USE OF FLUX AND MORPHOLOGIC SEDIMENT BUDGETS FOR SANDBAR MONITORING ON THE COLORADO RIVER IN MARBLE CANYON, ARIZONA

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INTRODUCTION

The magnitude and pfattern of streamflow and sediment supply of the Colorado River in Grand Canyon (Figure 1) has been affected by the existence and operations of Glen Canyon Dam since filling of Lake Powell Reservoir began in March 1963. In the subsequent 30 years, fine sediment was scoured from the downstream channel (Topping et al., 2000; Grams et al., 2007), resulting in a decline in the number and size of sandbars in the eastern half of Grand Canyon National Park (Wright et al., 2005; Schmidt et al., 2004). The Glen Canyon Dam Adaptive Management Program (GCDAMP) administered by the U.S. Department of Interior oversees efforts to manage the Colorado River ecosystem downstream from Glen Canyon Dam. One of the goals of the GCDAMP is to maintain and increase the number and size of sandbars in this context of a limited sand supply. Management actions to benefit sandbars have included curtailment of daily streamflow fluctuations, which occur for hydropower generation, and implementation of controlled floods, also called high-flow experiments.

Studies of controlled floods, defined as intentional releases that exceed the maximum discharge capacity of the Glen Canyon Dam powerplant, implemented between 1996 and 2008, have demonstrated that these events cause increases in sandbar size throughout Marble and Grand Canyons (Hazel et al., 2010; Schmidt and Grams, 2011; Mueller et al., 2014), although the magnitude of response is spatially variable (Hazel et al., 1999; 2010). Controlled floods may build some sandbars at the expense of erosion of sand from other, upstream, sandbars (Schmidt, 1999). To increase the frequency and effectiveness of sandbar building, the U.S. Department of Interior adopted a "high-flow experimental protocol" to implement controlled floods regularly under conditions of enriched sand supply (U.S. Department of Interior, 2012). Because the supply of sand available to build sandbars has been substantially reduced by Glen Canyon Dam (Topping et al., 2000) and depends entirely on infrequent tributary floods, monitoring of both sandbars and gross sand storage (the sand budget) is required to evaluate whether the high-flow protocol is having the intended effect of increasing sandbar size without progressively depleting sand from the system.

There are many challenges associated with monitoring sand storage and active sand deposits in a river system as large and complex as the 450-km segment of the Colorado River between Glen Canyon Dam and Lake Mead. Previous studies have demonstrated the temporal variation in sand storage associated with sand-supply limitation (Topping et al., 2000) and the spatial variability in the amount of sand stored in eddies and the channel associated with channel hydraulics (Grams et al., 2013). In this study, we report on companion measurements of sand flux and morphologic change to quantify, for the first time, the relation between changes in sand mass balance, changes

in within-channel sand storage, and changes in sandbars comprehensively for a 50-km river segment of the Colorado River in lower Marble Canyon within Grand Canyon National Park.

We show that, when measured over the scale of a 50-km river segment, these complementary measurements of the sand budget agree within measurement uncertainty and provide a rare opportunity to integrate the temporally rich sand-flux record with the spatially rich morphologic measurements. Both methods show that sediment was evacuated from lower Marble Canyon over the 3-year study period. The flux-based budget shows the timing of changes in storage relative to dam-release patterns, while the morphologic measurements depict the spatial distribution of erosion and deposition among different depositional settings.
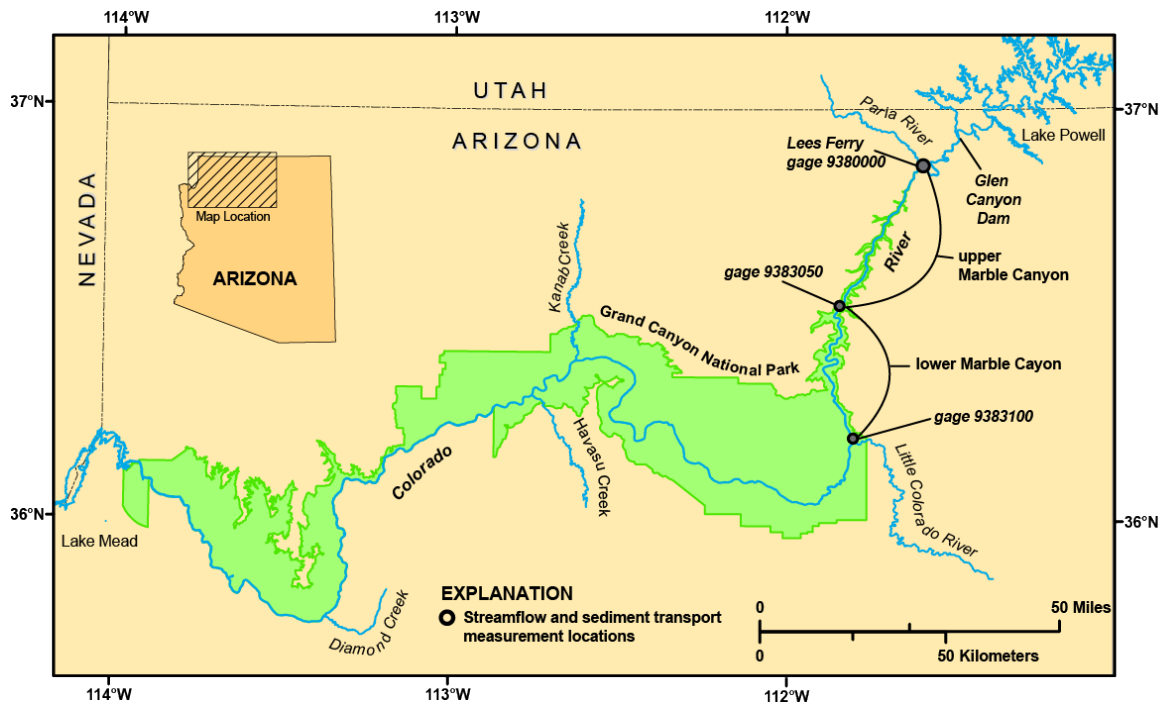
Figure 1 Map of Colorado River between Lake Powell and Lake Mead. Marble Canyon is the river segment between Lees Ferry and the Little Colorado River confluence. The focus of this study is lower Marble Canyon, which is the 50-km segment of Marble Canyon that begins 50 km downstream from the mouth of the Paria River. Grand Canyon is the segment of the Colorado River from the Little Colorado River confluence to Lake Mead.

METHODS

Flux-based Sand Budget: Streamflow and suspended sediment transport are monitored continuously (15-minute intervals) at the upstream and downstream ends of lower Marble Canyon (Figure 1). Streamflow is gaged by standard gaging methods (Rantz et al., 1982) and sediment concentration is monitored with acoustic instruments that are calibrated to conventional suspended-sediment samples (Griffiths et al., 2012; Topping et al., 2015). These data are used to compute 15-minute sediment loads separately for mud (silt and clay) and sand. The instantaneous values for discharge and concentration from each gage and sand budgets computed

for any time interval between 2002 and present are available at www.gcmrc.gov/discharge_qw_sediment/.

Morphologic-based Sand Budget: Riverbed and sandbar topography were measured by surveys with total stations, singlebeam sonar, and multibeam sonar during separate two-week field campaigns in May 2009 and May 2012. Multibeam sonar was used to map the river channel in all locations with sufficient depth, generally 2 m or deeper. Singlebeam sonar was primarily used to map shallower depths along the channel margins. Some reaches were mapped entirely with singlebeam sonar. Total stations were used to survey sand deposits along and above the water's edge. Gravel bars, talus slopes, and debris fans were not typically surveyed. Areas of the channel where upstream navigation was not possible and areas of the banks dominated by established woody riparian vegetation also were not surveyed. Thus, most of the area of the channel not surveyed consists of immobile or rarely mobile gravel and boulders; most of the area on the channel margins not surveyed has been stabilized by vegetation. Details on the methods of data collection, processing, construction of digital elevation models (DEMs), and analysis of uncertainty are described in Hazel et al. (2008) and Kaplinski et al. (2009; 2014).

The difference between the 2009 and 2012 DEMs was computed for each 1-m grid cell and uncertainty was assigned based on the method of data collection (Kaplinski et al., 2014). Volumes of erosion, deposition, and net change were tabulated by geomorphic unit. The primary geomorphic units are eddy, channel adjacent to eddy, other channel, onshore sandbar, and sandbar above reference stage (Figure 2). Eddies were defined as regions of recirculating flow based on water-surface streamflow paterns at 8,000 ft^3/s. The channel adjacent to the eddy is the entire width of downstream-directed current in the channel adjacent to the length of an eddy. The onshore sandbar category is comprised of all the morphologic types of sandbars described by Schmidt (1990) that occur in eddies. The geomorphic units were mapped in a geographic information system (GIS) with May 2009 digital ortho-rectified imagery as a base and subsequently checked in the field for accuracy. For the purposes of volumetric calculations, onshore sandbars are the portions of the sand deposits in eddies that are above the subhorizontal plane (defined by water surface) associated with a discharge of 8,000 ft^3/s. Thus, changes in the onshore sandbars represent changes in sand volume above the 8,000 ft^3/s stage. The "other channel" category includes all portions of the channel not included in the categories described above.

Uncertainty in the estimate of morphologic change is based on the method of data collection, potential changes in storage for the 30% of the reach that was not mapped, and the potential that some topographic change comprised sediment other than sand. For areas mapped by multibeam sonar and singlebeam sonar, we estimate the uncertainty to be ±0.06 m and ±0.12 m, respectively, based on analysis of repeat maps over stable areas reported by Kaplinski et al. (2014). We estimate uncertainty for areas mapped by total station to be ±0.04 m. These values were multiplied by the area mapped by each method, using the method with greatest uncertainty for areas mapped by different methods in each year. The potential change for the portion of the reach not mapped was estimated based on the mean change in each map unit for the portion of the reach that was mapped. Determining the proportion of morphologic change that involved sand is challenging, because bed texture measured before or after the topographic change is not necessarily indicative of the texture of the material that was eroded or deposited. A comprehensive analysis considering both the direction and magnitude of topographic change and

textural changes is ongoing. In this analysis, we make the conservative estimate that as much as 30% of the morphologic change involved sediment other than sand. We assume each of the sources of uncertainty to be independent and, therefore, the uncertainties are summed in quadrature to arrive at an estimate of gross uncertainty for lower Marble Canyon.
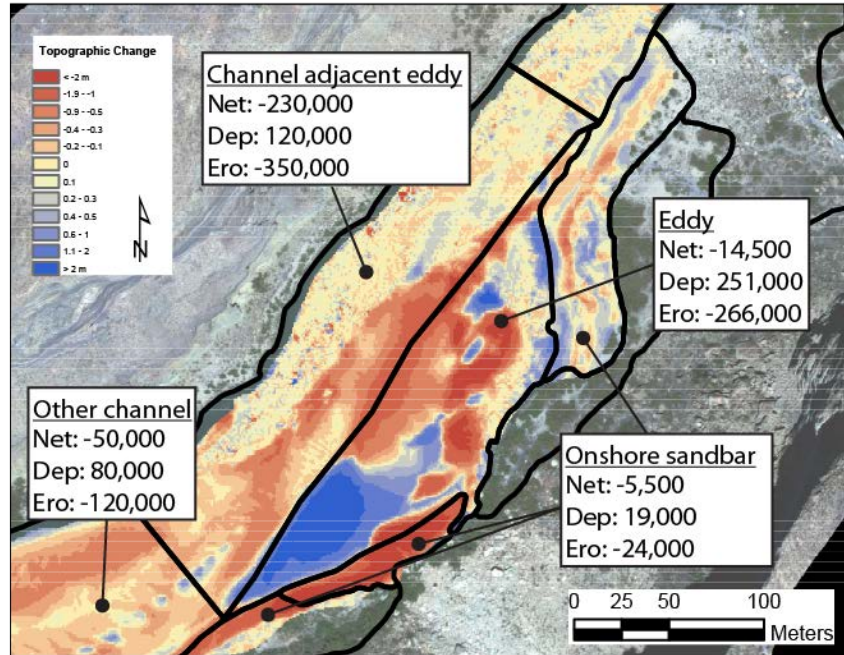

Figure 2 Illustration of sediment storage environments in lower Marble Canyon. Values indicate the volumes, in cubic meters, of net sand storage change, deposition, and erosion summed by indicated map unit for all areas mapped in lower Marble Canyon. Line separating onshore sandbars from eddy is water edge at 8,000 ft^3/s in May 2009. This example location is 71 km downstream from Lees Ferry. Streamflow is from upper right to lower left. All values are in cubic meters.

RESULTS

Comparison of Flux-based and Morphologic-based Sand Budgets: The sand budget computed by measurements of sand flux, and the sand budget computed as the difference between the two topographic surveys, agree within measurement uncertainty. Between May 1, 2009, and May 1, 2012, approximately 2.49 x 10^6 metric tons (Mg) of sand entered lower Marble Canyon at gage 9383050 (Figure 1) and approximately 3.06 x 10^6 Mg of sand was exported past gage 9383100. Ungaged tributaries added an estimated 20,000 Mg of additional sand to the reach. With uncertainty, this results in a flux-based sand budget of -550,000 ± 300,000 Mg (Figure 3). Based on a particle density of 2650 kg/m^3 and 35% porosity, that is equivalent to 320,000 ± 70,000 m^3 of net sand loss in the reach. Over the same time period, the repeat topographic measurements indicate approximately 770,000 m^3 of erosion and 470,000 m^3 of deposition resulting in a net change of -300,000 ± 250,000 m^3.

Most of the net changes in sand storage occurred in the areas of channel adjacent to eddies (Figure 2). However, net change in storage may not be the best metric to evaluate the relative

capacity of each storage environment. Although the net change in storage in eddies was relatively small, eddies were actually the most active storage environments in terms of gross storage change. Gross storage change is defined as the sum of the absolute values of erosion and deposition. For this period of net sand loss from lower Marble Canyon, there was widespread erosion in both the eddy and channel storage environments. However, erosion in eddies was compensated by an almost equally large volume of deposition. Relatively little deposition occurred in the channel. Thus, despite the relatively small net change, eddies were the most active storage environment. This new observation regarding the relative role of the eddy and channel storage environments likely has implications for the processes by which sand accumulates and evacuates from the river.
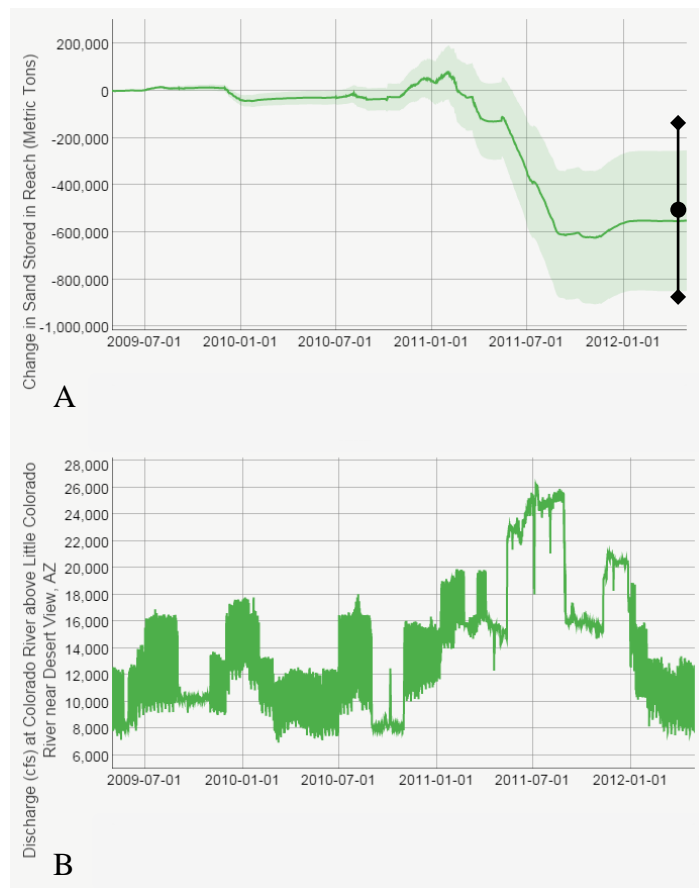

Figure 3 (A) Cumulative change in sand storage for lower Marble Canyon from May 1, 2009 to May 1, 2012. The solid line shows the zero-bias estimate; the shaded region shows the uncertainty band, which increases with time. The point with error bars shows the morphologic-based sand budget for the same period converted to units of mass, with uncertainty. (B) Discharge of the Colorado River at the upstream end of lower Marble Canyon (U.S. Geological Survey gage 9383050). Plot generated Nov. 6, 2014 at www.gcmrc.gov/discharge_qw_sediment/.

Spatial Variability in Sandbar Erosion and Deposition: The parts of sandbars that are exposed above the water surface and available for use by river runners as campsites are of the greatest management interest. Those areas, however, comprise a small proportion of the total

sediment budget. Both the net and gross changes in onshore sandbars were small fractions of the gross changes in other storage environments (Figure 2). Only 2% of the 300,000 m^3 of net storage change in lower Marble Canyon occurred in onshore sandbars above the elevation associated with a discharge of 8,000 ft^3/s, despite the fact that flows exceeded 8,000 ft^3/s over 95% of the time.

While changes in the channel, eddy, and sandbar storage environments are related on some relatively large spatial scale, changes in onshore sandbars and the adjacent eddy and channel appear to be poorly correlated. Over some spatial scale, when sand is depleted from the channel and eddies, more sandbars decrease in size than increase in size. This is shown in a plot of the cumulative changes in each geomorphic unit (Figure 4). Although the cumulative changes do not track precisely, there is consistency between loss of sand from the channel and eddies and decreases in the volume of sand in sandbars. Although this correspondence in the general direction of change exists, the changes are not well correlated at the scale of individual eddies (Figure 5). It is therefore not possible to predict the response of individual sandbars based on the response of the adjacent channel. Correspondingly, responses for individual sandbars cannot be inferred to be representative of the status of sand storage in the adjacent eddy and channel. Based on the data shown in Figures 4 and 5, it appears that there is correlation between onshore sandbar response and eddy/channel response at scales of a few km. However, the spatial scale of this coupling is likely to depend on many factors, including the length of the time interval analyzed, streamflow during the interval, the amount of sand-storage change, and the sand grain size. Thus, further investigation considering these and other factors is required.
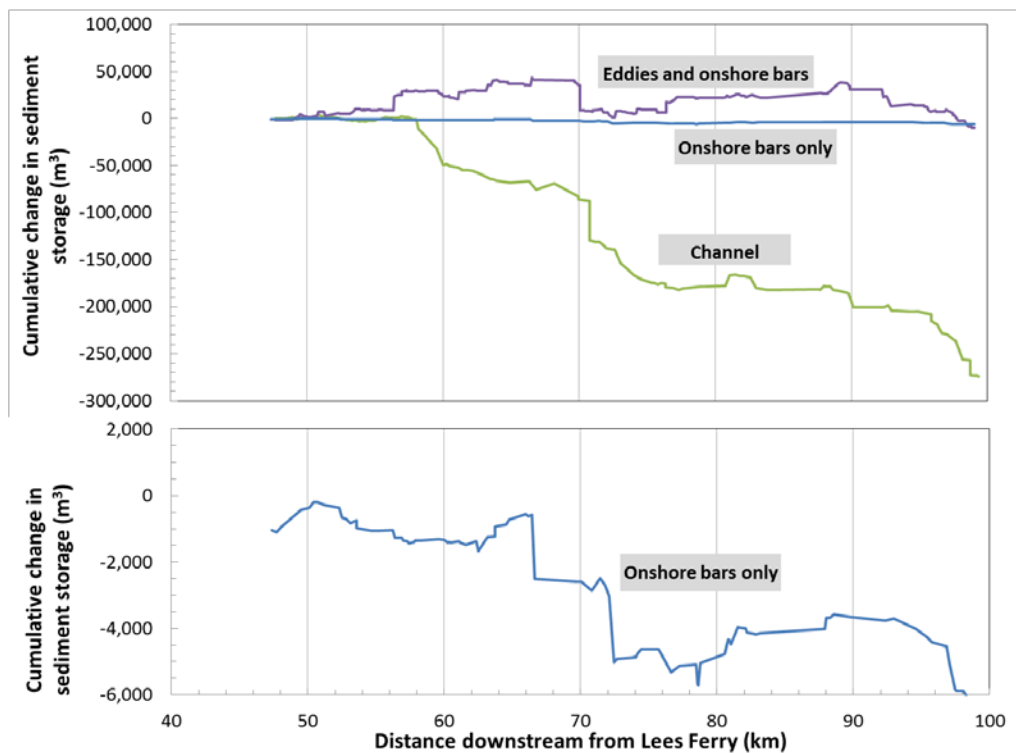

Figure 4 Cumulative downstream change in net sediment storage in lower Marble Canyon by depositional setting. Top panel shows all depositional settings, bottom panel shows the same data for onshore bars only at increased vertical scale.

Evaluation of Sandbar Sampling Design: Comprehensive measurements of onshore sandbar change made throughout lower Marble Canyon between 2009 and 2012 provide the opportunity to evaluate the sampling design for site-based sandbar monitoring that has been in place since 1990. Changes in sandbar topography have been monitored annually since 1990 at study sites throughout Marble and Grand Canyons (Hazel et al., 2010). In lower Marble Canyon, topographic changes of 18 sandbars in 14 different eddies are monitored above the 8,000 ft^3/s reference stage (Hazel et al., 2010). The success or failure of management actions, such as controlled floods, to cause net increases in sandbar size is based largely on the changes in sandbar volume measured at these sites. The maps of geomorphic units described above show that lower Marble Canyon contains 176 eddies larger than 1000 m^2 (combined area of eddy and onshore sand deposits), 84 of which had onshore sandbars larger than 100 m^2 and were mapped in both 2009 and 2012. Thus, the 18 sandbars that are monitored annually comprise a relatively small sample of the total number of large sandbars. Below, we compare topographic changes at the 18 sandbars that are monitored annually with changes that occurred at all 84 sandbars mapped in 2009 and 2012.
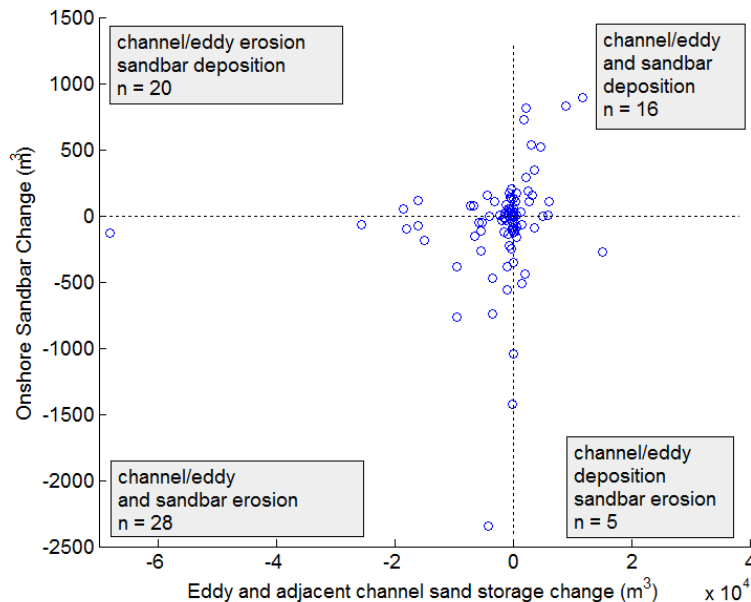

Figure 5 Change in onshore sandbar volume as function of change in channel and eddy storage for the corresponding eddy. This shows that changes in onshore sandbars are not well-correlated with sediment storage change in the same eddy and adjacent channel.

The mean change in sandbar thickness (volume normalized by area) between 2009 and 2012 for these sites (-0.06 m ± 0.06 m standard error), is consistent with the mean change among the much larger sample of 84 sandbars mapped throughout lower Marble Canyon (-0.10 m ± 0.06 m standard error) (Figure 6A). While the mean responses among the two sample sizes are similar for this period, they do not necessarily reflect the full range of sandbar responses, in particular those sites with large gains or large losses. The variance of sand thickness change between 2009 and 2012 among all sandbars in lower Marble Canyon (σ^2=0.12) is double the variance among the 18 monitoring sites (σ^2=0.06), showing that for this period, the monitoring sites had smaller-

magnitude changes than was observed among all sandbars. This suggests that while the set of long-term monitoring sites may adequately represent mean sandbar condition, it fails to capture the full extent of variability in sandbar condition. A bootstrap analysis using all 84 sites surveyed in 2009 and 2012 in lower Marble Canyon indicates that a random sampling of fewer than the current number of monitoring sites would be unlikely to capture mean bar condition better than the current configuration of monitoring sites. The standard error on the mean sandbar thickness as a function of sample size (Figure 6B) suggests that the 18 sites regularly surveyed would capture the trend in the mean sandbar thickness to within approximately 10 cm. While this is a marginally acceptable uncertainty, Figure 6B suggests that one would expect an exponential increase in this uncertainty with decreasing sample size, which is an important consideration for sampling design elsewhere in the canyon.
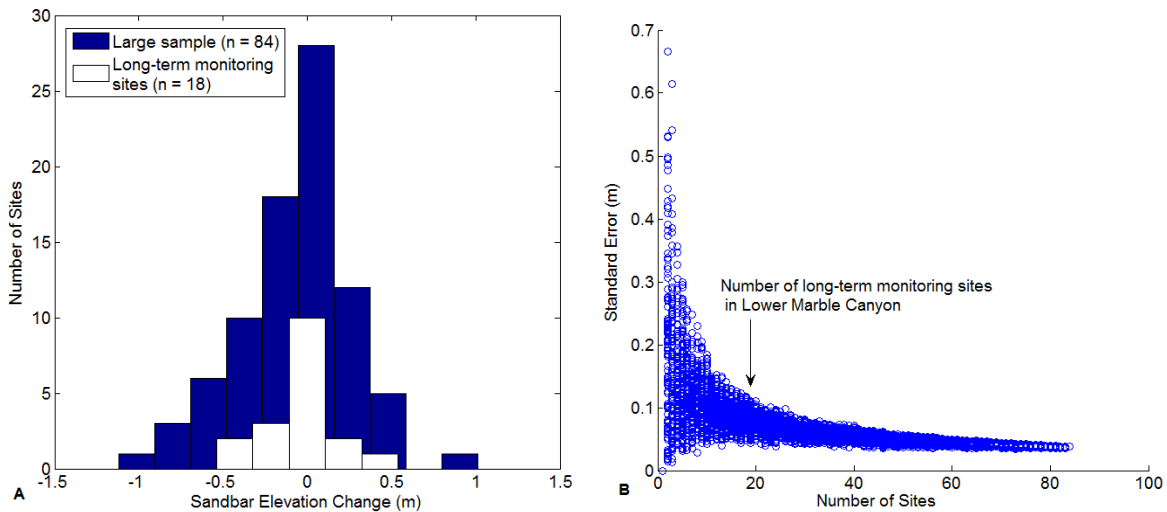

Figure 6 (A) Histograms showing frequency distribution of changes in sandbar elevation for the 84 onshore sandbars measured in lower Marble Canyon (blue) and the 18 of those that are also long-term monitoring sites (white). (B) Bootstrap simulation of expected standard error for estimates of sandbar thickness change as a function of sample size. Measurements of thickness change for 84 sandbars in lower Marble Canyon were sampled randomly using increasing sample size (1 to 84). For each sample size, 100 random selections of (1 – 84) sites were made from among the 84 sites, and the standard error calculated and plotted.

DISCUSSION AND CONCLUSIONS

The goals of resource managers on the Colorado River in Grand Canyon National Park include maintaining and improving the condition of alluvial sandbars in a system that has been perturbed into severe fine-sediment deficit by an upstream dam (Schmidt and Wilcock, 2008). While controlled floods are the most cost-effective management tool that is currently available to achieve that goal, it is uncertain whether sand supply is sufficient to support repeated sandbar building in the context of other dam operations, which also export fine sediment (Wright and others, 2008; Wright and Grams, 2010). The data reported here span a 3-year period that did not include controlled floods but did include over 3 months of steady dam releases that greatly exceeded the range of normal dam operations (Figure 3). The measurements of sand flux and the

measurements of sediment storage change both indicate that these releases evacuated on the order of 300,000 m^3 (500,000 Mg) of sediment from lower Marble Canyon.

Previous attempts to construct a closed sand budget for lower Marble Canyon based on measurements of morphologic change for short monitoring reaches were unsuccessful, because large spatial variability in erosion and deposition resulted in the inability to extrapolate measurements from short reaches to the entire 50-km segment (Grams et al., 2013). In this case, mapping morphologic change in approximately 70% of the same segment resulted in good agreement between the flux-based and morphologic-based budgets. This greatly increases confidence in both the measurements of flux and morphologic change. The results further demonstrate the challenge associated with using morphologic measurements to infer a sediment budget at a scale larger than the reach measured. Although a 10-km study reach might often be considered to be of sufficient length to be representative of a longer river segment, it is clear that in lower Marble Canyon, there are significant differences in the magnitude of sand-storage change between adjacent 10-km reaches (Figure 4). Therefore, without detailed knowledge about the behavior of all major sand-storage locations, it would not be possible to construct an accurate morphologic-based sediment budget for a long river segment like lower Marble Canyon based on a sub-sample of the segment.

The measurements of flux show that nearly all of the sand evacuation occurred during the high releases of summer 2011 (Figure 3). The maps of channel topographic change reveal the locations of that sediment evacuation. Previous studies concluded that most sand-storage changes in Marble and Grand Canyons occurred within zones of recirculating flow – eddies (Hazel et al., 2006). Our findings support that conclusion with some qualification. Between 2009 and 2012 in lower Marble Canyon, eddies were the most active sediment storage environment, but exhibited very little net change in sediment storage. Most net change in sediment storage occurred in the main channel adjacent to eddies. The Hazel et al. (2006) study was conducted over a period that that followed relatively high dam-release volumes and focused on changes that occurred over a short period during a controlled flood. In contrast, we studied changes over a three-year period following relatively low dam-release volumes. This illustrates that the behavior of different storage environments can vary widely depending on the period examined. Because both eddy and channel storage environments are very large and either may dominate the signal of net change in sand storage, both must be measured to compute an accurate sediment budget.

The observations also demonstrate that the entire debris-fan eddy complex (Schmidt and Rubin, 1995) is the dominant storage environment, not just the recirculation zone. The channel adjacent to the eddy includes a scour hole and pool exit slope, both of which accumulate and evacuate sediment. While the channel adjacent to eddies was the dominant location of net change in this period of scour, it is possible that the relative proportions of change between the eddies and channel could reverse in other periods.

This period of sand evacuation followed a period of large tributary inputs and sand accumulation from 2004 through 2010 (Topping et al., 2010). Repeat topographic maps of short reaches within lower Marble Canyon from 2002, 2004, and 2009 also indicate that 2009 was a period of enriched sand storage. We speculate that both channel and eddy sand-storage locations were relatively full at the beginning of the high dam releases in 2011. During the elevated sand concentrations that occurred as sand was exported from the reach, it is likely that eddies were

locations of substantial mixing between the bed and suspension, while sand was simply scoured from other storage locations. In this way, the eddies behave as a buffer for sand evacuation. If all of the sand mobilized in the 2009-2011 interval had been eroded (i.e. the sand deposited in eddies was instead exported), the net loss of sand could have been nearly twice as large as actually occurred. At least 250,000 m^3 of easily mobilized sand remained in storage within the eddies. Thus, if the 2011 high releases continued for a longer period of time, we would expect that sand evacuation would have continued at a high rate for much longer. This is consistent with the measurements of sand flux, which do not indicate a decline in the rate of evacuation during 2011 (Figure 3).

On the scale of the entire 50-km segment of lower Marble Canyon, the changes in onshore sandbars tracked with the overall decline in sand storage. There was net loss of sand from the river channel and net decrease in the volume of sand in onshore sandbars. Previous studies have shown that for short time periods (e.g. the several day span of a controlled flood), there can be widespread deposition on the onshore sandbars while there is net sand loss from the deeper parts of eddies and the main channel (Schmidt, 1999; Hazel et al., 2010; Wright and Kaplinski, 2011). The findings from this comprehensive sand budget for lower Marble Canyon suggest that over the time scale of a few years (e.g. the 3-year period of this study) or longer, onshore sandbars generally increase in size when the sand budget is positive and decrease in size when the sand budget is negative.

There is not, however, a direct correlation in the response between the combined channel/eddy storage environment and the adjacent onshore sandbar. The change in onshore sandbars can be muted or amplified relative to the change in the adjacent eddy and channel. In some cases, the change in the onshore sandbar is the opposite sign of the change in the channel and eddy. This means that in order to monitor both the status of the sand budget and the status of onshore sandbars, it is necessary to monitor both, even though the net changes in the onshore sandbars are small relative to the overall sand budget. Further investigation is required to better describe the spatial scale at which channel, eddy, and onshore sandbar response are coupled. Sandbar sampling design is further informed by an examination of the change in sandbar elevation for the onshore sandbars mapped in lower Marble Canyon. This analysis indicates that the 18 sites currently monitored in the 50-km reach is likely a minimum sample size to reasonably represent the mean response exhibited in the larger set of 84 sandbars.

REFERENCES

Grams, P. E., Schmidt, J. C., and Topping, D. J. (2007). "The rate and pattern of bed incision and bank adjustment on the Colorado River in Glen Canyon downstream from Glen Canyon Dam, 1956-2000," *Geological Society of America Bulletin*, *119*(5/6), 556-575.

Grams, P. E., Topping, D. J., Schmidt, J. C., Hazel, J. E., and Kaplinski, M. (2013). "Linking morphodynamic response with sediment mass balance on the Colorado River in Marble Canyon: Issues of scale, geomorphic setting, and sampling design," *Journal of Geophysical Research*, *118*, 21.

Griffiths, R. E., Topping, D. J., Andrews, T., Bennet, G. E., Sabol, T. A., and Melis, T. S. (2012). "Design and maintenance of a network for collecting high-resolution suspended-sediment data at remote locations on rivers, with examples from the Colorado River," *U.S. Geological Survey Techniques and Methods, book 8, chapter C2*, 44.

Hazel, J. E., Topping, D. J., Schmidt, J. C., and Kaplinski, M. (2006). "Influence of a dam on fine-sediment storage in a canyon river," *Journal of Geophysical Research*, *111*(F01025).

Hazel, J. E., Kaplinski, M., Parnell, R., Manone, M., and Dale, A. (1999). Topographic and bathymetric changes at thirty-three long-term study sites, in *The Controlled Flood in Grand Canyon*, edited by R. H. Webb, J. C. Schmidt, R. A. Valdez and G. R. Marzolf, American Geophysical Union.

Hazel, J. E., Jr., Grams, P. E., Schmidt, J. C., and Kaplinski, M. (2010). "Sandbar response following the 2008 high-flow experiment on the Colorado River in Marble and Grand Canyons," *U.S. Geological Survey Scientific Investigations Report 2010-5015*, 52.

Hazel, J. E., Jr., Kaplinski, M., Parnell, R. A., Kohl, K., and Schmidt, J. C. (2008). "Monitoring fine-grained sediment in the Colorado River Ecosystem, Arizona-Control network and conventional survey techniques," *U.S. Geological Survey Open-File Report 2008-1276*, 15.

Kaplinski, M., Hazel, J. E., Jr., Grams, P. E., and Davis, P. A. (2014). "Monitoring Fine-Sediment Volume in the Colorado River Ecosystem, Arizona: Construction and Analysis of Digital Elevation Models," *U.S. Geological Survey Open-file Report 2014-1052*, 36.

Kaplinski, M., Hazel, J. E., Parnell, R., Breedlove, M., Kohl, K., and Gonzales, M. (2009). "Monitoring Fine-Sediment Volume in the Colorado River Ecosystem, Arizona: Bathymetric Survey Techniques," *U.S. Geological Survey Open-File Report 2009-1207*, 41.

Mueller, E. R., Grams, P. E., Schmidt, J. C., Hazel, J. E., Jr., Alexander, J. S., and Kaplinski, M. (2014). "The influence of controlled floods on fine sediment storage in debris fan-affected canyons of the Colorado River basin," Geomorphology, 226, 65-75.

Rantz, S. E. (1982). "Measurement and computation of streamflow: Volume 1. Measurement of Stage and Discharge," *U.S. Geological Survey Water Supply Paper 2175*, 313.

Schmidt, J. C. (1990). "Recirculating flow and sedimentation in the Colorado River in Grand Canyon, Arizona," *Journal of Geology*, *98*, 709-724.

Schmidt, J. C. (1999). Summary and synthesis of geomorphic studies conducted during the 1996 controlled flood in Grand Canyon, in *The 1996 Controlled Flood in Grand Canyon scientific experiment and management demonstration*, edited by R. H. Webb, J. C. Schmidt, R. A. Valdez and G. R. Marzolf, AGU, Washington, D.C.

Schmidt, J. C., and Rubin, D. M. (1995). Regulated streamflow, fine-grained deposits, and effective discharge in canyons with abundant debris fans, in *Natural and anthropogenic influences in fluvial geomorphology*, edited by J. E. Costa, A. J. Miller, K. W. Potter and P. R. Wilcock, pp. 177-195, American Geophysical Union.

Schmidt, J. C., and Wilcock, P. R. (2008). "Metrics for assessing the downstream effects of dams," *Water Resources Research*, *44*(W04404).

Schmidt, J. C., and Grams, P. E. (2011). The high flows--physical science results, in *Effects of three high-flow experiments on the Colorado River ecosystem downstream from Glen Canyon Dam, Arizona, U.S. Geological Survey Circular 1366*, edited by T. S. Melis, pp. 53-91.

Schmidt, J. C., Topping, D. J., Grams, P. E., and Hazel Jr., J. E. (2004). System-wide changes in the distribution of fine sediment in the Colorado River corridor between Glen Canyon Dam and Bright Angel Creek, Arizona: U.S. Geological Survey, Grand Canyon Monitoring and Research Center, Flagstaff, Ariz., 107 p. http://www.gcmrc.gov/library/reports/Physical/Fine_Sed/Schmidt2004.pdf

Topping, D. J., Rubin, D. M., Grams, P. E., Griffiths, R. E., Sabol, T. A., Voichick, N., Vanaman, K. M. (2010). Sediment transport during three controlled-flood experiments on

the Colorado River downstream from Glen Canyon Dam, with implications for eddy-sandbar deposition in Grand Canyon National Park : U.S. Geological Survey Open-file Report 2010-1128, 111 p.

Topping, D. J., Rubin, D. M., and Vierra, L. E. J. (2000). "Colorado River sediment transport 1. Natural sediment supply limitation and the influence of Glen Canyon Dam," *Water Resources Research*, *36*(2), 515-542.

Topping, D.J., Wright, S.A., Griffiths, R.E., Dean, D.J. (2015). "Physically based method for measuring suspended-sediment concentration and grain size using multi-frequency arrays of acoustic-Doppler profilers," in Proc. of the 3rd Joint Federal Interagency Conference, Reno, Nevada, April 19-23, 2015.

U.S. Department of the Interior (2012). Environmental Assessment: Development and Implementation of a Protocol for High-Flow Experimental Releases from Glen Canyon Dam, Arizona, 2011 through 2020, Bureau of Reclamation, Salt Lake City, Utah, 546 p, http://www.usbr.gov/uc/envdocs/ea/gc/HFEProtocol/index.html.

Wright, S. A., and Grams, P. E. (2010). Evaluation of water year 2011 Glen Canyon Dam flow release scenarios on downstream sand storage along the Colorado River in Arizona, U.S. Geological Survey Open-file Report 2010-1133, 19 p.

Wright, S. A., & Kaplinski, M. (2011). "Flow structures and sandbar dynamics in a canyon river during a controlled flood, Colorado River, Arizona," *Water Resources Research*, 116(F01019). doi:10.1029/2009JF001442, 2011

Wright, S. A., Melis, T. S., Topping, D. J., and Rubin, D. M. (2005). Influence of Glen Canyon Dam operations on downstream sand resources of the Colorado River in Grand Canyon, in *The state of the Colorado River ecosystem in Grand Canyon*, edited by S. P. Gloss, J. E. Lovich and T. S. Melis, pp. 17-31, U.S. Geological Survey Circular 1282.

Wright, S. A., Schmidt, J. C., Melis, T. S., Topping, D. J., and Rubin, D. M. (2008). "Is there enough sand? Evaluating the fate of Grand Canyon sandbars," *GSA Today*, *18*(8).