LONG-TERM MONITORING OF SANDBARS ON THE COLORADO RIVER IN GRAND CANYON USING REMOTE SENSING

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INTRODUCTION

Closure of Glen Canyon Dam in 1963 dramatically changed discharge and sediment supply to the downstream Colorado River in Marble and Grand Canyons. Magnitudes of seasonal flow variation have been suppressed, while daily fluctuations have increased because of hydropower generation. Lake Powell, the upstream reservoir, traps all sediment, leaving the Paria and Little Colorado Rivers as the main suppliers of fine sediment to the system below Glen Canyon Dam. The reduction in sediment supply, along with changes in discharge, have resulted in fine-sediment deficit (Topping et al., 2000), leading to a decrease in the size and number of alluvial sandbars (Schmidt and Graf, 1990; Schmidt et al., 2004). However, the understanding of these important spatial and temporal changes in sandbars located along the banks of the river have been limited to infrequent measurements mostly made by direct visitation and topographic surveying (Hazel et al., 2010).

Aerial photographs are the only data available from which it is possible to evaluate changes in alluvial deposits at a large number of sites and compare recent conditions with those that existed prior to the initiation of ground-based monitoring in the early 1990s. Previous studies have evaluated the effects of Glen Canyon Dam on sandbars by analysis of comprehensive maps of surficial geology that are based on seven sets of aerial imagery taken between 1935 and 1996 for selected reaches in the first 120 km downstream from Lees Ferry, Arizona (Figure 1). These studies showed that the area of exposed sand in eddy-deposition zones was less in the post-dam period than in the pre-dam period (Leschin and Schmidt, 1995; Schmidt et al., 1999b; Sondossi, 2001, Sondossi and Schmidt, 2001, Schmidt et al., 2004).

In this study, we extend these analyses to encompass a 74-year period by including maps of sand deposits visible in aerial imagery taken in 2002, 2005, and 2009 for the same reaches that were mapped in the earlier studies. Results are analyzed for two post-dam periods, based on the implementation of the first controlled flood in March 1996. The period from 1965 to March 1996 is the pre-controlled flood period and was dominated by flows that fluctuated up to the maximum capacity of the Glen Canyon Dam powerplant. Beginning in 1991, fluctuations were constrained such that maximum daily flows were typically less than 65 percent of powerplant capacity. Thus, the pre-controlled flood period also includes five years of restricted dam operations. This period also included unplanned spills from the reservoir in 1983, 1984, and 1986. We refer to the period from April 1996 to 2009 as the controlled-flood period. This period consisted entirely of restricted dam operations and included three controlled floods conducted as sandbar-building experiments. We show that the areal extent of exposed sand was greater in the images taken in the controlled-flood period than in the pre-controlled flood period. We also show that in the controlled-flood period, the area of exposed sand is negatively correlated with the elapsed time

since the most recent controlled flood.

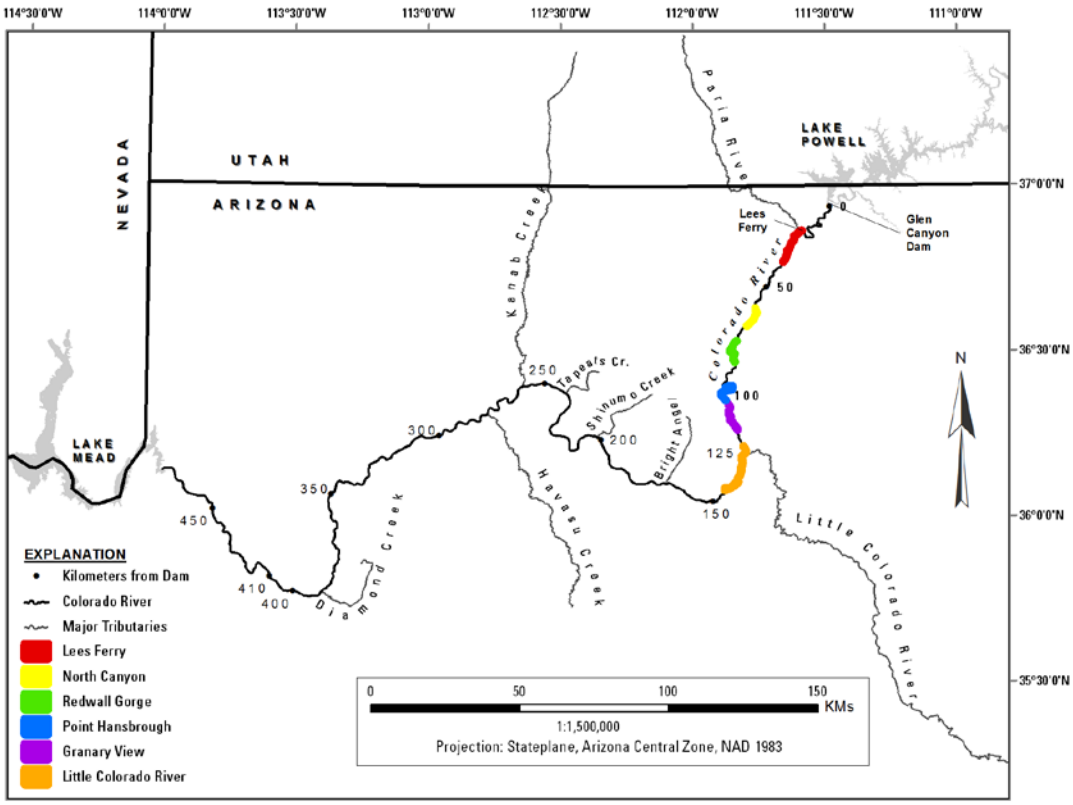

Figure 1 Location map of study area, showing Colorado River, major tributaries, and study reaches. The study reaches are informally named and range in length from 7.5 km to 20.3 km. The numbers show distance downstream from Glen Canyon Dam along the river centerline.

METHODS

We used high-resolution (25-centimeter pixel size) aerial imagery collected by fixed wing aircraft in May 2002, May 2005, and May 2009 to map the extent of exposed sand in each of the reaches examined by Schmidt et al. (2004). Each set of images was acquired during a steady dam release of approximately 227 m^3/s (8,000 ft^3/s), enabling a direct comparison of the area of deposits exposed above the water surface without introducing bias caused by difference in water surface elevation. Thus, we use the water surface elevation associated with 227 m^3/s as a reference elevation. The shoreline in each reach was determined by automated image classification of the water that was visually inspected for accuracy (Davis et al., 2012). We intersected the 227 m^3/s shoreline with the sand deposits mapped from the April 1996 images to create revised maps for the same sand deposits for 2002, 2005, and 2009 (Figure 2). Areas mapped as sand in 1996 and classified as water in the recent images were interpreted to have eroded. Conversely, areas that were below the water surface in 1996 and above the water surface in the recent images were interpreted to have aggraded. Eroded areas were subtracted from the 1996 maps and aggraded areas were added to produce the final maps of exposed sand deposits for 2002, 2005, and 2009.

We use the eddy-deposition zone (EDZ) accounting unit as defined by Schmidt et al. (2004) to track changes in sandbar area. The EDZ is the sum of all sand deposits that occur in an eddy that is downstream or immediately upstream from a channel constriction created by a debris fan (Figure 2). In this study, we report only on EDZs larger than 1000 m^2, consistent with the approach of Schmidt et al. (2004).

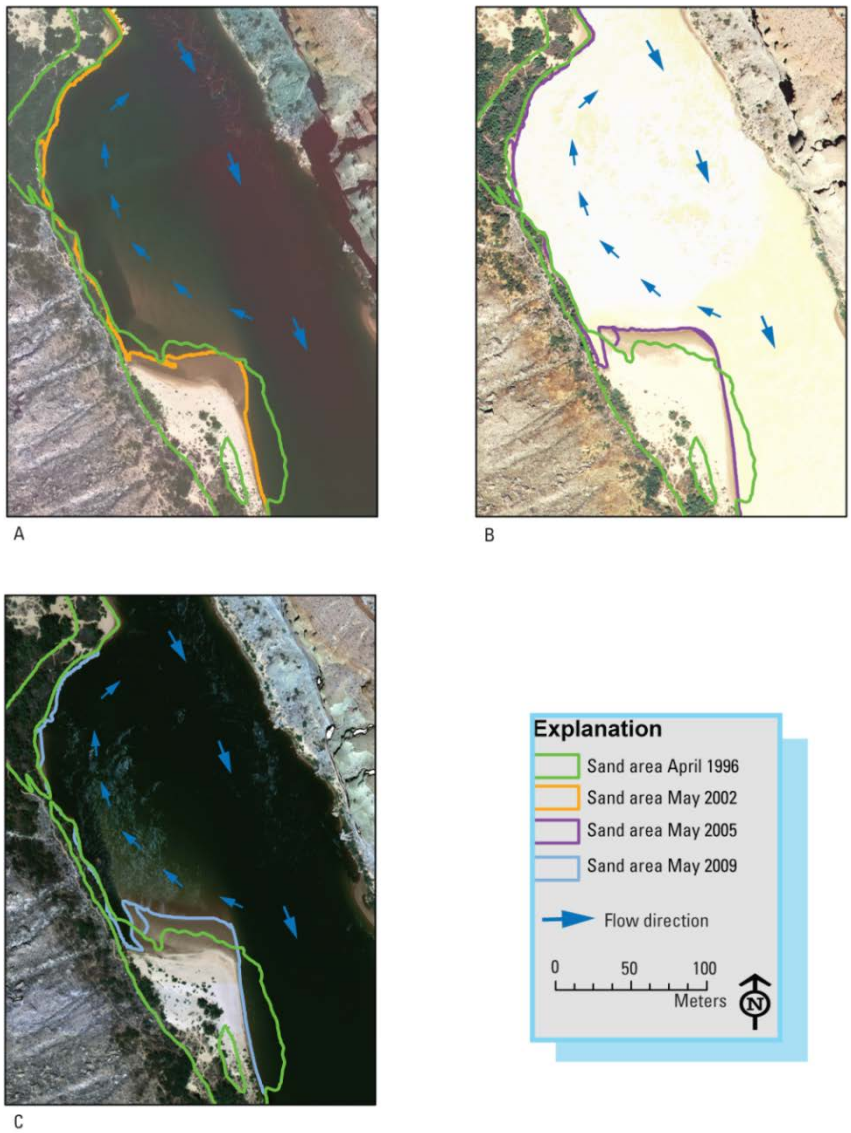

Figure 2 Aerial images at Saddle Canyon show comparisons of sand area mapped in April 1996 with sand area mapped in recent images. (A) Sand area in April 1996 and May 2002 on May 2002 image, (B) Sand area in April 1996 and May 2005 on May 2005 image, and (C) Sand area in April 1996 and May 2009 on May 2009 image. Blue arrows indicate flow direction. Debris fan constriction is in upper left area of images. Imagery from Grand Canyon Monitoring and Research Center archives.

Because the study reaches are of different lengths, ranging from 7.5 to 20.3 kilometers (km), we report the measurements of sand area as the total sand area within EDZs for each reach normalized by the reach length (m^2/km). Standard error was calculated for each reach by dividing the standard deviation of the area of exposed sand deposit per reach length by the square root of the number of sand deposits per reach length. Changes in exposed sand area greater than the standard error were considered significant. We also report on the eddy fill ratios, which are the ratio of exposed sand within each EDZ boundary to the area of the EDZ boundary. Thus, an eddy fill ratio of 1.0 would indicate the sandbar completely filled the eddy deposition zone. We compare eddy fill ratios from the 1935 images (the only set of pre-dam aerial photography that includes all reaches) with the average eddy fill ratio for the pre-controlled flood period and the average eddy fill ratio for the controlled flood period for each reach. We averaged the eddy fill ratio for each EDZ over the range of years of imagery common to all reaches, and then used the average value of the eddy fill ratios for all EDZs to determine the time period average. We chose these three time periods because they represent the pre-dam period of unregulated flows and two post-dam periods before and after controlled floods (Figure 3).

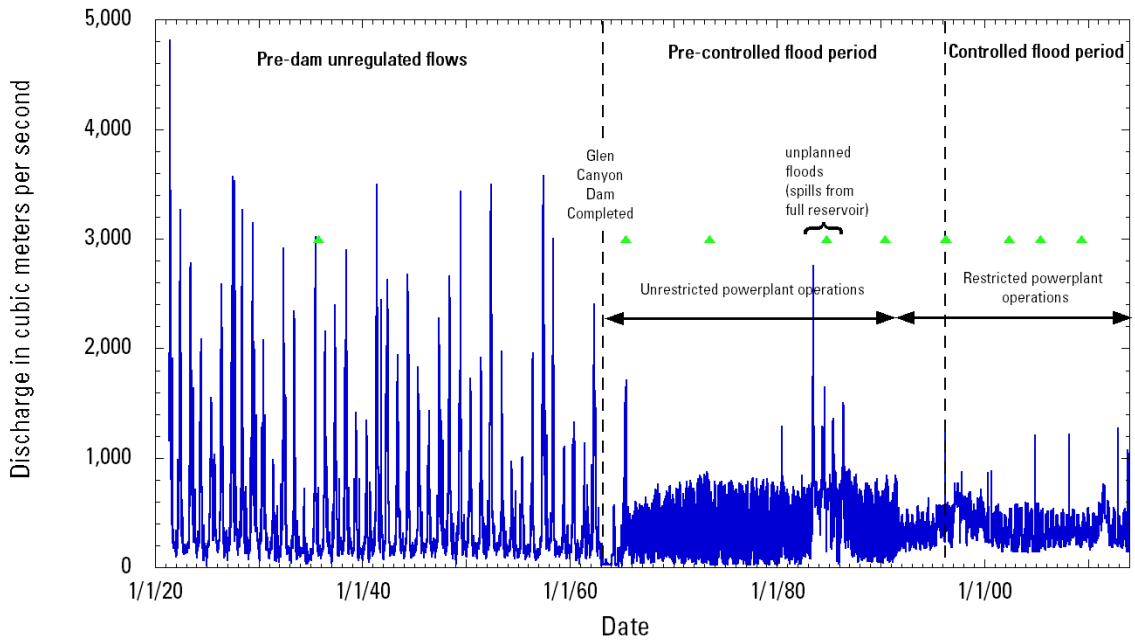

Figure 3 Discharge of the Colorado River at Lees Ferry, Arizona (USGS gage 09380000), 1922 to 2012. The pre-controlled flood period consists of unrestricted powerplant operations, restricted powerplant operations, and unplanned floods. The controlled-flood period consists of restricted powerplant operations and periodic controlled floods. Horizontal arrows show periods of unrestricted powerplant operations and restricted powerplant operations. Aerial imagery collection dates are marked with green triangles.

The first 26 years of the pre-controlled flood period consisted primarily of flows which fluctuated on a daily basis for hydroelectric power generation from daily low flows of about 140 m^3/s (5,000 ft^3/s) to daily high flows of about 850 m^3/s (30,000 ft^3/s). This period also included unplanned floods in 1983-86 that were spills from Lake Powell during years of large upper

Colorado River basin runoff. Beginning in 1991, the range of daily fluctuations was restricted such that daily low flows were about 200 m^3/s (7,000 ft^3/s) or higher and highs were 570 m^3/s (20,000 ft^3/s) or lower. The controlled-flood period consisted entirely of these restricted dam operations and included three dam releases above power-plant capacity (31,500 ft^3/s). Short-duration (less than 96 hour) controlled floods were released in April 1996, November 2004, and March 2008 to evaluate the use of dam releases for building sandbars (Webb et al., 1999; Melis, 2011; Schmidt and Grams, 2011).

We evaluated uncertainty by comparing the area of exposed sand we measured from the images to sand area measured by total station survey at 15 long-term monitoring sites for coincident dates in 2002, 2005, and 2009 (Hazel et al., 2010). To minimize the chance that deposits eroded or aggraded between comparisons, we only utilized total station surveys made within 2 weeks of aerial imagery collection. Analysis of the root-mean square error about the residuals indicates a 3,838 m^2 error between the sum of sand area from all 36 aerial photo measurements and the sum of total station measurements for all 15 sites, representing about 2 percent of the total sum of sand area (190,055 m^2) observed in all 15 EDZs as measured by total station (Figure 4). Error between the average of these 36 aerial photo measurements and the coincident total station surveys is 640 m^2, also about 2 percent of the average sand area (31,676 m^2) for the 15 sites.

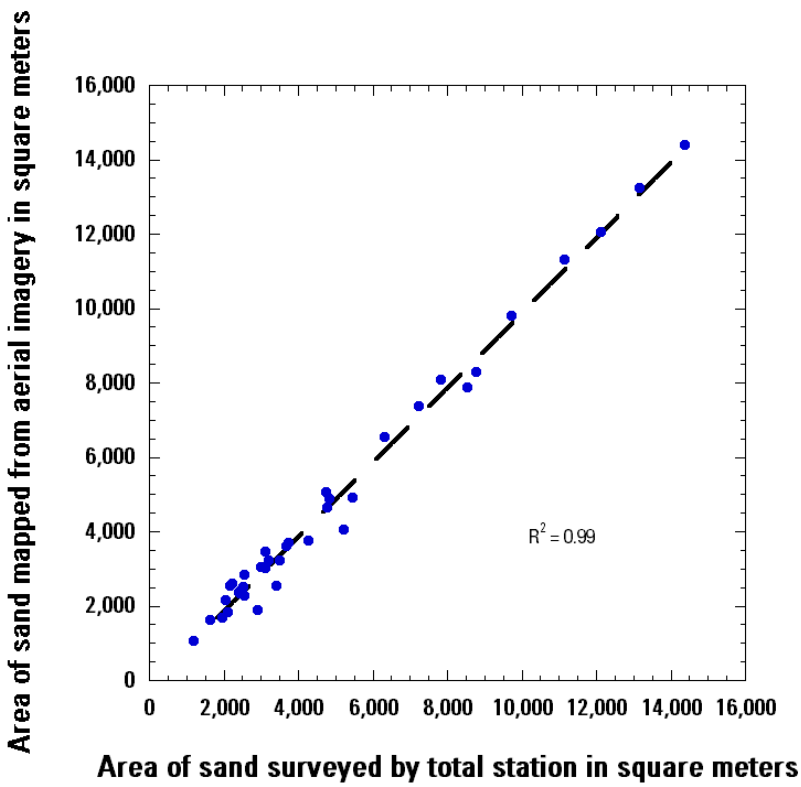

Figure 4 Comparison of change in sand area from aerial imagery to change in sand area measured by conventional total station survey of long-term monitoring sites. Line fit by least-squares regression shows a near perfect 1:1 correspondence between sand area surveyed by total station and sand area measured by analysis of aerial photographs.

RESULTS

In all reaches, sand area was less in 1965 than in 1935, supporting the conclusion previously reported by Schmidt et al. (2004). From 1965 to 1973, sand area decreased in all reaches (Figure 5). Between 1973 and 1984, sand area increased in all reaches. These increases are the result of deposition that occurred during the 1983 and 1984 reservoir spills (Schmidt and Graf, 1990). Sand area decreased from 1984 to 1990 in all reaches, except Granary View, which was not mapped from the 1990 images. From 1990 to March 1996, sand area increased in all reaches (except Granary View). During the 1996 controlled flood, bracketed by the March 1996 and April 1996 image collections, sand area increased in the Lees Ferry, North Canyon, Redwall Gorge, Point Hansbrough, and the Little Colorado River reaches, and decreased in the Granary View reach. These changes are consistent with the findings of Hazel et al. (1999) that many sandbars increased in elevation during the 1996 controlled flood without increasing in area. Sand area decreased from April 1996 to 2002 in the Lees Ferry, North Canyon, Redwall Gorge, and Little Colorado River reaches, and increased in the Point Hansbrough and Granary View reaches. From 2002 to 2005, sand area increased in all reaches. Between 2005 and 2009, sand area decreased in the Point Hansbrough and Little Colorado River reaches; no change occurred in the other reaches. In all comparison intervals described above, the reported changes are larger than the standard error of the population of all EDZs for each date and reach, respectively.

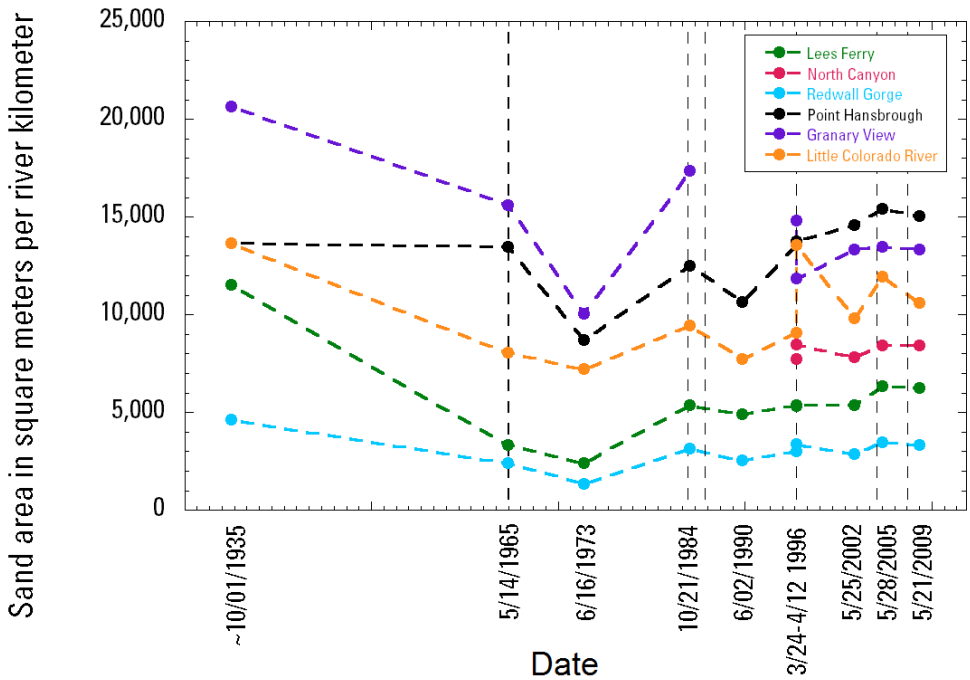

Figure 5 Total sand area within eddy deposition zones larger than 1000 m^2 per river kilometer (m^2/km) for all study reaches for 1935 through 2009, showing change between imagery collection dates. Vertical dashed lines indicate last flood event prior to imagery dates.

Median eddy fill ratios decreased from 1935 to the pre-controlled flood period, and then increased from the pre-controlled flood period to the controlled-flood period in three of five

reaches (Figure 6). Only in the Granary View reach did the median eddy fill ratio continue to decrease in the controlled-flood period. The Lees Ferry reach showed only a slight increase in eddy fill ratio value from the pre-controlled flood period to the controlled-flood period.

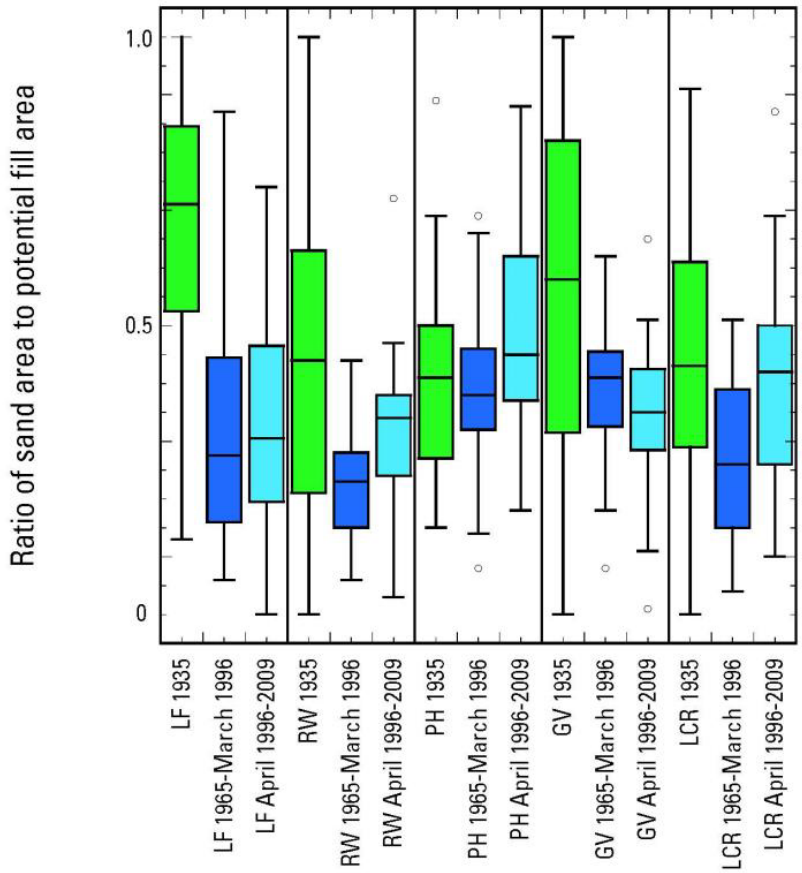

Figure 6 Box and whisker plots of the average eddy fill ratio (ratio of sand area to area of eddy deposition zone) for the pre-dam period, the pre-controlled flood period (1965 to March 1996), and the controlled-flood period (April 1996 to 2009). The median value is marked as the hingeline, the first and second quartiles are the boxes on either side of the median hingeline, the third and fourth quartiles are plotted as whiskers on either side of the boxes, and outliers are plotted as hollow circles.

We examined the effect of flow regime (Figure 3) on measured sandbar area by evaluating the relation between exposed sandbar area and elapsed time since the most recent flood event. Flood events were defined as releases of 1,161 m^3/s (41,000 ft^3/s) or more. The images from the pre-controlled flood period were collected between 1 week and almost 10 years following the previous flood. The images from the controlled-flood period were collected between 2 weeks and nearly 6 years following the most recent controlled flood. For the controlled-flood period, there is a strong correlation between measured sandbar area and elapsed time since the previous controlled flood (Figure 7). In this period, sandbar area was largest in April 1996, 0.5 months after the 1996 controlled flood; and sandbar area was smallest in 2002, 72 months after the 1996 controlled flood. The measurements of sandbar area in the pre-controlled flood period are not

strongly correlated with elapsed time since the most recent flood event.

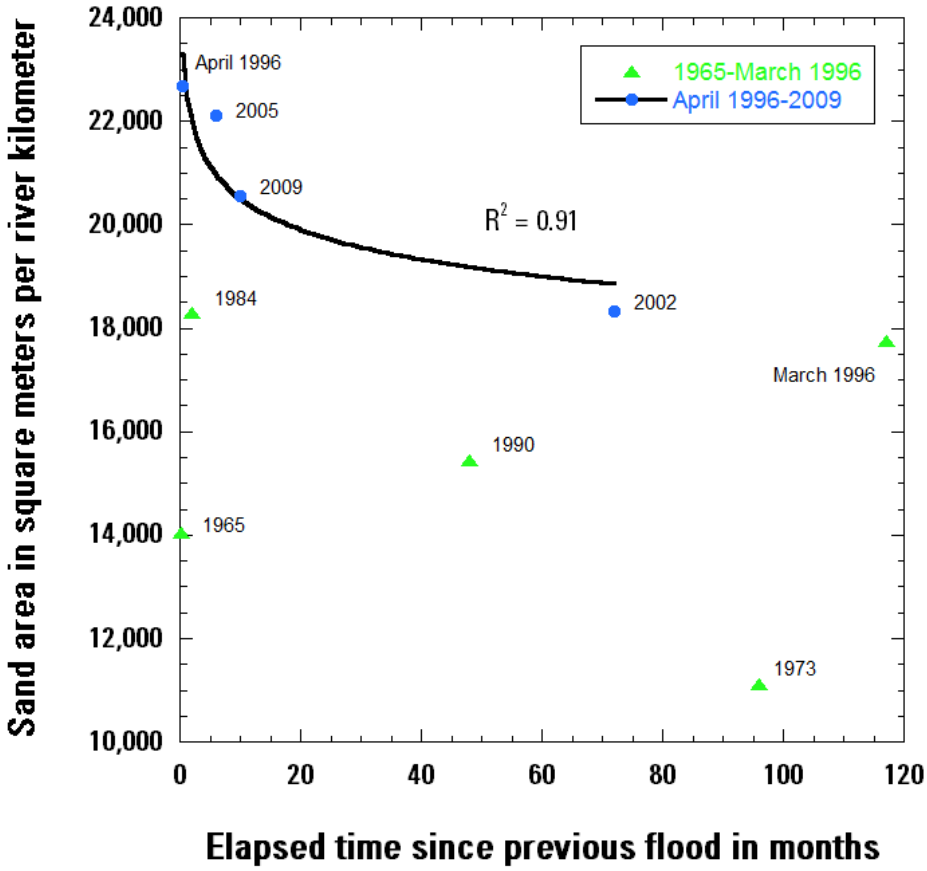

Figure 7 Post-dam reach area plotted against time elapsed since previous flood of 1,161 m^3/s (41,000 ft^3/s) in months. Power trendline fit to data from the controlled-flood period shows clear relationship with an R^2 value of 0.91, while no significant trend was observed in the data from the pre-controlled flood period.

DISCUSSION AND CONCLUSIONS

Previous analyses of aerial imagery concluded that the sandbar area in the post-dam photographs from the period before the first controlled flood was less than in the pre-dam era (Schmidt and Graf, 1990; Schmidt et al., 2004). Our analysis of more recent (2002 – 2009) post-dam imagery shows that sandbars in 2009 were still smaller than in the pre-dam period. There are, however, substantial differences in sandbar size between images collected in the periods with and without controlled floods. The relative proportion of EDZs occupied by exposed sand deposits was greater, on average, in the controlled-flood period than in the period preceding controlled floods. Only in the Granary View reach was the median sandbar size less in the images collected in the controlled-flood period than in the period preceding the first controlled flood, although some sandbars in this reach did increase in size. Importantly, the presence and absence of controlled floods are not the only differences between these two periods. The pre-controlled flood period consisted primarily of unrestricted fluctuating flows while the controlled-flood period consisted entirely of restricted fluctuating flows. Thus, the combination of controlled floods and restricted

powerplant operations is most likely responsible for the observed increases in sandbar size.

The strong correlation between sandbar area and elapsed time since the most recent controlled flood is consistent with previous studies of sandbar deposition and subsequent erosion of flood-formed bars (Hazel et al., 1999; Hazel et al., 2010; Grams et al., 2010). The negative correlation also illustrates that the mean among a set of images is sensitive to the timing of image collection. The image collection dates are neither a systematic nor a random sample. Thus, the average responses shown in Figure 6 only show the average among the image collection dates and are not necessarily representative for the time period. Because of this sensitivity to time of image acquisition and because all images were collected at different intervals relative to the most recent controlled flood, it is not possible to identify a trend in sandbar area with time between 2002 and 2009. The apparent trend between 2002 and 2009 shown in Figure 5 is most likely attributable to the shorter elapsed time between the 2008 controlled flood and the 2009 images.

Because the volume of sand above the reference discharge of 227 m^3/s is only a small fraction of the sand in storage (Hazel et al., 2006; Grams et al., 2015), changes in sandbar area determined from analysis of aerial images cannot be interpreted to reflect changes in total sand storage. Thus, although the images showed larger sandbars in the post-dam period with controlled floods than in the post-dam period before controlled floods, this does not mean that there was more sand in the system during this period.

This study involves only a subset of the reaches that comprise the entire length of the Colorado River in Marble and Grand Canyons, downstream from Glen Canyon Dam. These findings may not, therefore, be representative of the entire system. Ongoing work includes classification of the area of exposed sand for all of Marble and Grand Canyons using the same 2002 and 2009 images used in this analysis, and supplemented with images collected in 2013. This analysis will report on changes in sand area for approximately 1,400 EDZs between Glen Canyon Dam and Lake Mead, located 275 miles downstream.

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