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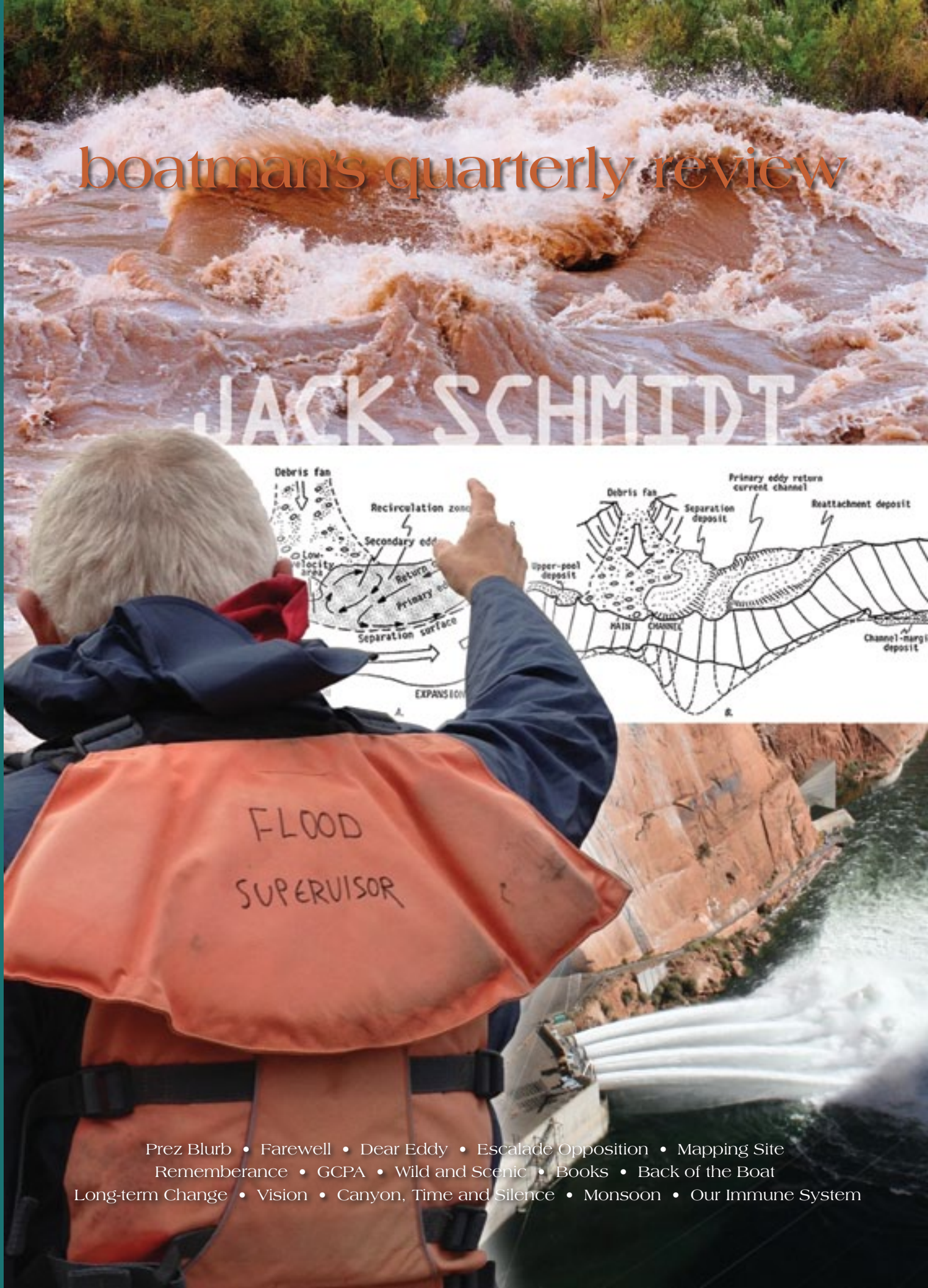

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Long-term Change Along The Colorado River In Grand Canyon National Park (1889–2011)

The Colorado River and its riverine resources have undergone profound changes since completion of Glen Canyon Dam in 1963, as every river runner with any history in Grand Canyon will attest. Long-term monitoring data are difficult to obtain for high-value resource areas (Webb et al. 2009), particularly in remote parts of national parks, yet these data are important to determining appropriate actions for restoration of resources and (or) potential modifications of flow releases on regulated rivers. The river corridor through the bottom of Grand Canyon creates a challenging environment for change-detection monitoring techniques (Belnap et al. 2008).

One long-used method for evaluating change uses ground-based repeat photography to match historical images of landscapes (Webb et al. 2010). The Brown-Stanton and Stanton river expeditions of 1889 and 1890 had the goal of photo-documenting a proposed railroad route through the canyons of the Colorado River, including Grand Canyon. The expedition had a professional photographer, Franklin A. Nims, who used a large-format camera to take all the 1889 images and a few in the winter of 1890 before injuring himself; after Nims was evacuated at Ryder Canyon, Robert Brewster Stanton took over the photographic duties and created the lion's share of the images of Grand Canyon. These expeditions produced a total of 452 large-format images of Grand Canyon that are preserved at the National Archives in College Park, Maryland, with photograph albums stored elsewhere. Another 60 images created by Nims are available for Cataract Canyon and its approaches in Canyonlands (Webb et al. 2004). These images are unsurpassed in the southwestern United States as a single collection taken over a short time period that documents one resource, because most photo collections span a considerable geographic area over a much longer time period.

Although some of the Stanton photographs were matched in the 1970s (Turner and Karpiscak 1990), most were matched from December 1989 through March 1993 using medium- and large-format cameras. Interpretations of changes apparent in comparisons of originals and matches were published in several places, notably in Webb (1996). This unique set of images documented a variety of geomorphic and ecologic changes along the corridor of the Colorado River, including occurrence of debris flows that altered rapids, changes in riparian vegetation along the river corridor, effects of feral burro grazing on desert vegetation, the extreme longevity of certain desert shrubs, and the influence of warming winter low temperatures on populations of frost-sensitive species (Webb and Bowers 1993, Bowers et al. 1995, Webb 1996).

In 2010 and 2011, we repeated those matches using several of the same cameras used in 1989–1993 about 120 years after the originals (Webb et al. 2011). These new images document changes in upland and riparian ecosystems along the river corridor, including change in the desert plant assemblages that are unrelated to dam operations. Preliminary analyses suggest that some of the changes documented from 1889–1890 to 1989–1993 are continuing, showing the response times of these ecosystems to climate change, flow regulation and changes in flow management.

Changes in Desert Vegetation

Repeat photography of sites with hot-desert vegetation shows that the framework of the plant community is anchored by long-lived species such as Mormon tea (*Ephedra torreyana* and *E. nevadensis*) and creosotebush (*Larrea tridentata*). These sites are extremely stable, often showing little or no change after 120 years (figure 1). Many species, notably creosotebush, Mormon tea, catclaw (*Acacia greggii*), mesquite (*Prosopis glandulosa*), and blackbrush (*Coleogyne ramosissima*), have individuals that live longer than a century (Webb 1996). With the recent work, we now know that Mormon tea and creosotebush have low rates of mortality even after 120 years. The 1990s matches showed that species-specific mortality rates (percentage of individuals that die per century) were 18% for Mormon tea and 7% for creosotebush (Bowers et al. 1995). Initial results of the second matching effort suggest that, in fact, these mortality estimates are high and these species live longer than previously documented.

Recruitment has exceeded mortality for most species, resulting in a net increase in individual plants identifiable in most matches. Because of this, there are more desert shrubs and trees along the river corridor than were present when Stanton went through Grand Canyon in 1890. In addition, some species, especially creosotebush, had much larger individuals in the 1990s and 2010s (figure 1), reflecting a general increase in biomass documented in most of the views. We believe these changes are related to the late 20th century wet period, which occurred between about 1975 and 1995 (Hereford et al. 2006), and a longer growing season.

We expected that the early 21st century drought

(Hereford et al. 2006), the most severe in a century, would result in widespread mortality of long-lived species along the river corridor. Our preliminary observations suggest, however, that few individuals of these species died in the two decades between the first and second matches. The ongoing severe drought that began in 2001 will likely represent future climate due to predicted increasing temperatures (Seager et al. 2007), and our preliminary results suggest that mortality of long-lived species may not increase correspondingly.

Figure 1A—Prospect Canyon, mile 179.3, view up Prospect Canyon from river left. (27 February 1890). In addition to views upstream and downstream from what is now the left scout point at Lava Falls Rapid, Stanton took this image looking up Prospect Canyon. The dominant shrub is creosotebush, and many barrel cacti are visible. (R.B. Stanton 620, courtesy of the National Archives)

Figure 1B—Prospect Canyon, mile 179.3, view up Prospect Canyon from river left. (11 February 1990). A cairn was found at the site of this triple set of photographs, one of the few physical signs of the Stanton expedition left in Grand Canyon. A century later, most of the creosotebush present in 1890 persist. One or two of the barrel cacti are in the same locations of individuals in 1890 but are likely not persistent; the number of barrel cacti present 101 years later is much larger than in the original view. (R.H. Webb)

Figure 1C—Prospect Canyon, mile 179.3, view up Prospect Canyon from river left. (27 September 2010). There has been little apparent change in the numbers of creosotebush after an additional 20 years. One of the ocotillos appears to have died, or died back. After 120 years, the creosotebush have changed little in number but have clearly increased in stature, while the number of barrel cacti have increased significantly. (Bill Lemke, Stake 1510a)

The effects of the early 21st century drought, with its decreased winter precipitation, may be offset by normal or above-normal summer precipitation, which can be used by many (but not all) species that also occur in the Sonoran Desert.

Webb and Bowers (1993) and Webb (1996) proposed that a regional decrease in frequency of extreme freezes would lead to an increase in frost-sensitive species along the Colorado River. The number of barrel cacti (*Ferocactus eastwoodii*; figure 1), which are common in western Grand Canyon, increased by an average of sixfold between 1890 and the 1990s, a result attributed in part to decreased frost frequency (ref). Such increases have continued over the last 20 years (figure 1). Numbers of brittlebush (*Encelia farinosa*), another frost-sensitive species, increased substantially between 1890 and the 1990s, with this likely also attributable to a rise in low temperatures (Webb and Bowers 1993; figure 2). This short-lived species has had considerable mortality over the previous two decades; however, since recruitment has exceeded mortality, we observed an overall increase in individual plants and biomass on the desert slopes.

Changes in Biological Soil Crusts

Biological soil crusts are communities of cyanobacteria, mosses, and lichens that dominate the soil surfaces of most desert regions (Belnap and Lange 2003), including those in Grand Canyon. These organisms provide important ecosystem services, including surface stability; nutrients, especially nitrogen; and carbon to soils. Biological soil crusts are considered well-developed if they have a high number of lichens and mosses. Those

present in Stanton views are especially well-developed on limestone substrates and moderately well-developed on sandstone-derived soils. Soils derived from meta-

Figure 2A—Bass Camp, Mile 108.5, view upstream from river right. (17 February 1890). John Wesley Powell and his geologist, Clarence Dutton, had warned Stanton that he would not find a level place to serve as a switching yard. With a touch of sarcasm, Stanton called the place where he would have built such a yard "Dutton's Depot." After the crew lined Bass Rapid and stopped for lunch just below, Stanton climbed up about 300 feet above the river to make one last view of his proposed switching yard. The extensive foreground shows ten individuals of Mormon tea and a few spiny asters. A prickly pear appears at lower right. (R.B. Stanton 518, courtesy of the National Archives)

Figure 2B—Bass Camp, Mile 108.5, view upstream from river right. (20 February 1992). We first replicated this view in 1990, but returned two years later to replicate the view under conditions more similar to those in 1890. Unfortunately, the bright sunlight of 1992 caused considerably deeper shadows than those caused by cloudy conditions in 1890. Only three of the individuals of Mormon tea have died during the century; all were in the center of the 1890 view. In contrast, brittlebush, shown here with its silvery leaves and hemispheric shape, dominates the assemblage, with about ten individuals now appearing in the view. The prickly pear did not persist, and spiny aster no longer appears in the foreground. (Steve Tharnstrom)

Figure 2C—Bass Camp, Mile 108.5, view upstream from river right. (22 September 2010). Many of the same brittlebush individuals that were present in 1992 are still alive; two have died. Most of the Mormon tea that had persisted the preceding century are still alive, but several more have died, notably in the lower right foreground and in the center of the view. This turnover in Mormon tea is unusually high compared to most views in Grand Canyon. (Bill Lemke, Stake 1479)

morphic rock have a low cover of lichens and mosses, but are still dominated by cyanobacteria. Crusts with more moss and lichen species contribute greater nutrients and stability than those that mostly contain cyanobacteria.

Biological soil crusts have low resistance to compression by feet or hooves, but they are extremely resistant to drought. Our repeat photos show that where these communities are undisturbed by animals or humans, which is the case in most of the Stanton views, there is almost no detectable change in extent or appearance (Webb 1996, figure 3). Further analyses will be required to determine changes in biological soil crusts, if any, in undisturbed sites. In contrast, areas that overlook rapids or favorite visitation spots show a complete, or almost complete, loss of soil crusts to trampling (figure 4).

Changes in Rapids

In the century spanning the original and matched images, debris flows occurred in approximately 60% of the 160 tributary canyons documented by Stanton photographs (Griffiths et al. 2004). Webb (1996) reported changes and lack of changes to numerous rapids, and the matches from 2010–2011 yielded little new documentation on debris flows in Grand Canyon not known from other evidence, including direct observations, repeat photography, and analysis of aerial photographs. In the last 120 years, Lava Falls and Granite Rapids have had the most debris flows (six and five, respectively) and arguably have changed more than any others in Grand Canyon, and these rapids were large navigational hazards in Stanton's day (figure 4). Crystal Rapid, which

was greatly enlarged during a debris flow in 1966, represents the greatest change in navigation hazard. On the other hand, some rapids have not changed in over 120 years, including Hance and Horn Creek Rapids as well as several rapids in the Jewels (Webb 1996).

Figure 3A—Garnet Camp, Mile 114.2, view upstream from river right. (19 February 1890). The day began hard, with a portage around Waltenburg Rapid, then ended easily for the Stanton expedition. In the afternoon, the cloudy sky of morning turned to sunshine, and the rough whitewater turned into a mostly quiet reach between cliffs of schist and granite. At mile 114.2, the expedition stopped and Stanton climbed up the right bank to capture this upstream view. Stanton's view is not totally clear in the center foreground; few desert plants can be identified beyond a pygmy cedar (Peucephyllum schottii) at lower left, and a distinctive patch of biological soil crust appears above it on the left edge of the view. (Stanton 539, courtesy of the National Archives)

Figure 3B—Garnet Camp, Mile 114.2, view upstream from river right. (1 March 1993). The pygmy cedar at lower left is dead. But at the lower left, the dark black soil surface is a biological soil crust that is still in the same position and approximately the same size a century later. Careful examination of the edge nearest the camera indicates the crust has retreated a maximum of about 15 cm; the edge farthest from the camera is nearly unchanged. Cursory examination of its surface indicated the crust contains mosses and lichens, which is suggestive of an old, complex assemblage of organisms. (Steve Tharnstrom)

Figure 3C—Garnet Camp, Mile 114.2, view upstream from river right. (23 September 2010). The new camera position is slightly to the right, but the various geologic and botanical features are still readily identifiable. Many of the foreground plants have grown considerably in the intervening 17 years between photographs, including Mormon tea, sweetbush, wire lettuce, and grizzlybear pricklypear. The biological soil crust, on the other hand, has suffered from trampling, likely by bighorn sheep, although its outline is approximately the same after 17 years. (Bill Lemke, Stake 2544)

Figure 4A—Crystal Rapid, mile 98.2, view downstream from river right. (8 February 1890). Before 1966, Crystal Rapid was a benign, long riffle, especially in comparison with the rapids a short distance upstream and downstream. Had the Stanton expedition not lost a boat upstream in Horn Creek Rapid, Stanton likely would have decided to run this rapid. Instead, the crew portaged their belongings and lined their boats on the right side. Immediately upon arriving here, Stanton did what many modern river runners do: he walked up to the scout point on the debris-flow terrace overlooking the rapid and took this photograph. His view shows biological soil crusts on the fine-grained soil between boulders and clumps of perennial grasses, five individuals of Mormon tea, a barren debris fan, and a long and wide riffle with no island downstream. (Stanton 248, courtesy of the National Archives)

Figure 4B—Crystal Rapid, mile 98.2, view downstream from river right. (1 February 1990). Stanton's view and its replicate illustrate a number of aspects of environmental change in the past century of Grand Canyon history. The change in the rapid, now one of the biggest on the Colorado River, was caused by a debris flow on December 6, 1966. An island, known to river runners as the Rock Garden, is prominent in the river downstream. Tamarisk, a non-native tree, chokes the once-barren mouth and debris fan of Crystal Creek, a perennial stream. Five individuals of Mormon tea persist on the edge of the debris-flow terrace, which likely is more than 10,000 years old. More subtle changes have occurred in the foreground, where biological soil crusts, which would have been very stable on this ancient debris-flow terrace, have been trampled by river runners intent on scouting Crystal Rapid. This impact has removed about three inches of soil from this site. (Ralph Hopkins)

Figure 4C—Crystal Rapid, mile 98.2, view downstream from river right. (22 September 2010). The riparian vegetation continues to increase, although native species seem to be increasing more in near-shore locations than the non-native tamarisk, which are increasing in size and stature. The five Mormon tea individuals, which were present 120 years ago, remain on the terrace edge. (Bill Lemke, Stake 1471)

No one with extensive Grand Canyon experience doubts that sand bars and campsites have decreased in size in Grand Canyon. Webb (1996) showed that decreases in sand bar size generally were greatest towards Glen Canyon Dam. Now, sand bars have decreased throughout Grand Canyon, particularly those used as campsites at higher flows (greater than 20,000 CFS). A large contributing factor is the increase in riparian vegetation within the last two decades, which has claimed large areas of once open sand that was available for use by river runners (figure 5). Surprisingly, the recent culprits generally are native species, such as arrowweed (*Pluchea sericea*) and seepwillow (*Baccharis salicifolia*), not non-native tamarisk (T*amarix ramosissima, T. chinensis*, and their hybrids; Friedman et al. 2005). Camelthorn (*Alhagi maurorum*), a rather nasty non-native species, contributes to the reduction in open sand bars downstream from the Little Colorado River.

Changes in Riparian Vegetation

Perhaps the greatest change documented in the 2010s matches, and certainly the most significant, is the increase in riparian vegetation along the Colorado River. Dam operations have reduced variability in annual flows, increasing discharge in formerly low-flow seasons and decreasing discharge during the early summer runoff period (Webb 1996). Reduced flow peaks, depleted of sediment, erode fine-grained bars, deposit coarser sand, and allow vegetation to encroach onto formerly active channel margins. In response to these hydrologic changes, there has been a transformative change in the distribution, abundance, and composition of riparian vegetation in Grand Canyon over the past 120 years. These changes are variable both in space and over time, ranging from imperceptible at some camera stations to striking state transitions at others; for example, some formerly bare channel bars and backwaters have been transformed into densely vegetated riverine marshes (figure 5).

Less striking but related changes in riparian vegetation involve the structural simplification and mortality of mesquite and net-leaf hackberry (*Celtis reticulata*), which once dominated the old high-water zone (occurring at about the 100,000 CFS stage). Before flow regulation, riparian vegetation in the area below the old high-water zone was scoured during the annual flood; the Stanton photographs generally show this part of the bank to be devoid of riparian vegetation. After construction and operation of Glen Canyon Dam, riparian vegetation established between the old and what became known as the new high-water zone (at about the 30,000 CFS stage). Between 1963, when the dam was completed, and the late 1970s, riparian vegetation—

Figure 5A—55-Mile Marsh, mile 55.8, view upstream from river left. (18 January 1890). This upstream view of the Colorado River from river left shows a mostly barren hillslope of colluvium derived from nearby cliffs of Muav Limestone (right side). A few Mormon tea appear in the foreground as well as one brittlebush, likely blurred in the wind because the exposure time was long; Stanton's camera had no shutter. The left side of this image shows what would become known as 55-Mile Marsh, but at this time, the site is barren sand with a few exposed boulders. One of the many backwaters once present in this wide, low-gradient reach appears at left center, and mesquite lines the old high-water line in the shadows. (Stanton 362, courtesy of the National Archives)

Figure 5B—55-Mile Marsh, mile 55.8, view upstream from river left. (5 February 1991). A century later, the vegetation in 55-Mile Marsh includes non-native tamarisk, along with the mesquite, catclaw, and common reed; other lower stature riparian species are undoubtedly present. This marsh is recovering from the high-water years of the mid-1980s, which removed much of the once thriving riparian ecosystem here and deposited considerable coarse sand in its place. Mesquite along the old high-water line at left center remains alive but has died back. The two Mormon tea individuals that were present in the foreground of the 1890 view are still alive 101 years later, but the original brittlebush is dead and a new one is closer to the camera station. (Ted Melis)

Figure 5C—55-Mile Marsh, mile 55.8, view upstream from river left. (19 September 2010). The density of the marsh vegetation has increased, especially the common reed that lines the shoreline, in part because discharges in the intervening 19 years have mostly been low with only brief flood releases. Unlike many reaches, the mesquite on the right bank appear to be alive despite flow regulation, which has negatively impacted the old high-water zone through most of Grand Canyon. Both Mormon tea individuals persist, although the one at front center is smaller; the brittlebush new in 1991 has died but three new plants appear in the view. (John Mortimer, Stake 2313a)

mostly non-native tamarisk—became established in this part of the bank (Turner and Karpiscak, 1980), but much of this post-dam riparian vegetation was scoured and the bars re-worked by high flows between 1983 and 1986, leaving banks somewhat barren looking in the first Stanton matches between 1989 and 1993 (Webb, 1996; figure 5).

Mesquite now occurs mostly well above the new riparian zone, although new individuals have become locally established closer to the channel. Net-leaf hackberry, less common, is becoming established lower on the once-barren channel margins. Whereas non-native species like camelthorn, Bermuda grass (*Cynodon dactylon*), and tamarisk comprise much of the novel assemblages of the new riparian zone, a diverse array of native woody riparian and herbaceous wetland species contribute to the mixture. The more common native species include coyote willow (*Salix exigua*), arrowweed, seepwillow, cattails (*Typha sp.*), common reed (*Phragmites australis*), horsetails (*Equisetum sp.*), and sedges (*Carex sp.*). Goodding willow (*Salix gooddingii*) is restricted locally to certain sites.

Transformative changes observed in riparian vegetation in the Grand Canyon are readily attributed to reductions in flood discharges and sediment load by operations of Glen Canyon Dam. Between 1890 and the 1990s, encroachment of woody riparian vegetation below the old high-water zone—primarily non-native

tamarisk—was expected because of trends observed elsewhere in the region. From the 1990s to the 2010s, more native species have become established in this new, post-dam riparian zone. One important hydrologic change is the three short-duration prescribed dam releases with peak discharges of 40,000–48,000 CFS within the last 16 years (1996, 2004, and 2008); these so-called habitat/beach-building floods were released in the winter-spring seasons when viable seeds of some native species, but not tamarisk, were available.

The spatially rich collection of historical photos from the Stanton expedition, along with precise matches in the early 1990s and 2010s, indicate the need for a more nuanced view of riparian vegetation change along the Colorado River, replacing the simple view of a rather uniform invasion of non-native species. Encroachment of vegetation over the past two decades onto depositional surfaces that were unvegetated in the early 1990s suggests that there are a range of hydrogeomorphic environments that have responded, and may continue to respond, to subtle changes in flow management in the post-dam period. Despite relatively large dam releases, within the post-dam perspective of flood control, colonization of low-stage habitat continues, creating a much more structurally and compositionally diverse riparian assemblage than was present in the 1990s. This is consistent with a growing body of evidence that measurable shifts in riparian vegetation accompany modest climate-related shifts in flow regime for rivers across the Colorado Plateau that are less intensely regulated than the Colorado River (Allred and Schmidt 1999, Birkeland 2002).

Conclusions

Repeat photography in Grand Canyon documents long-term change caused by a variety of processes, ranging from climate change to visitor impacts and the influence of Glen Canyon Dam. Upslope from channel margins under the direct influence of the Colorado River, a framework of long-lived shrubs and small trees with lifespans exceeding 120 years survived the extreme early 21ST century drought. This desert zone is changing with the increase of frost-sensitive species, mostly cacti and brittlebush. The riparian zone continues to respond to changes brought about by operations of Glen Canyon Dam, including flood control, changes in seasonality of large dam releases, and diminished sediment supply. The net result in both desert and riparian ecosystems is an increase in apparent biomass on the landscape—Grand Canyon has never looked so green!

Robert H. Webb, Jayne Belnap, Michael L. Scott, Jonathan M. Friedman, and Todd C. Esque

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THANKS TO ALL YOU poets, photographers, writers, artists, and to all of you who send us stuff. Don't ever stop. Special thanks to the Walton Family Foundation, the Adopt-a-Boatman sponsors, "Circle of Friends" contributors, and immumerable GCRG members for their generous and much appreciated support of this publication.

Photo Match

Upper South Canyon beach—Bryan Stone (NPS River) relocated the photo location showing the trail that the Katie Lee group used in 1956 (back page of BQR, Volume 25:2, Summer 2012). Check out the amazing difference in vegetation and beach sand after 56 years!

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Photo by Greg Woodall.