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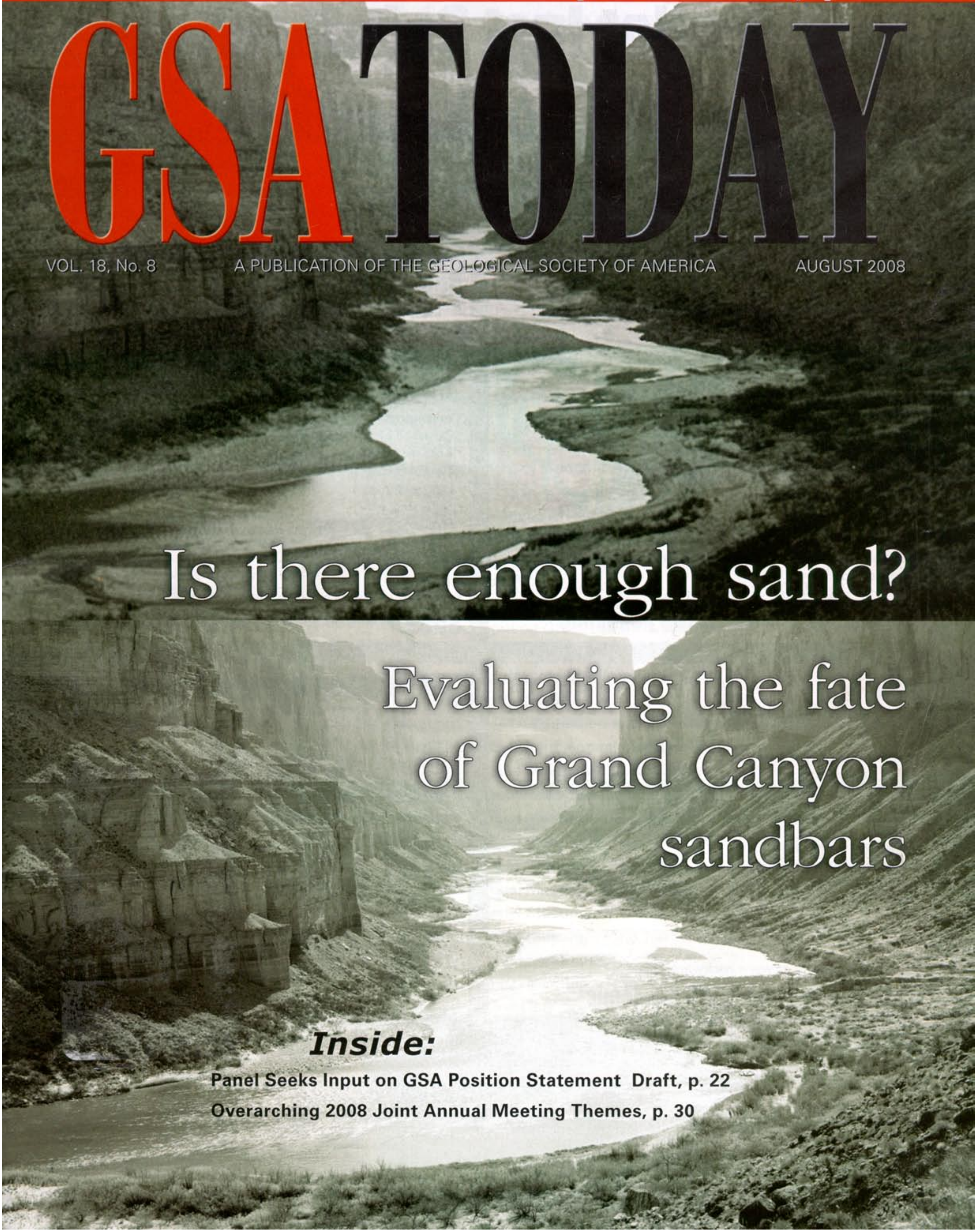

Is there enough sand?

Evaluating the fate of Grand Canyon sandbars

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Is there enough sand?
Evaluating the fate of Grand Canyon sandbars

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ABSTRACT

Large dams have the potential to dramatically alter the flow regime, geomorphology, and aquatic ecosystem of downstream river reaches. Development of flow release regimes in order to meet multiple objectives is a challenge facing dam operators, resource managers, and scientists. Herein, we review previous work and present new analyses related to the effects of Glen Canyon Dam on the downstream reach of the Colorado River in Marble and Grand Canyons. The dam traps the entire incoming sediment load in Lake Powell and modulates the hydrologic regime by, for example, eliminating spring snowmelt floods, resulting in changes in the geomorphology of the river downstream. The primary geomorphic impact has been the erosion of sandbars along the banks of the river. Recognition of this impact has led to many scientific studies and a variety of experimental operations of Glen Canyon Dam with the goal of rebuilding the eroding sandbars. These efforts have thus far been generally unsuccessful and the question remains as to whether or not the dam can be operated such that sandbars can be rebuilt and maintained over extended periods with the existing sediment supply. We attempt to answer this question by evaluating a dam operation that may be considered a "best-case scenario" for rebuilding and maintaining eroded sandbars. Our analysis suggests that this best-case scenario may indeed have viability for rebuilding sandbars, and that the initial rate at which sandbars could be rebuilt is comparable to the rate at which sandbars have been eroded since dam construction. The question remains open as to the viability of operations that deviate from the best-case scenario that we have defined.

INTRODUCTION

Large dams have the potential to profoundly transform downstream riverine hydrology, geomorphology, and ecosystem function (Nilsson et al., 2005; Collier et al., 2000; Williams and Wolman, 1984; Syvitski et al., 2005). Flood control and elimination of the upstream sediment supply perturb the downstream sediment balance (Grant et al. 2003; Schmidt and Wilcock, 2008). Immediately below a large dam, sediment deficit conditions exist because the transport capacity of the river exceeds the supply. In such a situation, fine sediment is evacuated from the channel, and the bed may become incised, potentially causing disconnection with the pre-dam floodplain and changing the distribution and availability of aquatic habitats. Sediment evacuation caused by deficit conditions has been described on many large rivers, including the Rio Grande below Elephant Butte Dam (Stevens, 1938), and the Colorado River below Glen Canyon Dam (Grams et al., 2007) and Hoover Dam (Borland and Miller, 1960). At some point farther downstream, sediment mass balance conditions may shift to surplus if there is sufficient resupply of sediment by tributaries. An extreme example of surplus is that of the Rio Grande near Presidio, Texas (Everitt, 1993). The location of the transition from deficit to surplus depends on the rate that downstream tributaries supply sediment as well as the flow regime released from the dam, which controls the transport capacity of the post-dam river. Understanding the relationship between downstream sediment supply and transport capacity is essential for resource management downstream from dams where aquatic habitat is linked to river morphology.

One notable effort to understand these relationships has been ongoing for several decades on the Colorado River in Glen and Grand Canyons downstream from Glen Canyon Dam (Fig. 1). The completion of Glen Canyon Dam in 1963 substantially reduced the downstream sediment supply by trapping in Lake Powell reservoir (Topping et al., 2000a, 2000b). In addition, flow regulation by the dam has eliminated the large annual snowmelt floods while increasing base flows (Topping et al., 2003); flow releases through the power plant also contain seasonal and daily cycles that follow electricity demand in the western U.S. (White et al., 2005). Environmental flow constraints were imposed on the dam's power plant operation after 1991 due to perceived effects on downstream physical, biological, and cultural resources (U.S. Department of the Interior, 1995, 1996). These "Record-of-Decision" (ROD) operations reduced the daily range and daily peaks of fluctuating flows, and subsequent experimental releases have included low steady flows and large simulated floods. However, more than four decades after construction of this large dam (the fourth highest in the United States) and after considerable scientific research and monitoring, scientists and river stakeholders continue to debate its impacts on downstream resources and how to reverse those environmental conditions that are deemed undesirable by society (Lovich and Melis, 2005; Melis et al., 2006).

One of the distinctive environmental attributes of the pre-dam river are sandbars that form in large eddies downstream of tributary debris fans (Schmidt, 1990; Schmidt and Rubin, 1995; Fig. 2) and floodplain-like channel-margin deposits.

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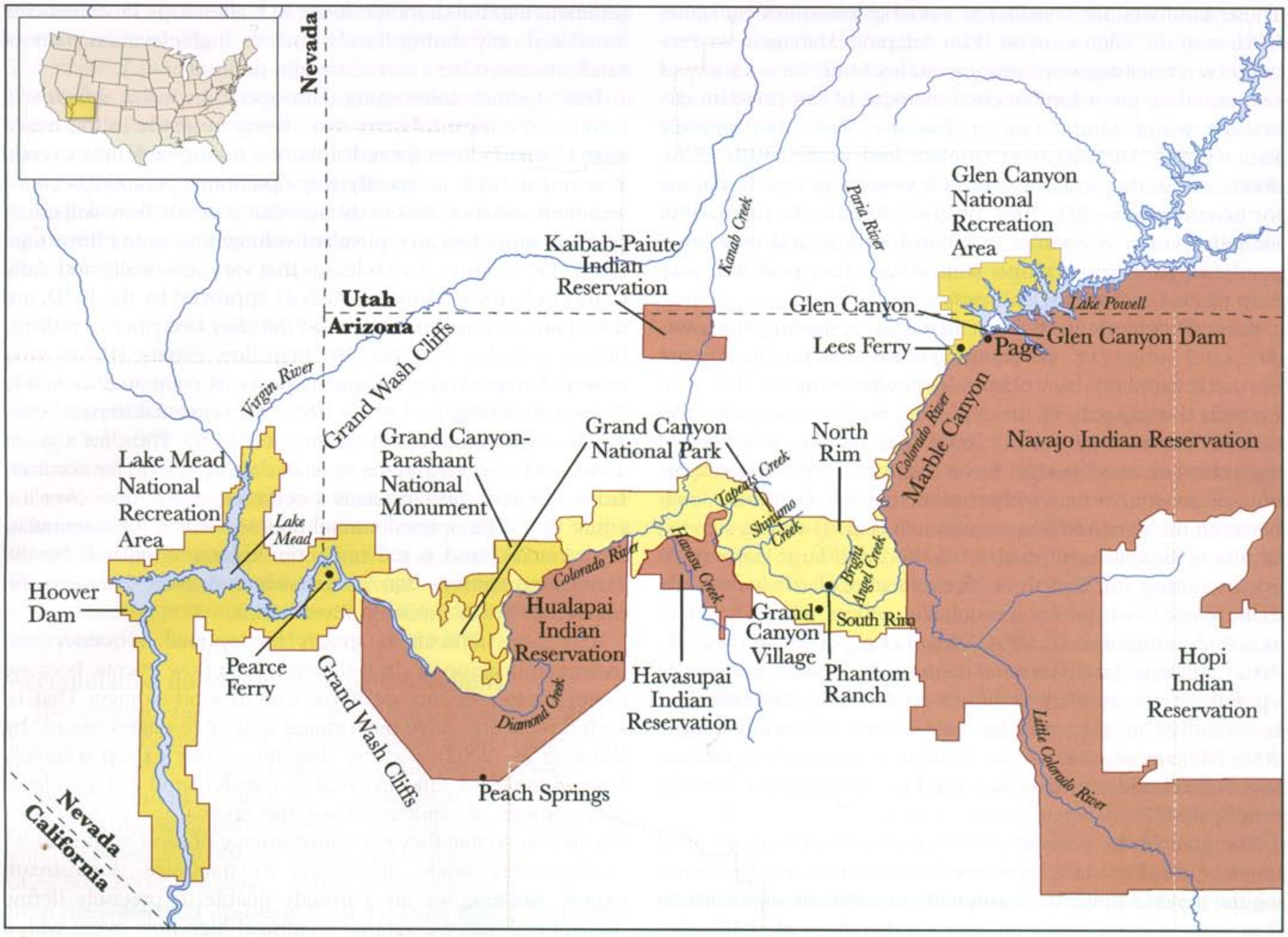

Figure 1. Location map of the Colorado River between Lakes Powell and Mead in northern Arizona, USA. Marble Canyon is the reach of river between Lees Ferry and the confluence with the Little Colorado River.

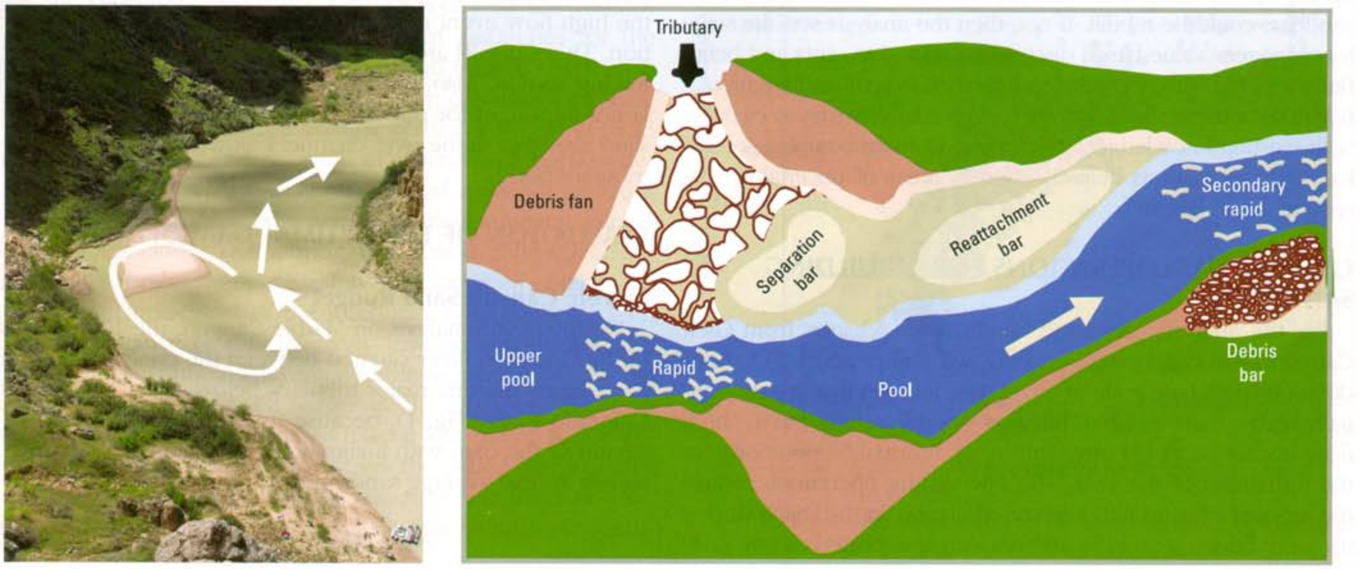

Figure 2. Example of a recirculating eddy and sandbar formed around the flow reattachment point along the Colorado River below Glen Canyon Dam. Image on right reproduced from Webb et al. (2005).

tributaries, M_{io} is the mass of sand exported during intervening operations, and M_{bf} is the mass exported during high flows. The mass of sand coming into the reach from upstream (Glen Canyon) is assumed to be zero because releases from the dam contain almost no sediment, and the 25-km-long reach from the dam to Lees Ferry is substantially depleted of sand (Grams et al., 2007). Since the tributary inputs will almost always occur during intervening operations, M_{in} and M_{io} can be combined into a term representing the change in storage during intervening operations:

$$\Delta M = \Delta M_{io} - M_{bf}, \qquad (2)$$

where $\Delta M_{io} = M_{in} - M_{io}$. From (Eq. 2) it is apparent that in order for the overall storage in the reach to be positive, the export during high flow events must be less than the amount of sand that accumulates in the reach during intervening operations. It follows that if ΔM_{io} is negative, then no sand would be available, on average, for redistribution during high flows, and it would thus be impossible to rebuild and maintain sandbars. The first step, then, in evaluating the optimal dam operation is to estimate the potential sand accumulation during intervening operations (i.e., the sign and magnitude of ΔM_{io}).

Accumulation during Intervening Operations

The average annual sand supply from tributaries (M_{in}) is relatively well constrained. The Paria River is the primary sand supply to Marble Canyon (Fig. 1) and delivers ~1,500,000 metric tons of sand per year (t/yr) (Topping et al., 2000a). Smaller tributaries are estimated to supply ~290,000 t/yr to Marble Canyon (Webb et al., 2000), resulting in total tributary sand supply of ~1,800,000 yr. Pre-dam, ~23,000,000 yr of sand was supplied from the watershed upstream from the Paria River (Topping et al., 2000a), such that the post-dam sand supply to Marble Canyon is ~7%–8% of the pre-dam supply.

In order to estimate export during intervening operations, the year-round steady flow rate must be specified. This rate depends on the minimum annual release volume from the dam. In December 2007, the U.S. Secretary of the Interior signed a ROD that implemented interim guidelines for the coordinated operation of Lakes Powell and Mead (U.S. Department of the Interior, 2007a). These interim guidelines stipulate a minimum objective release volume of 10.2×10^9 m^3/yr (8.23 million acre-feet [MAF]) as well as operational tiers under which the annual release may be reduced to as low as 8.6×10^9 m^3 (7.0 MAF). However, the final environmental impact statement concludes that during the period 2008–2026, the probability of releases being below the minimum objective is ~10% (U.S. Department of the Interior, 2007b, figures 4.3-13, p. 4-43). Because of this relatively low probability and the uncertainty surrounding future hydrologic conditions in the basin (Barnett et al., 2008; Seager et al., 2007), we chose to evaluate the minimum objective release volume of 10.2×10^9 m^3 (8.23 MAF), which, averaged over the entire year, equates to a steady flow of 322 m^3/s. We also note that this has been the annual release volume since 2001 due to drought conditions and low reservoir levels.

The next step is to estimate the sand concentration at the steady 322 m^3/s water discharge. Several previous studies have attempted to define a relationship between water discharge and sand concentration, such as Randle and Pemberton (1987), upon which the ROD operation was based. Subsequent research, however, has shown that the relationship between suspended-sand concentration and water discharge is not constant in this reach of river; rather, substantial shifts occur due to changes in the upstream supply of sand (Topping et al., 1999, 2000a, 2000b, 2005, 2007; Rubin and Topping, 2001). These shifts make the estimation of sand concentration at a steady 322 m^3/s water discharge a more complicated affair than in rivers where discharge and sediment supply are more in equilibrium. That is, some assumptions regarding the state of sand supply must be made in order to estimate the sand concentration.

Figure 3 shows suspended-sand concentration versus water discharge as measured at two gages in Marble Canyon between August 1999 and January 2008, illustrating the wide range in sand concentration that can occur for a given water discharge. The 30-mile gage is located in middle Marble Canyon, and the 61-mile gage is located at the lower end of Marble Canyon (see Topping et al., 2006a, 2006b). At the 30-mile gage, sand concentrations for flows within ±5% of 322 m^3/s ranged from 9 to 104 mg/L, with median, mean, and standard deviation of 51, 51, and 31 mg/L, respectively. At the 61-mile gage, sand concentrations ranged from 11 to 150 mg/L, with median, mean, and standard deviation of 23, 34, and 29 mg/L, respectively. Figure 4 illustrates the effects of sand supply on sand concentration by plotting the concentrations contained in the box of Figure 3 along with the daily water discharge record for the Paria River (U.S. Geological Survey gage 09382000). During periods of little tributary activity, when the sand budget tends to be negative under ROD releases, such as 2001–2003 (Wright et al., 2005), the sand concentrations are lower. During periods

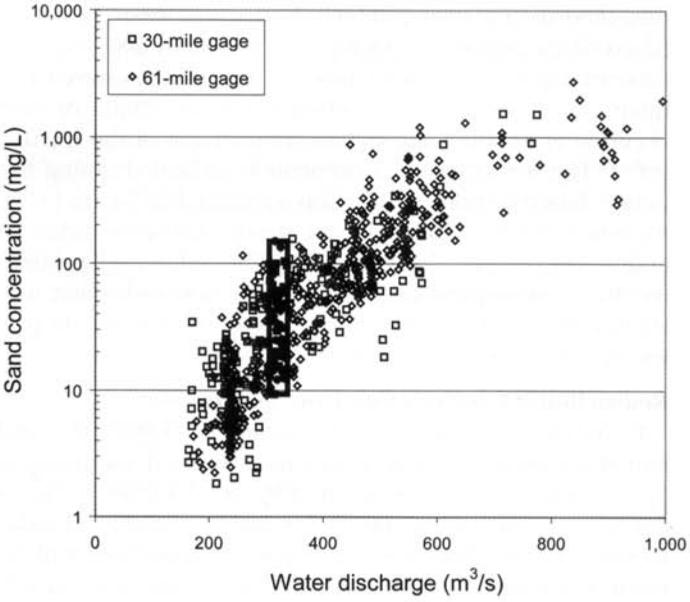

Figure 3. Suspended-sand concentration versus water discharge as measured in middle Marble Canyon (30-mile gage) and at the lower end of Marble Canyon (61-mile gage) for August 1999–January 2008. Bold rectangle encloses measurements made in the water discharge range of 322 m^3/s ±5%.

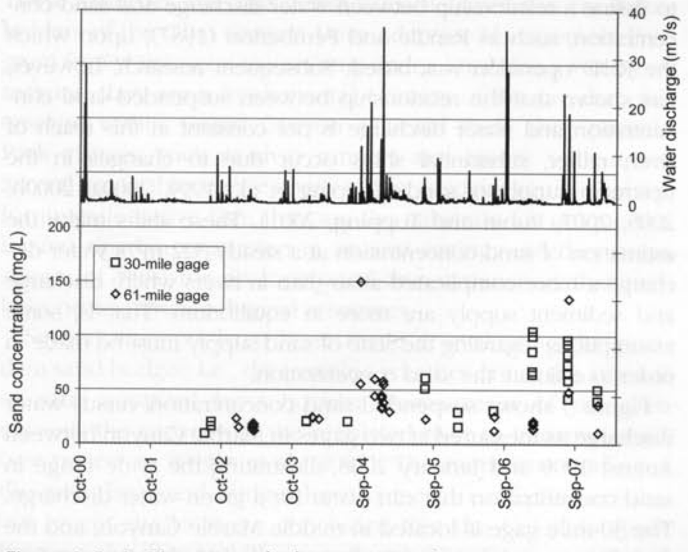

Figure 4. Paria River water discharge (top) and mainstem Colorado River sand concentrations for mainstem discharges in the 322 m^3/s ±5% range (bottom) for October 2000–April 2008. Sand concentrations increased during temporary sand accumulation in Marble Canyon following Paria floods in fall 2004, winter 2005, and fall 2006 and subsequently decreased as the tributary sand was exported from Marble Canyon.

of substantial tributary flooding and temporary accumulation of sand in Marble Canyon, such as fall 2004 (Topping et al., 2006b), winter 2005, and fall 2006 (U.S. Department of the Interior, 2008), concentrations are higher because sand supply is greater.

Because the steady 322 m^3/s operation is expected to transport substantially less sand than ROD operations, the sand supply should be greater on average such that sand concentrations under this operation would tend toward the high end of those measured during 1999–2008. Given this, our best estimate is based on the period from October 2006–January 2008, because tributary inputs were above average, dam releases were minimum annual volumes, and substantial accumulation of sand occurred in Marble Canyon (U.S. Department of the Interior, 2008). The median sand concentration measured during this period, based on both Marble Canyon gages, was 54 mg/L (Fig. 4), which when combined with steady 322 m^3/s yields an annual sand flux of ~500,000 t. This is the value we have used for M_{io} in subsequent calculations while acknowledging substantial uncertainty in the estimate due to the difficulty in projecting future sand supply conditions.

Redistribution during High Flow Events

Using these estimates for tributary inputs (1,800,000 t) and export during intervening operations (500,000 t), the potential accumulation in Marble Canyon, ΔM_{io}, is ~1,300,000 t. This is the mass of sand, on average, that would be available for redistribution during a high flow and is near the upper bound of the estimate for sand storage in upper Marble Canyon going into the November 2004 high flow (Topping et al., 2006a). In the pre-dam river, Topping et al. (2000a) estimated seasonal fine sediment accumulation in an average year of ~7,000,000 t, such that the potential accumulation during intervening dam operations described herein is ~20% of the estimated pre-dam seasonal accumulation. There would be substantial variation in the amount of sand accumulation from year to year owing to variability in tributary inputs, but we have chosen to focus on the average response instead of the variability because it provides more insight with respect to the long-term prospects for rebuilding and maintaining sandbars.

The degree to which sandbars can be rebuilt depends on how much of the sand that accumulates during intervening operations remains in sandbars following a high flow event. That is, what fraction of the accumulated sand is exported downstream, eventually to Lake Mead, versus deposited in sandbars? Topping et al. (2006b) estimated that ~10%–20% of the tributary sand that had accumulated in upper Marble Canyon was still in the reach following the 2004 high flow, presumably in sandbars. Though the 1996 high flow event resulted in an overall net loss of sediment from sandbars (Schmidt, 1999; Hazel et al., 2006), there was a gain in high-elevation volume. ~20% of that was the losses from the low-elevation portions of sandbars and the channel. Hazel et al. (2006) estimated the potential active storage in sandbars in Marble Canyon to be ~13,000,000 t, or ~20% of the total pre-dam fine sediment load. Thus, it appears that a reasonable estimate for the fraction of sand transferred to sandbars during high flow events is ~10%–20% of the available supply. It follows, then, that ~200,000 t/yr of the 1,300,000 t/yr of potential sand accumulation could go toward building sandbars.

Comparison with Post-Dam Erosion Rates

Several existing data sets and previous analyses facilitate comparison of the potential annual accumulation in sandbars with the rate of sandbar erosion since dam closure. Using daily sediment records from gages near Lees Ferry and Phantom Ranch (Fig. 1), Rubin and Topping (2001) estimated that 16,000,000 t of fine sediment was eroded from this reach during high flow releases in April–June 1965. It is impossible to know precisely how much of this sediment came from sandbars versus the channel bed, but even a conservative estimate of 10% from sandbars yields 1,600,000 t of erosion during this three-month period, which is eight times our estimated potential annual accumulation. Schmidt et al. (2004) and Hazel et al. (2006) estimated the loss of fine sediment from sandbars from the pre-dam era through the 1990s to be ~6,000,000 t. Over the ~40 years since dam construction, this equates to an average annual erosion rate of ~150,000 t, which is in the same range as our estimated potential annual accumulation in sandbars (200,000 t). Thus, our analysis indicates that under the "best-case scenario" for hydrologic conditions and dam operations, sandbars could potentially be rebuilt, at least initially, at approximately the same rate as they have eroded since dam construction.

DISCUSSION

Though our analysis suggests potential annual sandbar accumulation at about the same rate as the post-dam erosion rate, we do not mean to imply that pre-dam conditions could be achieved in 40 years; this is almost certainly not the case. The cumulative rate of sandbar building depends on how much of the annual accumulation is maintained between high flow events, how the system changes as accumulation occurs over time, and the frequency and magnitude of deviations in future annual release volumes from the minimum objective volume. Our analysis evaluates only the potential for accumulation in a given "average" year and does not address cumulative accumulation because there is too much uncertainty about how the system would evolve over multiple years, or even decades, under these operations. For example, we know that as accumulation occurs, sand export during intervening operations will increase, but we do not know by how much. Also, we have very little information on how stable the sandbars would be under steady flows. Finally, the probability that annual releases will exceed the minimum objective release in a given year is ~60% (U.S. Department of the Interior, 2007b, figure 4.3-13, p. 4–43) such that incremental gains in sandbar building made during periods of minimum objective releases would be subjected to higher flows more than half the time in the future.

The question remains open as to the viability of operations that deviate from the optimal conditions that we have defined, such as the current ROD operations that contain seasonal and daily variations in flow releases. One of the advantages of the operation we have defined is that it is simple enough that it can be evaluated relatively quickly with our existing knowledge. More complicated scenarios that include variability in upper basin hydrology, dam releases, and tributary sand supply become much more difficult to evaluate, particularly over extended periods, and require models that are as yet not available. Currently, all that we can say is that deviations from the optimal operation, such as annual volumes that exceed minimum objective releases and/or seasonal and daily flow variations, will either reduce the rate of sandbar building or lead to continued erosion instead of accumulation. That is, the sandbar rebuilding rate under the optimal operation can be considered an upper bound.

The ability to evaluate more complex operational scenarios will require future research, and one of the reasons for conducting the analysis presented here was to identify areas with the greatest uncertainty. Considerable research and monitoring has been conducted to define the magnitude of tributary inputs and the rate at which these inputs are exported from the system by ROD dam releases such that we feel these components of the analysis are relatively well constrained. The greatest uncertainty lies with our understanding of the processes of sandbar building during high flows and readjustment during subsequent flows. For example, our estimate for the transfer of sand from the channel to sandbars during high flows is made on the basis of only two experimental releases, conducted in 1996 and 2004 (data from a third experimental high flow test in March 2008 are still being collected and analyzed as of this writing). Also, significant uncertainty exists as to the rate at which recently deposited sandbars are eroded by subsequent flows, particularly under steady flows.

CONCLUSIONS

Despite extensive research and monitoring over the past several decades, the question of whether sandbars can be rebuilt and maintained in a sustainable manner along the Colorado River in Grand Canyon below Glen Canyon Dam has remained unanswered. Here, we have drawn from this extensive literature to conduct a relatively simple analysis of the potential for rebuilding sandbars under what might be considered a "best-case scenario" in terms of hydrologic conditions and dam operations. Our analysis suggests that this scenario may indeed have viability for rebuilding sandbars. We estimate a potential sandbar rebuilding rate of ~200,000 t/yr, which is comparable to the estimated average sandbar erosion rate since dam construction of ~150,000 t/yr. However, the similarity in these rates should not be used to infer that pre-dam conditions could be achieved in 40 years. Potential cumulative sandbar building would depend on how much of the annual accumulation is maintained between high flow events, how the system changes through time as accumulation occurs, and the frequency and magnitude of deviations in future annual release volumes from the minimum objective release. Deviations from our best-case scenario, such as seasonal variability in flow releases, daily flow fluctuations, or greater than minimum release volumes would either reduce the sandbar accumulation rate or result in continued erosion of sandbars.

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