GEOMORPHIC RESPONSE OF SANDBARS TO THE MARCH 2008 HIGH-FLOW EXPERIMENT ON THE COLORADO RIVER DOWNSTREAM FROM GLEN CANYON DAM

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ABSTRACT: The completion of Glen Canyon Dam in 1963 drastically altered the downstream flow regime and resulted in more than a 90 percent reduction of sand supply to the Colorado River in Grand Canyon National Park. Sandbars that were maintained by annual floods and a large sediment supply are now fewer in number and smaller in area and volume. Efforts to maintain sandbars in the current era of dam management utilize controlled floods timed to occur during brief periods of sediment enrichment that result from tributary floods. Repeat surveys of 22 sandbars made before and after controlled floods conducted in 1996, 2004, and 2008 document changes in sandbar volume; and repeat surveys at more than 100 sites document changes in sandbar elevation and morphology for the 2008 event. Each of the controlled floods resulted in sandbar deposition that was followed by erosion in the 6-month post-flood period. Erosion rates are positively correlated with post-flood dam release volumes and negatively correlated with post-flood tributary sediment supply volume. October 2008 sandbar volume was similar or larger than sandbar volume in February 1996, before the first of the three controlled floods. Deposition during the 2008 controlled flood was also associated with increases in the quantity of backwater habitat, which is used by native and non-native fish.

INTRODUCTION

Prior to completion of Glen Canyon Dam in 1963, sand accumulated on the bed of the river during much of the summer and fall (Howard and Dolan, 1981; Topping and others, 2000). Annual snowmelt-driven spring floods typically redistributed this sediment to form expansive sandbars (Schmidt and Graf, 1990; Webb, 1996). These sandbars are a unique feature of the predam landscape, provided substrate for riparian vegetation, created beaches for recreational use, shaped aquatic habitat for native fish, and deposited fluvial terraces which buried archeological sites (Howard and Dolan, 1981; Kearsley and others, 1994; Stevens and others, 1995). Completion of Glen Canyon dam in 1963 reduced the supply of sand to the Colorado River downstream from Lees Ferry, Arizona by more than 90 percent (Topping and others, 2000). In addition, dam-regulated flows that are constrained to the range of powerplant operations limit the area over which deposition can occur during the infrequent periods of increased tributary sand supply. Sandbars in the post-dam era are fewer in number (Schmidt and Graf, 1990), smaller in areal extent of exposed sand (Schmidt and others, 1999; Hazel and others, 1999; Wright and others, 2005), and are lower in elevation (Schmidt and others, 1995).

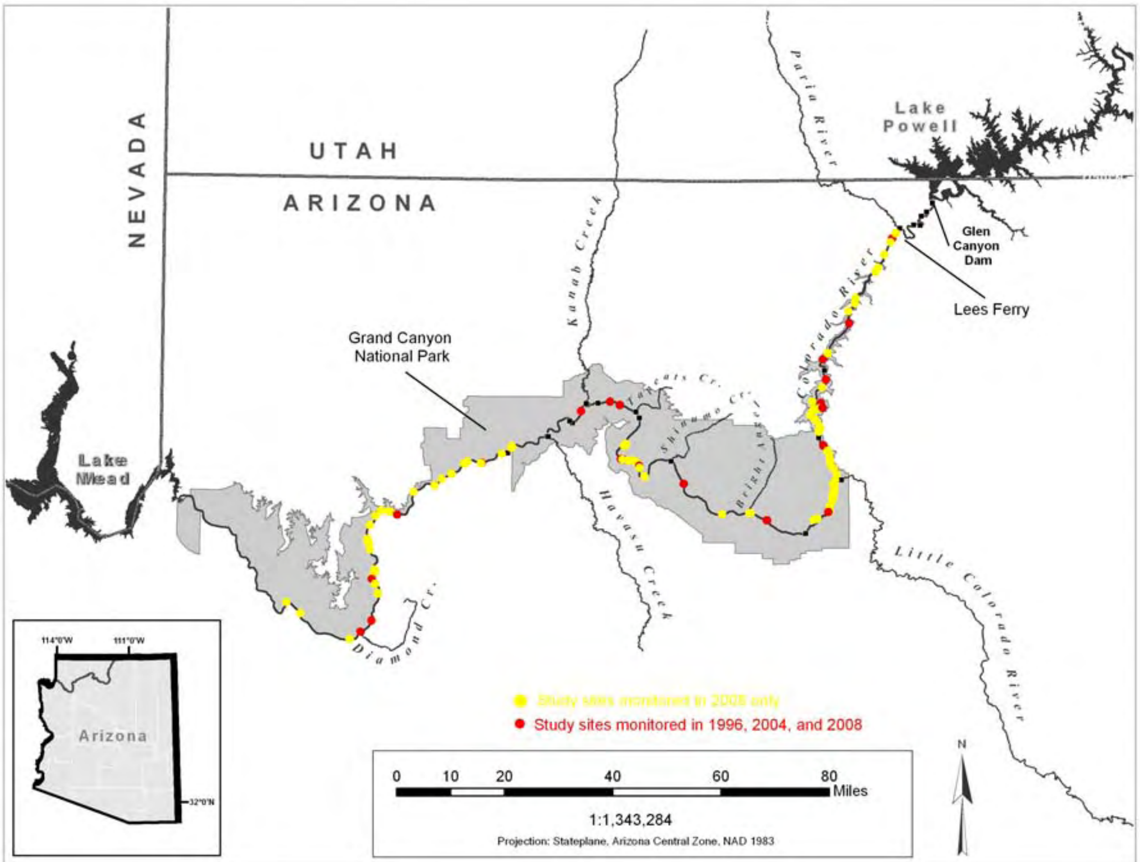

Figure 1 Study sites monitored in each controlled flood (red), and additional study sites monitored in 2008 (yellow). The Marble Canyon reach extends from Lees Ferry, Arizona to the Little Colorado River; the Grand Canyon reach extends from the Little Colorado River to Diamond Creek.

Since 1996, three controlled floods have been conducted in the Colorado River downstream from Glen Canyon Dam (Figure 1). In this context, a controlled flood is defined as a planned release from the dam that exceeds the peak capacity of the hydroelectric powerplant (~940 m^3/s) by at least 30 percent (U.S. Department of the Interior, 1995). In the management context, these events have also been termed “beach habitat-building flows” and “high-flow experiments.” The central purpose of these experiments has been to determine whether controlled floods can be used to increase and maintain the amount of sand present in sandbars that are located in eddies and along the channel margins and thereby increase the number and size of beaches used by campers and sustain certain aspects of aquatic habitat. During the first controlled flood, conducted in March and April 1996, water was released at a rate of about 1,274 m^3/s (as measured at Lees Ferry, Arizona) for 7 days (Figure 2). Although this event resulted in an increase in sandbar elevations, measurements made of sand-storage change in eddies (Andrews and others, 1999; Hazel and others, 1999; Schmidt and others, 1999), measurements of sand flux (Topping and others, 1999; Rubin and others, 2002); and sand budgets (Schmidt, 1999; Hazel and others, 2006) indicated net erosion of sand from low-elevation (that is, below the stage associated with a discharge of approximately 227 m^3/s) parts of eddies and the channel. The second controlled flood, with a shorter duration of 2.5 days and a slightly lower peak magnitude (1,187 m^3/s at Lees Ferry), was conducted in November 2004 following tributary sediment input events from the Paria River (located 25 kilometers below the dam). The purpose of the 2004 controlled flood was to test whether it was possible to increase sandbar size without causing net erosion from eddies and the channel. Measurements of sand-storage change and sand flux showed that net deposition did occur in the upstream portion of Mable Canyon (from Lees Ferry to 69 km downstream of Lees Ferry) where pre-flood sediment enrichment was greatest (Topping and others, 2006). Downstream from this point, where sand enrichment was less, there was less deposition.

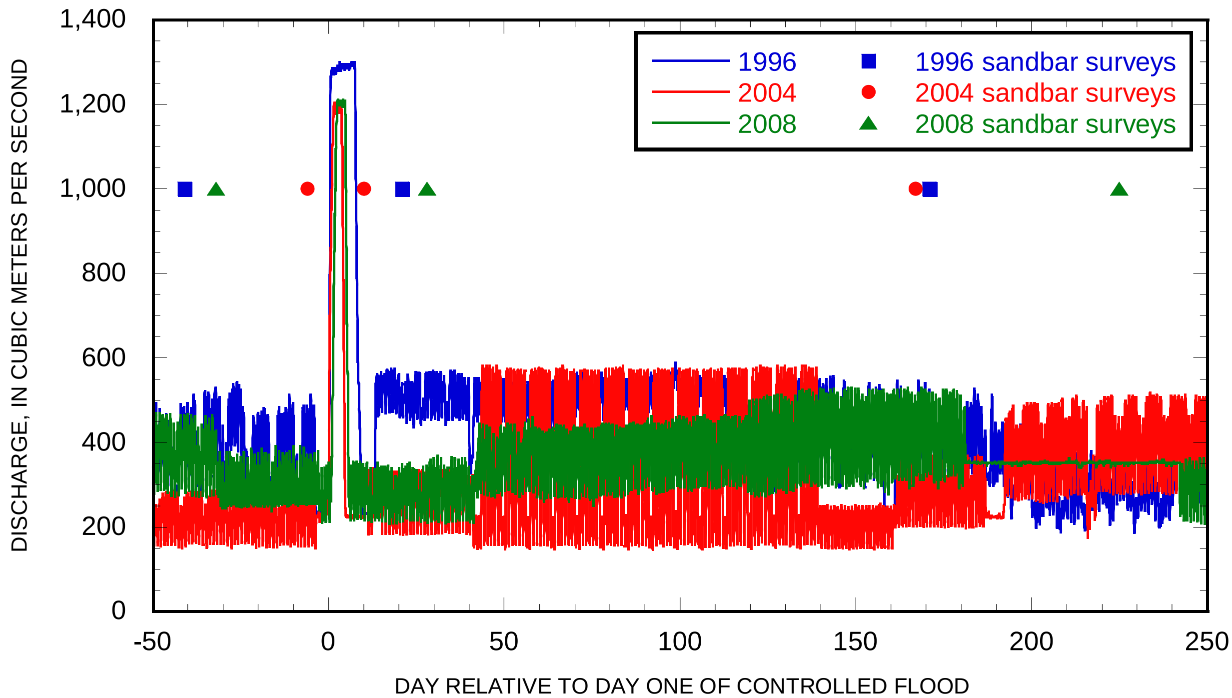

Figure 2 Discharge for the Colorado River at Lees Ferry, Arizona (USGS Station 09380000) for the 50 days preceding and the 250 days following each of the controlled floods. The dates of the pre-flood, post-flood and 6-month post-flood sandbar surveys are also shown.

Tributary sediment inputs in 2006 and 2007 resulted in sand accumulation in all river segments between Lees Ferry and Diamond Creek. The March 2008 high-flow experiment (HFE) was conducted to determine whether a controlled flood conducted under these conditions of greater sand supply would result in net sandbar deposition over a greater portion of the river corridor in Marble Canyon and Grand Canyon. The average discharge of 1203 m^3/s during the 2008 HFE was about six percent lower than the average discharge during the 1996 controlled flood, but similar in magnitude and identical in duration to the 2004 controlled flood (Figure 2). Inflow from the Little Colorado River during the 2008 HFE increased the average magnitude of the event to 1,248 m^3/s downstream from the confluence, 49 m^3/s less than the average flow during the 1996 controlled flood for that segment of the river.

This paper reports results associated with the 2008 HFE and subsequent dam operations with respect to changes in sandbar size and extent and changes in associated backwater aquatic habitat. Sandbar deposition and post-controlled flood sandbar erosion rates for 2008 are compared with observations from the 1996 and 2004 controlled floods. These findings summarize results reported by Hazel and others (2010) and Grams and others (2010).

METHODS

The 2008 controlled flood was monitored by repeat topographic and bathymetric surveys of selected study sites that were analyzed to determine changes in sand storage volume and changes in backwater habitat volume. A total of 108 sites were surveyed four times in 2008. Surveys at 41 sites included measurements of sandbar topography and channel bathymetry, while surveys at the remaining 67 sites consisted only of sandbar topography. Sandbar topography was surveyed by electronic total station and bathymetry was surveyed by multibeam sonar (Hazel and others, 2010).

Comparison between the three controlled floods was only possible for the subset of sites that were surveyed before and after the previous controlled floods. There were 7 sites in Marble Canyon that were surveyed before, immediately after, and six months after all controlled floods; and 15 sites in Grand Canyon surveyed before, immediately after, and six months after the 1996 and 2008 controlled floods (Figure 1). The Marble Canyon reach extends from Lees Ferry 100 km downstream to the Little Colorado River confluence. The Grand Canyon reach extends from the Little Colorado River confluence 264 km downstream to Diamond Creek.

The volume of sand contained within study sites was calculated for the entire study site and for the portion of the study site above the stage of 227 m^3/s, referred to hereafter as the reference stage (Figure 3). This discharge was chosen as the reference stage because it is the discharge associated with the low end of normal hydroelectric powerplant operations. Total sand volume and sand volume above the reference stage were calculated between the topographic surface for that particular date and a predefined underlying minimum surface (Hazel and others, 2010). To allow comparison of study sites that are of different size, the sand volumes were normalized as ratio between the sand volume for a given measurement and the sand volume measured in February 1996. Erosion rates following each of the controlled floods were determined by summing the sandbar volume above reference stage by reach for the post-flood and 6-month post-flood surveys, calculating the difference in volume, and dividing that by the number of days between surveys. Post-flood erosion rates following each controlled flood were determined for 14 sites in Marble Canyon and 20 sites in Grand Canyon. For the study sites that were monitored only in 2008, average sandbar elevation was calculated as the average surface elevation above the 227 m^3/s stage for the region common to all 2008 surveys.

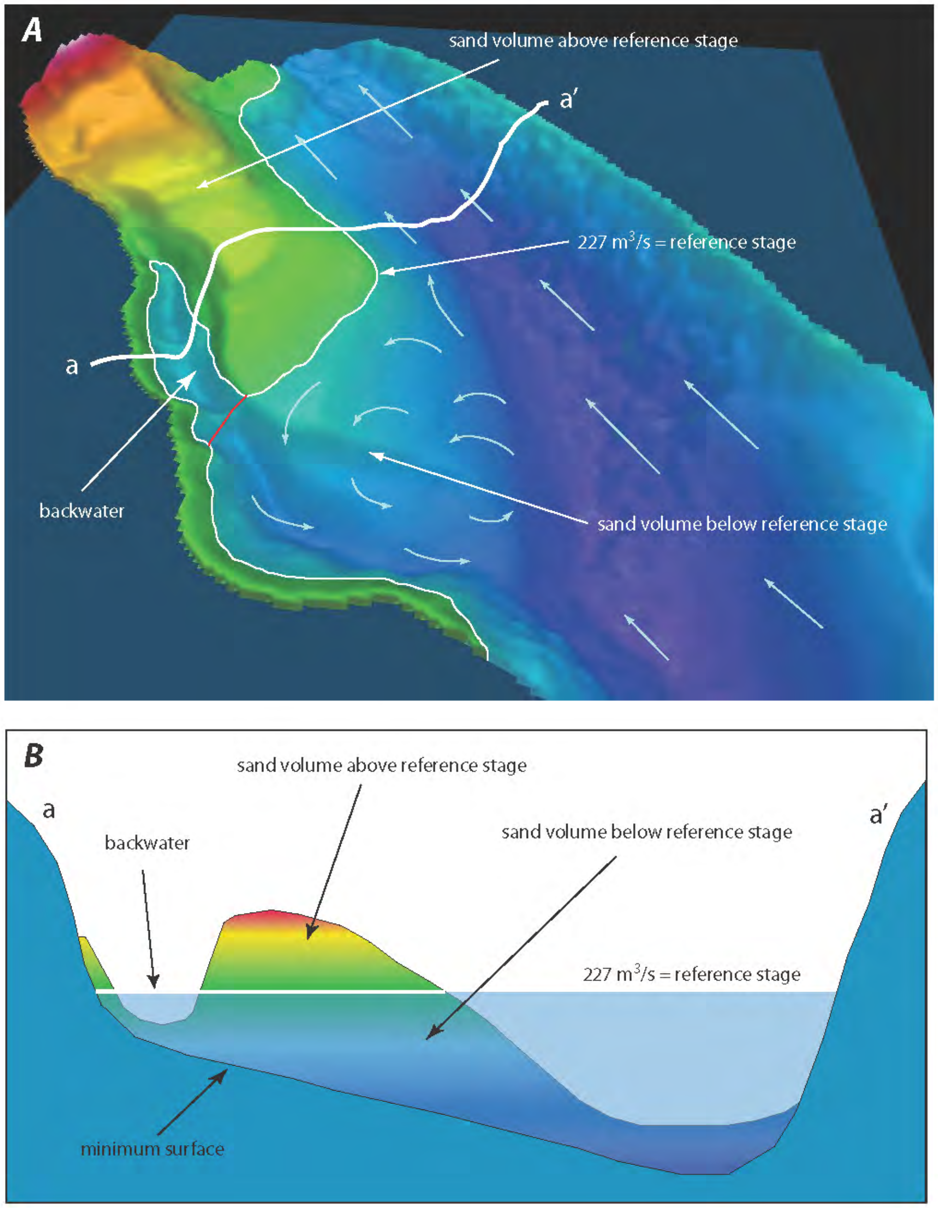

Figure 3 (A) Perspective view based on 1-m resolution digital elevation model of a typical eddy sandbar and adjacent channel showing pattern of recirculating flow, the reference stage of 227 m^3/s in white, and a typical backwater "closure" line in red. The portion of the sandbar above the reference stage and below the reference stage is illustrated. Mainstem flow is from bottom right to top left. (B) Cross-section view of eddy sandbar and channel illustrating the computational region for sand above reference stage and total sand (sand above reference stage plus sand below reference stage).

Many sandbars along the Colorado River in Marble Canyon and Grand Canyon have the form of a bar platform that projects from the bank out towards the channel and upstream into a zone of lateral flow recirculation, or eddy (Figure 3). During high flows, the bar platform is submerged and flow circulates upstream along the bank in a return-current channel between the bar platform and the shoreline. At lower flows, the emergent bar is often separated from the bank by a channel of low-velocity or stagnant water. This return-current channel provides low-velocity and often warm-water habitat to native fish, including Humpback Chub (*Gila cypha*) and is known to fishery biologists as backwater habitat (Valdez and others, 2001). We calculated the volume of backwater habitat for each survey at each study site for five discharges (227, 283, 340, 453, and 566 m^3/s). This was done by determining the shoreline for each discharge, delineating the backwater by adding a closure line to separate the backwater from the main channel (Figure 3), and calculating the volume of water that would be contained in the backwater depression below the water surface associated with that discharge. These methods are described in more detail by Grams and others (2010).

RESULTS

Each of the three controlled floods resulted in increases in sandbar volume above the 227 m^3/s reference stage in Marble Canyon and Grand Canyon (Figure 4). The median sandbar volume above reference stage following the 2008 controlled flood was similar to the median volume above reference stage following the 1996 and 2004 controlled floods in Marble Canyon and was also similar to the median volume above reference stage following the 1996 controlled flood in Grand Canyon. However, a greater number of the study sites had larger sandbars following the 2008 event relative to the 2004 event in both Marble Canyon and Grand Canyon, shown by the position of the upper quartile (Figure 4). The antecedent sandbar size, which is the total sand volume in the study sites preceding a controlled flood, was generally greater for the 2008 controlled flood than for the other controlled floods. Because of this, the increase in total sand volume during the 2008 event was smaller compared to the increases that occurred during the 1996 and 2004 events in Marble Canyon. Thus, for the 7 sites that were monitored before and after all events in Marble Canyon, sandbar volume above reference stage was similar following each of the controlled floods, despite differing antecedent total sand storage volumes. A similar comparison is not possible for Grand Canyon, because no sites were monitored in 2004.

There was a greater difference in behavior between the controlled floods for changes in total sand volume within the study sites. Although the measure of total sand volume includes the volume above the reference stage, the response in this zone is dominated by changes below that stage, where 80 percent or more of the sand occurs (Hazel and others, 2006). The 1996 controlled flood resulted in a large decrease in total sand volume for the study sites in Marble Canyon, as reported by Hazel and others (1999). While decreases in total sand volume also occurred at the Marble Canyon study sites during the 2004 and 2008 controlled floods, these decreases were much less than occurred in 1996 (Figure 4). Total sand volume for the study sites located in Grand Canyon increased slightly during both the 1996 and 2008 controlled floods. Thus, the deposition above the reference stage that occurred in 2008 was not systematically linked with erosion in eddies and the main-channel bed below the reference stage, as was observed during the 1996 controlled flood.

Sandbars eroded substantially following each of the three controlled floods (Figure 4). Following the 1996 and 2008 floods, erosion occurred relatively rapidly during summer fluctuating flows that peaked at about 560 m^3/s or greater (Figure 2). The 1 year period following the 2004 controlled flood did not include a sustained period of equally high flows and erosion was not documented until October 2006 (Figure 4).

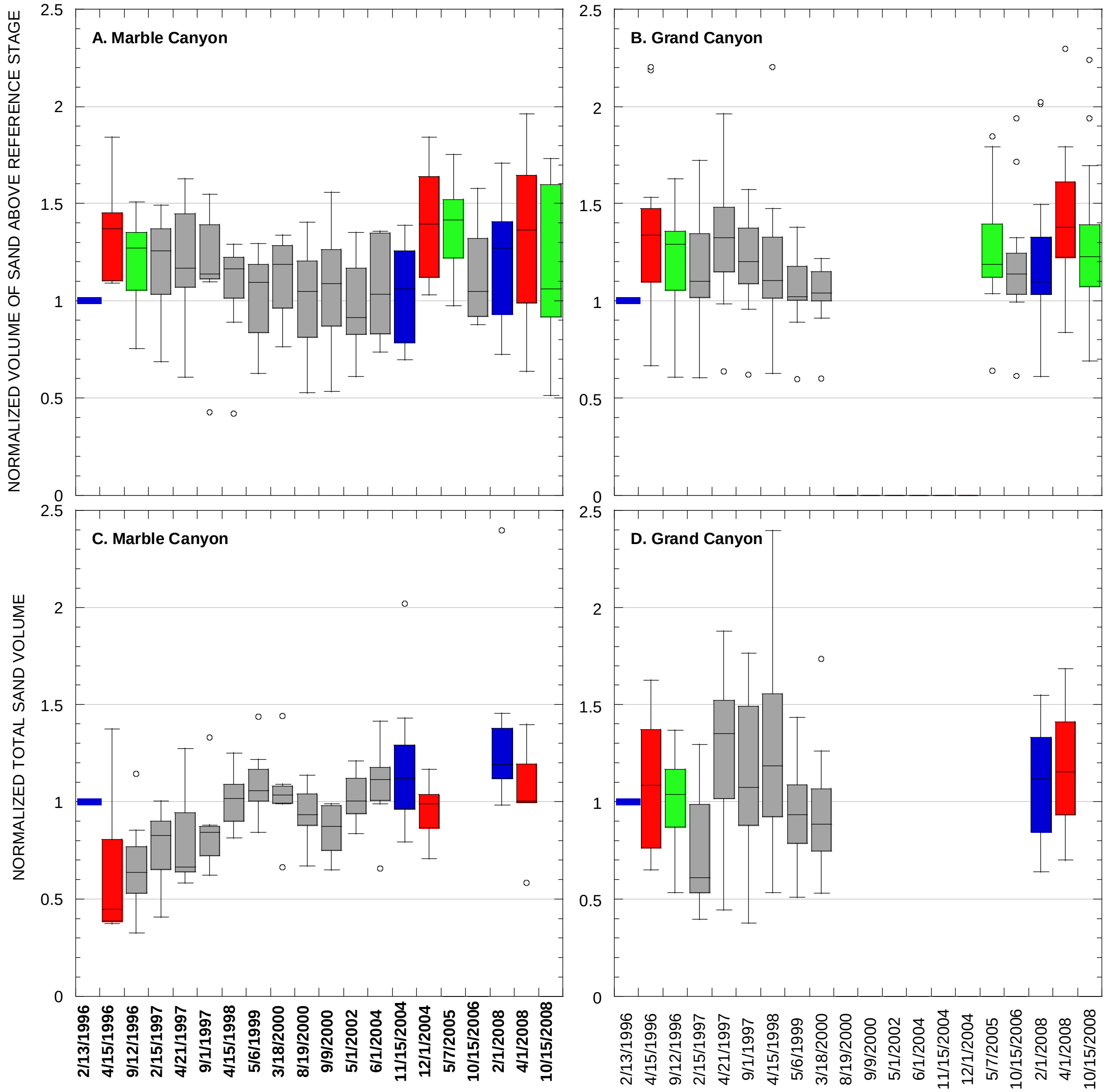

Figure 4 Sandbar volume normalized by the volume measured in February 1996, before the 1996 controlled flood. (A) Normalized sandbar volume above reference stage in Marble Canyon, (B) Normalized sandbar volume above reference stage in Grand Canyon, (C) Normalized total sandbar volume in Marble Canyon, and (D) Normalized total sandbar volume in Grand Canyon. In each plot, the shaded region shows the upper and lower quartiles, the line shows the median value, the whiskers show the range of all data within 1.5 times the distance between the bounds of the upper and lower quartiles. Outliers outside this range are shown with unique symbols. Because values are normalized to the February 1996 survey, all values for that date equal one (thick blue line). Pre-flood measurements are all shown in blue, post-flood measurements are all shown in red, 6-month post-flood measurements are all shown in green, measurements made between controlled floods are shown in gray.

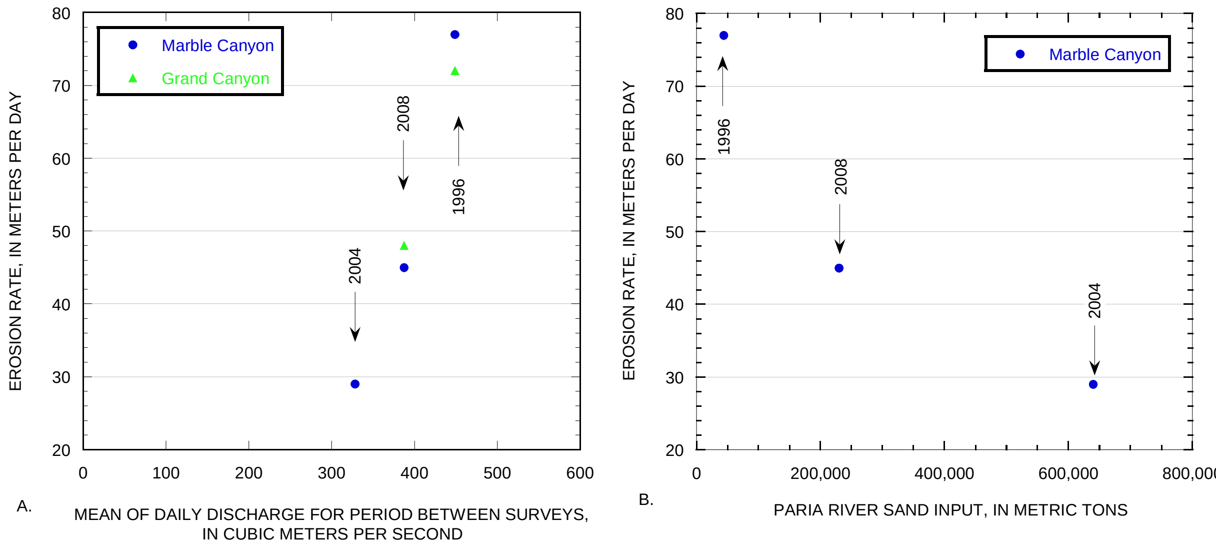

Figure 5 (A) Rate of sandbar erosion as a function of the mean of mean daily discharge for period between post-flood surveys and 6-month post-flood surveys for sites in Marble Canyon, Eastern Grand Canyon, and combined Central and Western Grand Canyon. Each year is associated with a single mean of daily discharge, as indicated. (B) Rate of sandbar erosion as a function of the total magnitude of Paria River sand inputs that occurred in the period between post-flood surveys.

Erosion rates may be affected by the relative magnitude of release volumes and by mainstem sediment concentrations, which could result in deposition in some parts of eddies at the same time as flood-formed deposits erode. Because both average dam releases and sediment supply varied among the three post-flood periods, it is not possible to decouple the relative influence of these factors. Erosion rates for the post-flood periods are, in fact, positively correlated with average dam releases and negatively correlated with Paria River sand inputs (Figure 5). The greater average dam releases that occurred following the 1996 controlled flood were associated with the highest average erosion rates among the study sites in Marble Canyon and Grand Canyon. The lower average dam releases that occurred following the 2004 controlled flood were associated with the lowest average sandbar erosion rates. Alternatively, the high erosion rates observed in 1996 were also associated with the post-flood period of least Paria River sand input. In 2004, when erosion rates were lowest, the Paria River supplied over 600,000 metric tons of sand in a six month period.

Sand deposition and scour during controlled floods alters the morphology of deposits within eddies. Where deposition on a reattachment bar is accompanied by scour in the eddy return-current channel, increases in backwater habitat area and volume may occur (Grams and others, 2010). This type of morphologic response occurred frequently enough among the 108 sites monitored before and after the 2008 controlled flood to cause increases in backwater area and volume (Figure 6). These changes increased the volume of available backwater habitat for all flows. However, because backwater habitat before the controlled flood was most abundant at low flows, there was a larger proportional increase in available habitat at high flows. As sandbars eroded between April and October 2008, backwater volume also decreased. Increases in backwater size are generally associated with sandbar deposition (Figure 7). There is not, however, a linear relation between the magnitude of sandbar deposition and increase in backwater volume. For some sites, deposition results in enlarged backwaters, while for other sites deposition may either not affect backwater size or may decrease backwater size. Similarly, decreases in sandbar elevation are generally associated with decreases in backwater volume, but not uniquely. There are several cases where backwater volume decreased when sandbars increased in size and where backwater volume increased as sandbars eroded.

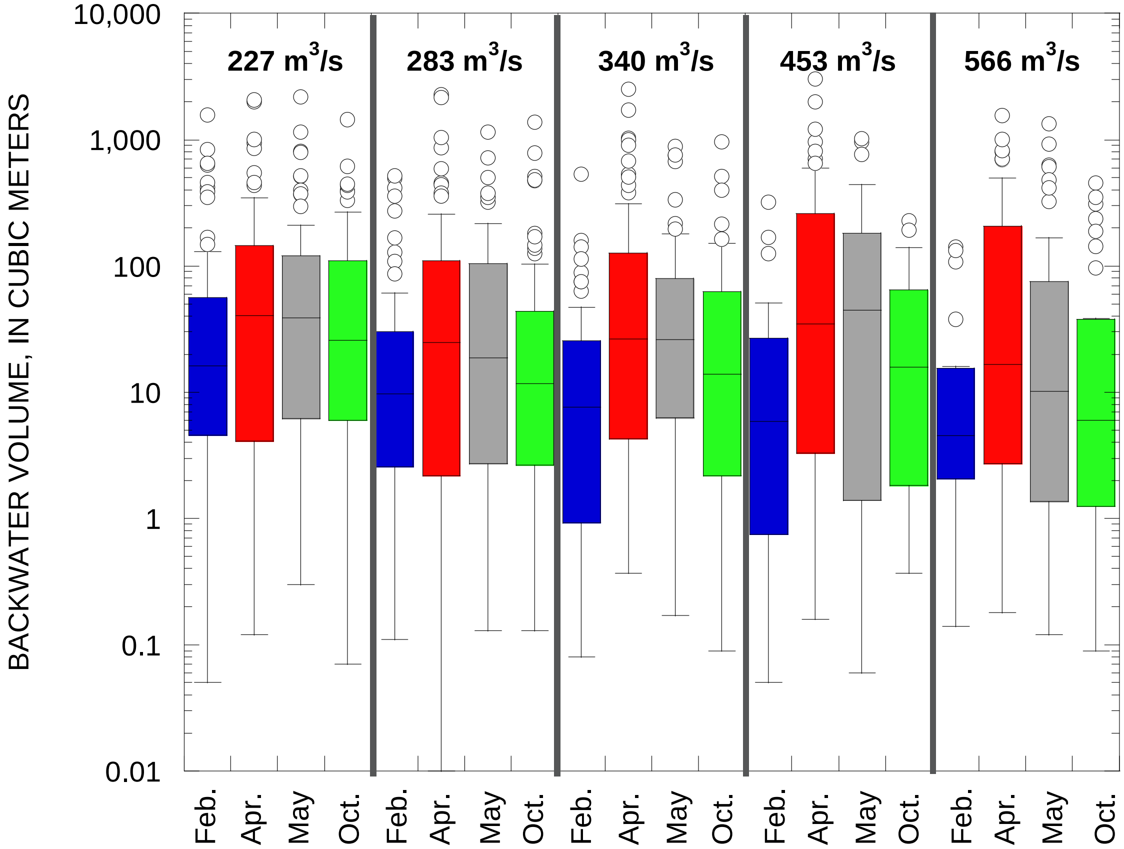

Figure 6 Volume of backwater habitat as a function of discharge for each of the four sandbar/backwater surveys made in 2008. The February (blue) survey shows conditions before the March 2008 controlled flood, the April survey (blue) shows conditions after the controlled flood, the May survey shows conditions two months after the controlled flood (gray), and the October survey (green) shows conditions six months after the controlled flood.

DISCUSSION AND CONCLUSIONS

Each of the three controlled floods resulted in sandbar deposition above the reference stage (the stage associated with a discharge of 227 m^3/s) at the monitored study sites. Sandbar size following a flood is likely determined by site characteristics, flood stage, flood duration, and sand concentration during the flood. Antecedent sandbar size and the magnitude of deposition during each event varied among the controlled floods. However, for the 7 sites monitored before and after all events in Marble Canyon and the 15 sites monitored before and after the 1996 and

2008 events in Grand Canyon, the post-flood sand volume above the reference stage was similar following each event. This suggests that water stage, which was essentially the same for each of the controlled floods, may play an important role in determining post-flood sandbar size, at least within the range of sand supply conditions that existed for these three controlled floods. The 1996 controlled flood resulted in a large net decrease in the total sand volume contained at the study sites in Marble Canyon, while the 2004 and 2008 controlled floods resulted in smaller decreases in total sand volume. Neither the 1996 nor the 2008 controlled floods resulted in decreases in the total sand volume at study sites in Grand Canyon. Thus, even under conditions of high sediment enrichment, such as existed in 2004 (Topping and others, 2006) and 2008, deposition above the reference stage was associated with some loss of sand below the reference stage at the sites in Marble Canyon. For these controlled floods that were conducted following tributary sediment inputs, the loss of total sand volume at the study sites in Marble Canyon approximately balanced the gains in total sand volume that occurred during periods of tributary supply, resulting in no net decrease in total sand volume at the study sites.

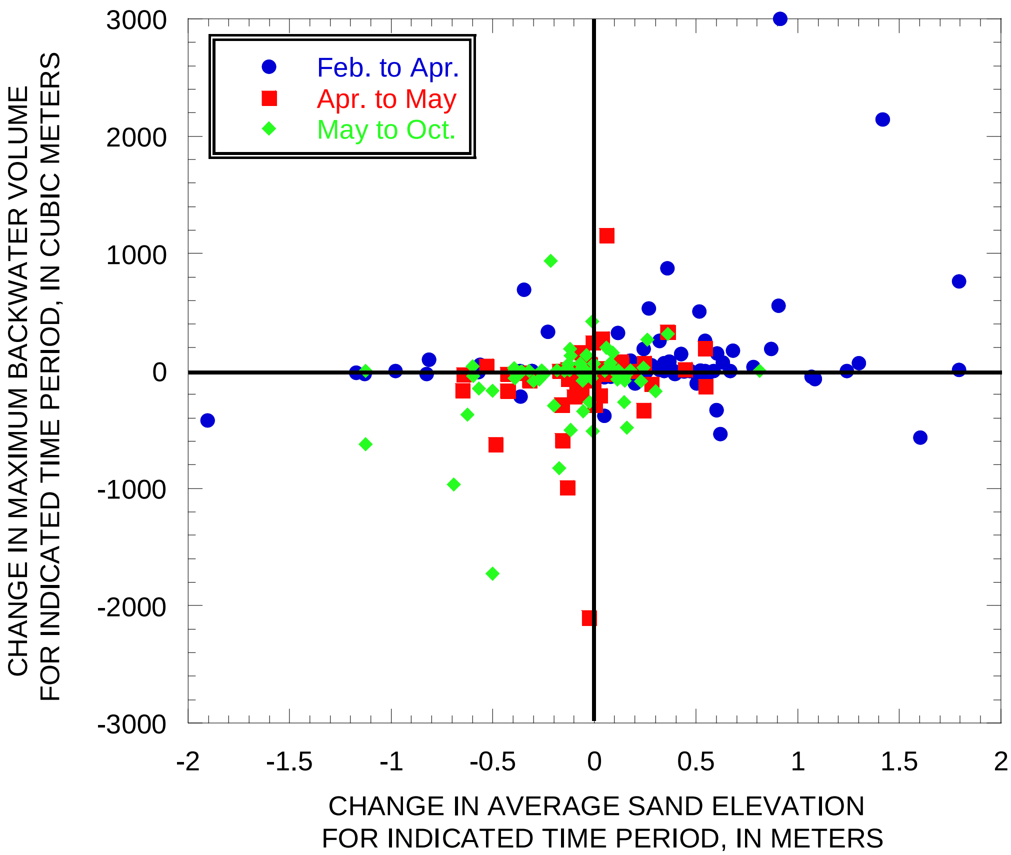

Figure 7 Change in maximum backwater volume plotted as a function of change in average sand elevation for the time periods between the 2008 sandbar/backwater surveys. Maximum backwater volume is the maximum volume across all discharges for the given measurement.

Deposition of sandbars during the 2008 controlled flood resulted in increases in the number and size of aquatic backwater habitats. Although increases in the quantity of backwater habitats are generally associated with increases in average sandbar elevation and decreases in the quantity of backwater habitat are generally associated with decreases in average sandbar elevation, there is not a direct linear relation. These results demonstrate that controlled floods result in sandbar deposition and increases in backwater habitat. However, the magnitude of habitat increase is not necessarily proportional to the magnitude of sandbar deposition.

Following each of the three controlled floods, sandbars eroded. In 2008, the median volume of sand above the reference stage at the study sites in Marble Canyon 6 months after the controlled flood was similar to the median volume above the reference stage before the controlled floods. However, in Grand Canyon, median sandbar volume above the reference stage was still greater 6 months after the controlled flood than it was prior to the event. The rate of sandbar erosion following the controlled floods varied among the events and was positively correlated with the magnitude of average dam releases and inversely related to the magnitude of Paria River sand inputs for Marble Canyon. Erosion rates were lowest following the 2004 controlled flood when average dam releases were low and Paria River sand inputs were high. Erosion rates were highest following the 1996 controlled flood when average dam releases were high and there was very little sand supplied by the Paria River.

The sandbar results presented here are based on 22 study sites that were monitored before and after each of the three controlled floods that have occurred since 1996. The degree to which these results are representative of the estimated hundreds of sandbars that occur in Marble and Grand canyons is uncertain. Schmidt and others (1999) reported that the sign and magnitude of deposition above the reference stage reported for these sandbar study sites was consistent with results based on mapping from aerial photographs over longer reaches. However, 80 percent or more of the sand in active storage is below the reference stage (Hazel and others, 2006). In some cases, changes in sand volume for this set of study sites has been shown to be consistent with reach-scale trends in sand storage (Schmidt, 1999; Hazel and others, 2006); while for other cases, changes in sand volume over short reaches has been shown to be inconsistent with reach-scale sediment budgets (Topping and others, 2006). It is likely that the sites are most representative when there are large system-wide perturbations, such as controlled floods or large tributary sediment inputs that are likely to result in similar responses over long river segments. The relation between sandbar response at these discrete study sites and reach-scale response is under continued investigation.

In summary, these results demonstrate that the 3 controlled floods resulted in repeated sandbar deposition at the sites monitored, that sandbar deposition is also associated with increases in backwater habitat, and that sandbars eroded substantially within 6 months after each of the controlled floods. Despite erosion, the median sandbar size at the monitored sites was similar or slightly larger in October 2008, 6 months after the third controlled flood than before the first controlled flood in February 1996. Whether the approach of using controlled floods and the sand supplied by tributaries to build and maintain sandbars is sustainable over decadal time scales remains uncertain. The outcome will depend on dam operations between controlled floods, which are largely determined by legal requirements for water delivery, and other factors that are difficult to predict such as river basin hydrology and tributary sediment production.

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