly, coinciding with a wet episode beginning about 1980 and extending through the 1990s (Reynolds et al. 2014; Webb et al. 2007).

New High-Water Zone

The original Stanton photos show little or no vegetation below the old high-water zone. These surfaces, particularly in narrow canyon settings, were apparently reworked frequently enough by pre-dam flows that they were largely devoid of vegetation, except in a few protected settings (see figs. 29-33). Turner and Karpiscak (1980) qualitatively described widespread establishment of riparian vegetation on formerly active channel deposits in the mid-1970s below Glen Canyon Dam. By 1973, the greatest increase in vegetated area (up to 20 percent) occurred in those areas of the channel above the 878 cms (~31,000 cfs) stage, or the maximum hydropower peaking flows, and remained 10 percent or less below this stage (Sankey et al. 2015). As predicted by Turner and Karpiscak (1980), the vegetation established below the old high-water zone following flow regulation was susceptible to removal by subsequent high flows. It would not take long for the effects of flooding and prolonged inundation on the newly formed riparian ecosystem to be realized.

The largest flood in the post-dam record occurred in 1983, resulting from a series of late snow and rainstorms and rapid runoff in the basin. The flood peaked at 2,621 cms (92,560 cfs) and was of unusually long duration. Comparatively large, long-duration floods followed in 1984 and 1986 (fig. 28). Mortality, resulting from physical removal or prolonged inundation, exceeded 45 percent at some locations for tamarisk, honey mesquite, and catclaw, which had established below the 1,700 cms (~60,000 cfs) stage in the new high-water zone (fig. 29). Clonal species like sandbar willow and arrow-weed had lower mortality rates of 7 percent and 33 percent respectively. Shallowly rooted species like the seep-willow (*Baccharis* spp.) suffered 90 percent mortality (Johnson 1991; Stevens and Waring 1985).

The flooding in 1983-1986 killed or removed up to 10 percent of all riparian vegetation (Waring 1996), particularly at lower river stages (fig. 29), and vegetated cover below 1,274 cms (~45,000 cfs) showed little or no increase over the interval from 1973 to 1984. Presumably, any increases prior to the flood were offset by mortality from the flood (Sankey et al. 2015). Because of species-specific differences in flood mortality and early differences in post-flood reestablishment patterns, Stevens and Waring (1985) suggested that post-dam flooding from 1983 to 1985 had the potential to shift composition in favor of species like tamarisk and catclaw acacia and away from species like seep-willows and longleaf brickellbush (*Brickellia longifolia*). By the 1990s, tamarisk remained a prominent component of the new riparian assemblage and it appeared in 71 percent of the views of the river corridor taken by Webb (1996).

In August 1991, operating rules for power generation at Glen Canyon Dam changed and maximum releases were limited to 708 cms (~25,000 cfs) (US DOI 1996; fig. 28) and by 1992, vegetated cover values above this stage and below the maximum stage of the 1983 flood increased to between 25 and 30 percent. Values remained at about 10 percent below the new hydropower maximum (Sankey et al. 2015). Three short-duration, high-flow experiments (HFEs) occurred in 1996, 2004, and 2008 (fig. 28). By 2002, cover had declined in the zone between the maximum HFE flood and the 1983 flood and remained low through 2009. In contrast, cover increased from 5 to 15 percent below the peak stage of the HFE floods, particularly between 2005 and 2009 (Sankey et al. 2015). Our photo matches in 2010-2012 are consistent with the aerial imagery analysis results of Sankey et

Figure 29—Tamarisk in Glen Canyon (photo 751; online Appendix, <http://dx.doi.org/10.5066/F76W988R>).

(a) (top) (1889) This downstream view, 11 river kilometers above Lees Ferry, shows a remarkably clear view of fine-grained alluvium draped over talus. Except for a few scattered plants near the top of the bank, the deposit is largely free of vegetation.

(b) (bottom) (1975) Within 12 years following closure of Glen Canyon dam, the bank is heavily vegetated with primarily tamarisk and sand-bar willow. The large tamarisk stem, high on the bank, may have established during high flows before the dam.

(c) (next page) (1989) Near-shore stands of tamarisk and willow appear to have been removed or killed-back by flooding a few years preceding this view. **(d) (next page)** (2011) Woody riparian vegetation, including tamarisk, seep-willow, and sand-bar willow, have reestablished near shore and a diversity of grasses, herbs, and small shrubs fill spaces in between. The large tamarisk on the high bank is still alive but has many dead branches in the crown.



al. (2015) and show increases in riparian vegetation in 90 percent of the views compared with 1989–1992. Tamarisk was present in 79.5 percent of the 1989–1992 views we examined (compared with 71 percent of the total matched population examined by Webb 1996) and increased to a presence of 96.9 percent by 2010–2012 (table 8).

There was no indication that sandbar willow was replacing tamarisk, as it increased in only 1.9 percent of the views (table 9). This contrasts with earlier speculation that sandbar willow might gradually replace tamarisk under the post-dam flow regime (Stevens 1989). Conversely, our data suggest that the recent increases in riparian vegetation at lower stages reported by Sankey et al. (2015) involve a number of other native species such as seep-willow. Overall, native woody species increased in 87.3 percent of our views, with seep-willow increasing in 53.4 percent of the views over the past 20 years (tables 8 and 9). Seep-willow suffered high flood mortality in the mid-1980s and had lower representation in 1990 matched photos. Much of the increase in tamarisk, seep-willow, and arrow-weed



occurred in near-shore locations (figs. 30 and 31). Sankey et al. (2015) found that vegetation expansion into lower elevations of the riparian zone occurred during periods when peak flows were lower and base flows higher and when inundation duration fell below about 5 percent.

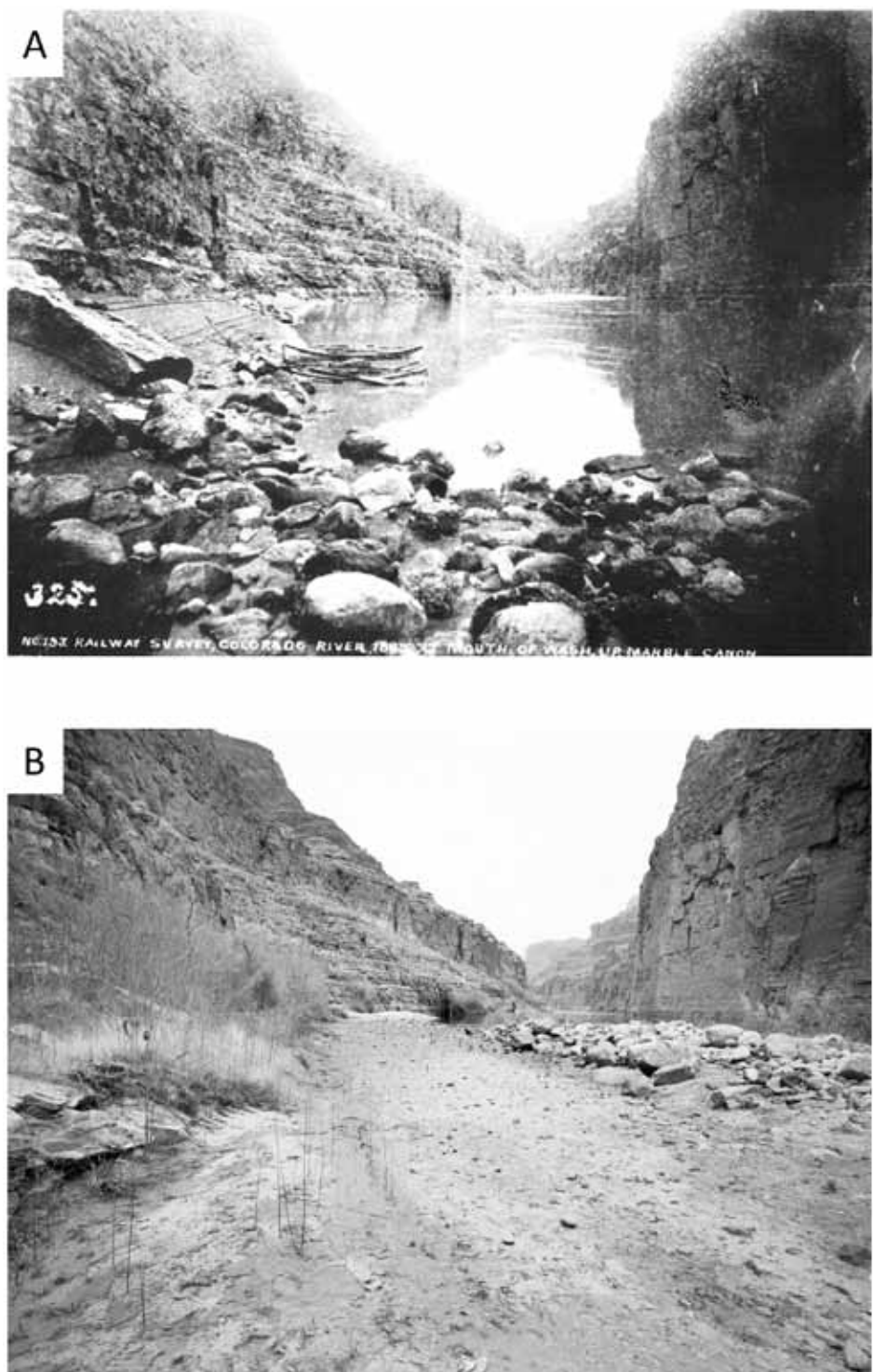
Any role that HFEs (fig. 28) may have played in the recent encroachment of riparian vegetation is unclear. A more explicit linkage between the increase in native and nonnative woody shrubs and specific flow events is difficult to make without much shorter time steps between photo matches that tightly bracket the events. Data presented by Sankey et al. (2015) suggest an increase in near-shore vegetation sometime between 2005 and 2009 (see his figure 6). However, whether this was an event-specific response

Figure 30—Channel narrowing in Marble Canyon (photo 2526; online Appendix, <http://dx.doi.org/10.5066/F76W988R>).

(a) (top) (1889) View upstream into still water from the upstream edge of the South Canyon debris fan (river kilometer 51). A channel margin deposit of fine alluvium along the near wall is devoid of vegetation and is marked by a series of flow recession lines.

(b) (bottom) (1992) The channel margin deposit has expanded and is now stabilized by tamarisk, sand-bar willows and grasses. Leafless, small stems of what may be sand-bar willow or tamarisk grow along the edge of a secondary channel adjacent to a cobble bar with small tamarisk lining the stream ward edge.

(c) (next page) (2010) A dense stand of tamarisk, sand-bar willow, and seep-willow now flank the narrowing secondary channel and the cobble bar is largely covered by vegetation and fine sediment.



to the 2008 HFE or simply subtle shifts in inundation duration during the period can only be answered by detailed vegetation monitoring in real time or by aging encroaching vegetation retrospectively.

The Glen Canyon Dam Adaptive Management Program (www.gcdamp.gov) conducted three HFEs in 1996, 2004, and 2008. Results from the 1996 and 2008 HFEs indicate that some near-shore wetland plants were removed by these flows and woody riparian plants were buried by sediment, which temporarily reduced vegetation cover. Losses, however, were short-lived (12 months or less). Recovery favored



woody and herbaceous species that were able to reproduce vegetatively, like sandbar willow. Because the timing of these flows occurred predominantly before the seed dispersal window for tamarisk, the establishment of this species following the releases was comparatively low (Kennedy and Ralston 2011). Strategies for subsequent HFEs have focused on building and maintaining sandbars from tributary-derived sand and balancing the effects of releases in order to limit competition between nonnative trout (*Oncorhynchus mykiss*) and native humpback chub (*Gila cypha*) populations (Wright and Kennedy 2011). The timing of HFEs, which is largely driven by sediment inputs from tributary sources and competitive interactions between fish, could have important implications for riparian plant species that reproduce by seed. This is especially true for woody riparian pioneer species like native cottonwood, willow, and nonnative tamarisk. Because these species have partially non-overlapping seed dispersal periods, subtle differences in flood timing within these seed release periods can have profound influences on the composition of newly established seedling cohorts (Shafroth et al. 2010). Continued monitoring of wetland and riparian vegetation relative to HFEs is important to understanding ecosystem level responses to flow management in the Grand Canyon.

Only ~1 percent of the views showed a decrease in woody native riparian species, whereas 11.5 percent of the views showed no change in cover and density of these species (table 8). The images reveal that in certain narrow canyon settings, shear stresses are likely to remain high enough under the current flow regime to preclude colonization and persistence of native riparian vegetation (fig. 32). Thus, unless the flow regime changes in the future, certain channel locations should remain free of persistent vegetation. Finally, catclaw acacia and honey mesquite increased in the new high-water zone in 10.6 percent and 6.8 percent of our views, respectively (table 9). For both species, this pattern was especially pronounced beginning at about rkm 105 and some stands are now several meters tall (fig. 33). The widespread occurrence of tamarisk, honey mesquite, catclaw acacia, and a number of other native and nonnative riparian plants in





Figure 31—Vegetation encroachment, upper Grand Canyon (photo 1749 b; online Appendix, <http://dx.doi.org/10.5066/F76W988R>).

(a) (1890) Looking downstream to a sand and gravel bar on river right, upstream of the Papago Creek debris fan, upper Grand Canyon (river kilometer 123). Both fan and bar features are low and devoid of vegetation. (b) (1991) Tamarisk has colonized the higher portions of the sand bar and the Papago Creek fan, which appears to have increased slightly in elevation. (c) (2011) Tamarisk has increased in size and number on both the bar and debris fan. On the bar, dense stands of tamarisk, sand-bar willow, arrow-weed, and seep-willow have filled in between the older, higher tamarisk and the channel bank. Tamarisk and seep-willow also line the channel margin upstream of the fan as well as the upstream edge of the debris fan.

the new high-water zone predominantly reflect natural establishment and survival in the post-dam period. However, nonnative Russian olive and tamarisk have and are being removed within Grand Canyon National Park.

At the same time, native plants have been planted in various locations, including cottonwoods at Lees Ferry (rkm 0) (Stevens and Burke 2001), various native plants at Soap Creek Camp (rkm 18.5) (Theobald 2001), and honey mesquite and catclaw acacia at Nankoweap (rkm 85) and Granite Park (rkm 336) (Anderson and Ruffner 1987). Additionally, in 2012–2013, the NPS initiated a riparian restoration project at Granite Camp, upstream of Monument Creek (rkm 151) (McMaster 2012). This effort included removing tamarisk and planting honey mesquite, along with other woody native species (<https://www.nps.gov/grca/learn/nature/granite.htm>). Similar restoration efforts are being planned as part of the Long-term Experimental Management Plan for the operation of Glen Canyon Dam (<https://itempeis.anl.gov>). The presence of sites in the new high-water zone, where vegetation has been established and maintained artificially, or removed, could potentially muddle future interpretations of vegetation responses to flow management, particularly if the increasing number of restoration activities are not systematically tracked into the future.





Figure 32—Stasis in upper Granite Gorge (photo 2319; online Appendix, <http://dx.doi.org/10.5066/F76W988R>).
(a) (1890) Upstream view of the Granite Gorge from Clear Creek (river kilometer 136). The walls of Vishnu schist and Zoroaster granite are too steep and narrow to support any riparian vegetation. **(b)** (1991) After a century and the closing of Glen Canyon dam, the inner gorge appears little changed. **(c)** (2011) In spite of large increases in riparian vegetation in wider canyon reaches, some steep, narrow canyon settings are not likely to provide conditions for establishment and persistence, even under current regulated flow conditions.

Old High-Water Zone

In 1973, Turner and Karpiscak (1980) saw limited evidence for declines in trees in the old high-water zone. Aside from crown dieback and increases in density for honey mesquite, Webb (1996) found little compelling evidence suggesting widespread declines in the old high-water stands; catclaw acacia, for example, seemed little affected. Similarly, results of Sankey et al. (2015) show little directional change in vegetated cover in this zone from 1965 through 1992 but sustained decreases starting in 2002. They point to the early 21st century drought, beginning in the late 1990s, as a likely cause. This is consistent with Webb's predictions that following flow regulation species like honey mesquite would be susceptible to drought and undergo slow structural decline (Webb 1996).

In 72 percent of the initial matched views by Webb (1996) containing honey mesquite ($n = 58$), the trees either increased or showed no change in density. In 10 percent of the views with density increases, there were corresponding decreases in plant stature, suggesting possible climate-related factors like drought and frost. Decreases in severe frosts after 1890 may have spurred new establishment in some settings. Increases in precipitation and streamflow in the early 20th century (Hereford et al. 2006; fig. 27) could





Figure 33—(left and above) A new high water line in lower Grand Canyon (photo 1772 a; online Appendix, <http://dx.doi.org/10.5066/F76W988R>).

(a) (1890) Looking upstream and across the upper portion of the fan at Parashant Wash (river kilometer 320). A depression filled with fine sediment at the lower right of the image has a patch of sizable vegetation, which is not identifiable. Upstream, and on both sides of the river, a distinct and largely continuous band of woody vegetation can be seen above the old high water line. **(b)** (1991) Bermuda grass dominates that portion of the fan, which contained fine sediment and vegetation in the previous image. Scattered, taller tamarisk and desert broom occur on the upper portion of the fan. Stunted and dead tamarisk occupy lower portions of the fan, possibly reflecting flood mortality from the mid-1980s floods. Across the river, a dense line of tamarisk occurs below the band of old high water vegetation, which appears to have thinned and some dead stems are apparent. **(c)** (2011) Tamarisk higher on the bar appears stressed and is dying back and the desert broom is gone. Closer to the river, a dense band of woody vegetation, dominated by mesquite, is tall enough to obscure the river.

have contributed to height growth, which might then have been lost to drought-pruning following dam closure (Webb 1996). Although Webb thought it unlikely that honey mesquite would be lost from this relict riparian assemblage over the short-term, he suggested disconnection from the river in the post-dam era might lead to long-term reproductive failure and that future meteorological drought could reduce existing honey mesquite stands to scattered individuals.

In the 2010–2012 matches that we examined, the old high-water zone occurred in 30 percent ($n = 48$) of our views (table 8). In 18 of those views, an evaluation of change in this pre-dam riparian plant assemblage was not possible, primarily because plant growth in the new high-water zone over the past 20 years obscured the view of the old high-water zone (see fig. 33). In spite of a relatively small number of unobstructed views of the old high-water zone ($n = 30$), our results generally support the observations of Sankey et al. (2015) that this zone showed declines in overall cover beginning in 2002. In our 2010–2012 matches, none showed increase in cover

of this vegetation. Rather, cover declined in 19 percent of our views and showed no discernable change in 44 percent of our views (table 8). This suggests that in spite of generalized regional drought over the past decade (Hereford et al. 2002), factors such as aspect, microclimate, and side-slope drainage in high-relief canyons may buffer some stands of old high-water zone vegetation from the effects of drought. Some of these stands may in fact have become established because of the presence of shallow groundwater of local origin (e.g., the stands at Ledges Camp, rkm 245) and may therefore be largely unaffected by river flows.

Plant pathogens and unintended introductions of insect pests have had unexpected and profound influences on long-term compositional changes in riparian forest ecosystems (Johnson et al. 2012). A new factor potentially influencing the long-term distribution and importance of tamarisk in riparian systems throughout the western United States is the purposefully introduced tamarisk leaf beetle (*Diorhabda* spp.; see Chapter 5). Monitoring data from the Colorado River Basin show that the beetle was present throughout Marble and middle and lower Grand Canyon by 2011 and 2012 ([http://www.tamariskcoalition.org/sites/default/files/files/2014 percent20Distribution percent20Map percent20CRB.pdf](http://www.tamariskcoalition.org/sites/default/files/files/2014%20Distribution%20Map%20CRB.pdf)). We observed tamarisk defoliation and premature leaf senescence related to beetle activity in 3.7 percent of our views. Anticipating the effects of the beetle on the structure and composition of riparian vegetation assemblages in the Grand Canyon is not yet possible and, as stated earlier by Turner and Karpiscak (1980), will require the passage of time.

Our recent work provides another point-in-time assessment of riparian vegetation change in canyons of the Colorado River influenced by Glen Canyon Dam. This is an effective way to monitor changes that unfold slowly but is inadequate for capturing the details of processes that occur more rapidly, such as event-specific mortality or establishment and removal processes on dynamic geomorphic surfaces. Such refinements require a more mechanistic understanding that explicitly links vegetation with hydrology and climate. Relationships between vegetation and streamflow have been used to predict vegetation response to flow alterations (Auble et al. 1994; Primack 2000). Using surveyed vegetation plots and a hydrologic model, Auble et al. (2005) modeled individualistic plant responses to inundation duration. This relation was used to predict changes in vegetation patterns away from the channel following changes in flow. Because of limits to the amount of topographic data that Auble et al. (2005) could collect, their work was limited to a short reach and could not account for longitudinal variation in the flow-vegetation relationship. However, Sankey et al. (2015) have recently developed fine-resolution spatial and temporal relationships between variations in riparian vegetation cover relative to streamflow and climate. They accomplished this using aerial imagery, instantaneous flow and topographic data, and a spatially extensive hydrologic model of Marble and Grand Canyons. These data provide the basis for predicting future vegetation change in this system. Thus, we examine our findings and earlier predictions in the context of these new results. We used photographic data at a scale fine enough to identify changes in numbers of individuals of particular species. This complements the analysis of Sankey et al. (2015), which was based largely on aerial imagery that was spatially more extensive but lower in resolution.

Management Implications

1. Tamarisk was present in Glen, Marble, and Grand Canyons in the pre-dam period (Clover and Jotter 1944). With other native riparian species, it spread rapidly, likely from both tributary sources and existing stands along the Colorado, throughout the Grand Canyon following dam closure. Despite extensive mortality following flooding from 1983–1986, tamarisk is still a dominant riparian species. Based on photographic evidence, it was widespread by 1989–1992 and was found in 71 percent of the views examined by Webb (1996) and in 79.5 percent of the views we examined for the same time period.
2. Woody riparian vegetation has increased throughout the river corridor in Grand Canyon between the 1990s and 2012. In general, total woody riparian vegetation, including tamarisk, showed increased cover and density during this period in 89.3 percent of the matched images in 2010–2012. Recent work shows that vegetation expansion into lower topographic position in the riparian zone occurred during periods when peak flows were lower and base flows higher and when inundation duration fell below about 5 percent (Sankey et al. 2015). There was no evidence that brief, pulsed inundation during HFEs limited vegetation expansion. Gains in riparian vegetation cover over the past two decades were primarily below the maximum stage of post-dam controlled floods (1,274 cms [$\sim 45,000$ cfs]), especially in near-shore locations for species like tamarisk, seep-willow, and arrow-weed.
3. Whether HFEs have been a factor in the recent expansion of riparian vegetation is unknown and will require careful, real time monitoring of vegetation following HFEs or retrospective analyses examining the age structure of encroaching vegetation. The seasonal timing of HFEs also warrants further study as they could preferentially shift the structure and composition of riparian vegetation.
4. In contrast to observed vegetation increases, 9.4 percent of the rematches in 2010–2012 show no apparent change, and <2 percent of the views show a decrease in woody riparian vegetation cover and density. Under the current flow regime, some narrow canyon settings are likely to remain free of persistent riparian vegetation.
5. Some of the increase in riparian vegetation results from continued spread and growth of tamarisk, but an important component of the increase includes the establishment of native woody riparian species, including old high-water line species, such as catclaw acacia, honey mesquite, and desert broom, in the new high-water zone or below the stage of the 1983 flood (2,747 cms [$\sim 97,000$ cfs]).
6. In addition to the natural establishment of riparian vegetation in the new high-water zone, nonnative species like tamarisk and Russian olive have been removed and native vegetation planted as part of experiments or restoration efforts in Marble and Grand Canyons. Artificial manipulation of vegetation should be tracked, actions and locations clearly documented, and the information easily accessible, so that cause-and-effect relationships between flow management and vegetation response can be assessed as accurately as possible.
7. Disconnection of the old high-water assemblage from river flows has left species, like honey mesquite, vulnerable to drought stress, and recent evidence suggests that

vegetated cover has declined during the period of early 21st century drought, beginning in the early 1990s. The work of Webb (1996) suggests species like catclaw acacia may be less affected. Some stands may be buffered against drought by factors such as aspect and local ground-water sources.

8. The effects of the recently introduced tamarisk leaf beetle on long-term structure and composition of riparian assemblages in Glen, Marble, and Grand Canyons remain uncertain.

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