

Sediment Response to Construction and Recent Adaptive Management of Glen Canyon Dam, Colorado River, Arizona

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ABSTRACT

Glen Canyon Dam has dramatically affected the sediment resources by eliminating the upstream source of sediment and changing the flow regime. The historical major source of sediment to the Grand Canyon is now deposited in Lake Powell and the tributary sources of the Paria River and the Little Colorado River now supply the Grand Canyon with a majority of the sediment input. The new flow regime created by Glen Canyon Dam has eliminated the historical periods during the year when sediment accumulated during low flows and when sediment was redistributed to high-elevation sand bars during the high flows. The obvious change in the hydrograph due to the dam has been the elimination of the annual high flow events but just as critical is the fact that the new flow regime is substantially more erosive due to the reduction in the duration of low flows that allow for sediment accumulation. This more erosive flow regime has substantially degraded the sand bar resources of the Grand Canyon that provide campsites for river runners and habitat for a diverse collection of native plants and animals that are now largely threatened. Efforts, including the 1996 and 2004 controlled floods, have been made to more effectively manage the sediment resources to benefit the vast amount of constituencies concerned with the Grand Canyon's future. While these efforts have provided many lessons for researchers, they have not reversed the trend of sand bar degradation. More research associated with the use of controlled high flow events needs to be done to better utilize the available sediment supply from tributaries to rebuild sand bars. However, since the loss of sediment supply to this system is so profound, the idea of sediment augmentation also needs to be explored.

INTRODUCTION

The name given to the river that created the Grand Canyon and now sits at its bottom, Colorado, means 'colored'. This name was once very appropriate in all stretches of the Grand Canyon due to the incredible amount of sediment transported by the river. This enormous amount of sediment would accumulate during the low-flow months and be redistributed as high

elevation sand bars during the high-flow months. These sand bars created substantial habitat for a suite of native plants and animals (see rest of volume).

Then, in 1963, the Glen Canyon Dam was completed in order to create an enormous amount of water storage to ensure that the Upper Colorado River Basin could deliver the specified amount of water stated in the Colorado River Compact to the Lower Colorado River Basin despite a highly variable flow regime. Several other objectives including hydroelectric power were also present in the construction of the dam. Once the Glen Canyon Dam was completed, the vast majority of sediment supplied to the Grand Canyon was cut-off by the dam-created reservoir. The 'Colorado' was no longer an appropriate name downstream of the dam as water was very clear due to this loss of sediment. Since then, the sediment resources of the Grand Canyon have been degraded by a flow regime that does not allow for the accumulation of sand or for the redistribution of sand to high-elevation sand bars.

This chapter explores the effects of Glen Canyon Dam on the sediment resources of the Grand Canyon. The basic mechanics behind sediment transport is first addressed to give the necessary background on the relationship between flow and sediment. Then, the effects of the closure of Glen Canyon Dam in 1963 are discussed. Next, the efforts of the adaptive management program of Glen Canyon Dam to conserve sediment resources starting in the early 1990's are presented. Finally, several conclusions and recommendations for the future of sediment resources management within the Grand Canyon are given.

SEDIMENT TRANSPORT: JUST THE BASICS

Rivers not only transport water, they also transport sediment that plays an invaluable role in the health of ecosystems. As sediment is transported, nutrients attached to sediment particles sustain ecosystem production. Sediment deposited within or alongside the river channel provides critical habitat for all aquatic organisms. However, before transport and deposition can be discussed in any detail, the basic mechanics behind these processes must be understood.

Since all sediment on Earth has been at rest for at least one moment in time, a discussion of the balance of forces that act upon a single particle of sediment at rest (Fig. 1) is necessary. The forces acting to move this particle are drag (F_D), lift (F_L), and turbulence (F_T). The forces that keep a particle from moving are gravity (F_G) and the force (F_W) exerted by adjacent grains that the particle is wedged in between.

Perhaps the easiest force to recognize is the drag force exerted in the downstream direction by the moving water on the face of the particle. Based on the principal that velocity increases away from the channel bed, a vertical pressure difference develops across the particle and actually produces a lift force that acts vertically upwards on the particle. The turbulence force is caused by turbulent eddies formed behind the particle that also act to move the particle upwards in a sweeping motion. All three of these forces increase as the river velocity and depth increase (i.e. flow increases).

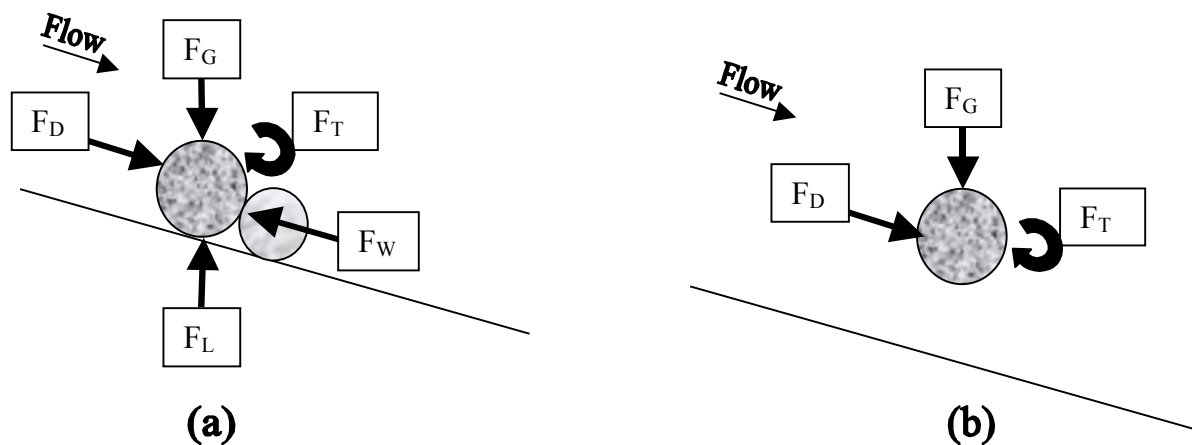


Figure 1. Forces acting on a sediment particle at rest (a) and in suspension (b).

Conversely, the forces acting to keep the particle where it is are not directly-related to the flow conditions. The force of gravity (i.e. the submerged weight of the particle) is a function of the density and size of the particle. Also, particles are often wedged in between other particles on the bed; thus a force exerted onto the particle of interest by its neighbors can develop and is only a function of the arrangement of this neighborhood of particles. Since neither of these forces are directly-related to the flow conditions, if the river's velocity and depth increase, the forces acting to move the particles increase while the forces keeping it in place remain the same. Therefore, with higher flows the larger forces can move more and larger particles of sediment. This idea is the basis for using controlled high flows to redistribute sand in the Grand Canyon.

Once the particle is lifted off the channel bed, some of the forces previously mentioned are no longer factors. The lift force is no longer a major player because the differences in velocity above and below the particle are not large enough to create a significant pressure difference. Also, since the particle is no longer in contact with the bed, the wedging forces are no longer present. So all that is left is drag (F_D , moving the particle downstream), turbulence (F_T , keeping the particle in suspension), and gravity (F_G , pulling the particle back down towards the bed). However, if the particle is in suspension, the velocity at which the particle falls due to gravity is an important factor influencing how the particle is transported downstream. This settling velocity is a function of the particle's density, size, and shape. Even though this settling velocity equation does not hold true for turbulent flows (because the turbulence force acts to keep the particle in suspension), the main principle holds true in all flows: the finer the particle, the smaller the settling velocity and therefore the finer the particle, the longer it stays in suspension. This principle explains why fine sediment in a flood wave travels faster than coarser sediment and may create flood deposits that fine upwards (depending on availability of sediment). This phenomenon also occurred in the controlled flood of the Grand Canyon in 1996 when the finer sediment quickly moved through the system and was exhausted within the first few days of the flood leading to sand bar erosion in the final days of the flood.

Given the preceding elements of sediment transport, the sediment load of a river can be classified into two elements: suspended load and bed load. Suspended load consists of sediment small enough to remain suspended in the water while bed load consists of sediment that is too large to stay in suspension but small enough to allow forces to overcome the threshold for initial motion. Suspended load transport is a continuous process, yet the paths of particles are not straight lines as the forces of turbulence work in a chaotic manner. The paths of bed load particles in transport are also inherently irregular due to the heterogeneity of the bed surface and the chaotic behavior of turbulence. Finally, it is important to recognize that the relationship between suspended load and bed load is a continuum because the velocity and depth of the river can change greatly through time. A particle that is transported along the bed during low flow may be a part of the suspended load during a flood event. Also, a large cobble-size particle in a debris flow deposit at the base of the Grand Canyon may be immobile for years and then a large flood could mobilize it as it becomes part of the bedload.

By looking at the initial motion and the transport of sediment, we now know that the river's ability to transport sediment increases with higher velocity and depth. Two concepts are commonly used to characterize this relationship: competence and capacity. The competence refers to the largest particle that the flow can transport and the capacity is the maximum amount of sediment that the flow can transport. Both competence and capacity increase with higher flow.

In addition to capacity and competence, sediment transport within a river is a function of the total sediment contribution from the upstream area. This concept is known as sediment yield and is the total sediment outflow from a basin over a specified time period. As this sediment moves through a watershed it is temporarily or, in some cases, permanently stored within

channels, bars, and floodplains. A sediment budget encompasses these concepts by accounting for the sources of sediment, routes that sediments take to and through the channel, and considers various opportunities for storage within the system.

SEDIMENT IN THE GRAND CANYON

The very name given to the Colorado River alludes to its sediment-laden water. For thousands of years, the vast majority of this sediment derived from upstream sources in the Upper Colorado River Basin. This upstream source accounted for an estimated sediment yield of 57 million tons per year (MTPY) at the Lees Ferry gage (Topping et al. 2000) (for gage locations, see Fig. 2). The next two biggest contributors of sediment were the Paria River, which yielded an estimated 3.0 MTPY and the Little Colorado River, which provided approximately 8.6 MTPY to the Colorado River (Topping et al., 2000). After the two main tributaries and various other smaller ungaged tributaries joined the main-stem of the Colorado River, the sediment yield at the Grand Canyon gage was approximately 83 MTPY (Topping et al. 2000).

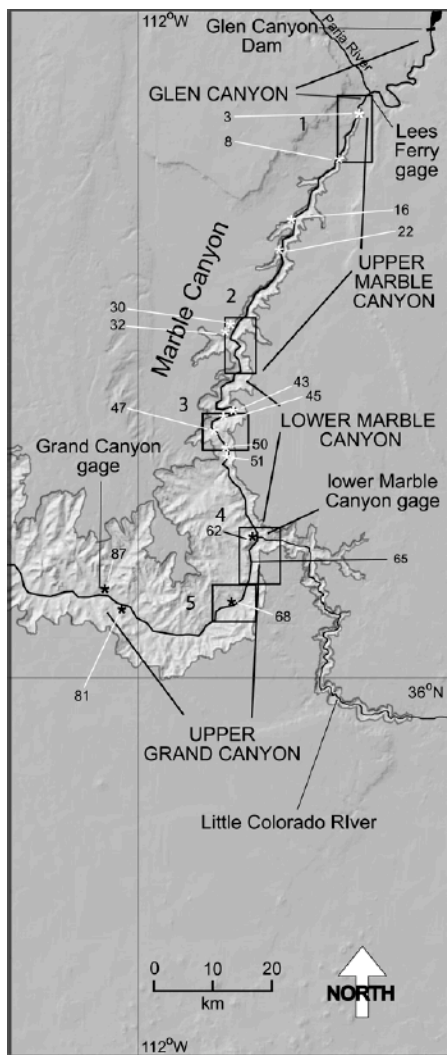


Figure 2. Map of study area which includes the major sources of sediment to the Colorado River in the Grand Canyon: Paria River and Little Colorado River.

Then in 1963, the Glen Canyon Dam was finished and the main source of sediment was trapped behind the dam in Lake Powell. The Upper Colorado River Basin is now only contributing approximately 0.24 MTPY, a loss of 99.5% (Topping et al. 2000). Now that this main source is cut off, the two large tributaries downstream from the dam (Paria River and Little Colorado River) play much larger roles at 70-80% of the total sediment yield at the Grand Canyon gage, which is estimated to be only 14 MTPY (down from approximately 83 MTPY before the dam) (Topping et al. 2000).

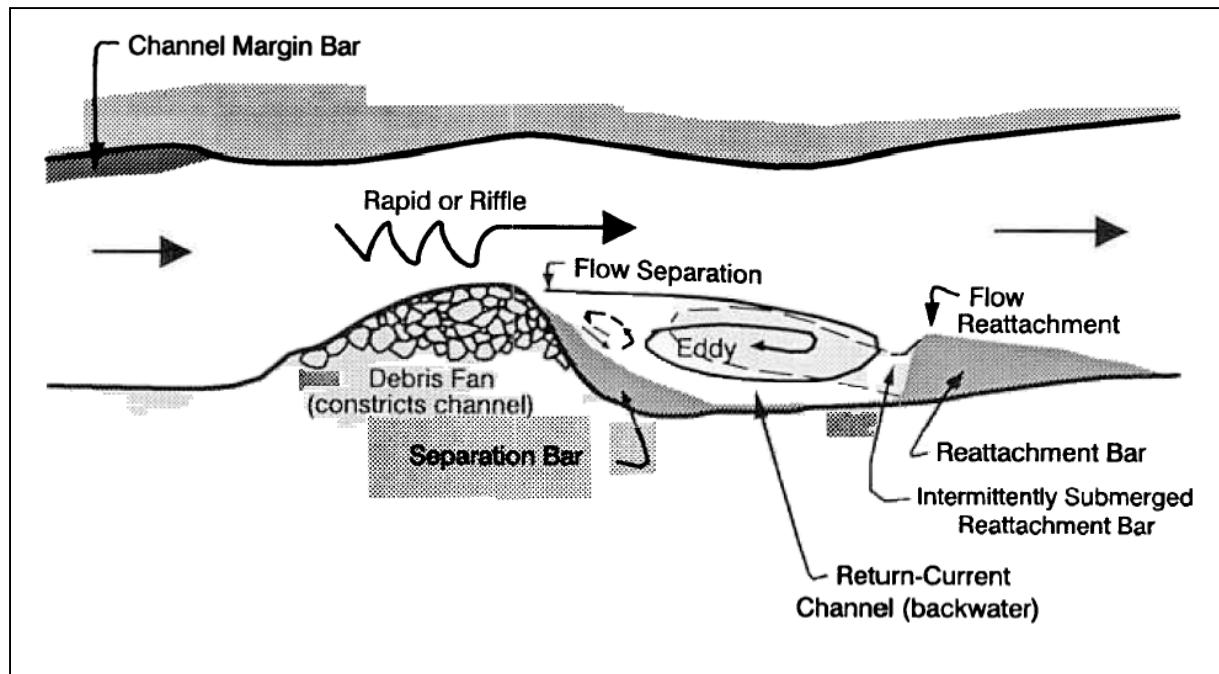


Figure 3. Diagram showing the three types of sand bars found along the Colorado River: channel margin, separation, and reattachment. (U.S. Department of the Interior, 1995)

With or without the dam, however, the storage of sediment within the Colorado River is essential for ecosystem processes. The two main storage units (or sinks) can be divided up into sand bars and the channel bed itself. Figure 3 shows three types of sand bars that are common in the Grand Canyon: channel margin, separation, and reattachment. The first type, channel margin bar, is formed by a small eddy caused by some flow obstruction such as a boulder. These bars can occur at any point along the river bank as long as an obstruction is present. The second and third types, separation bar and reattachment bar, are formed immediately downstream from a flow constriction (usually associated with a debris flow) where an eddy occurs (see Fig. 3). The turbulent and high velocity flows in the constriction (i.e. rapids) suspends fine sediment that is

subsequently deposited in the tranquil eddy currents. The river segment consisting of a debris fan constriction, downstream eddy, and eddy deposits is referred to as a fan-eddy complex (Buer 2005, this volume). The channel bed is the other main storage unit and can also hold vast amounts of sediment during low flow periods.

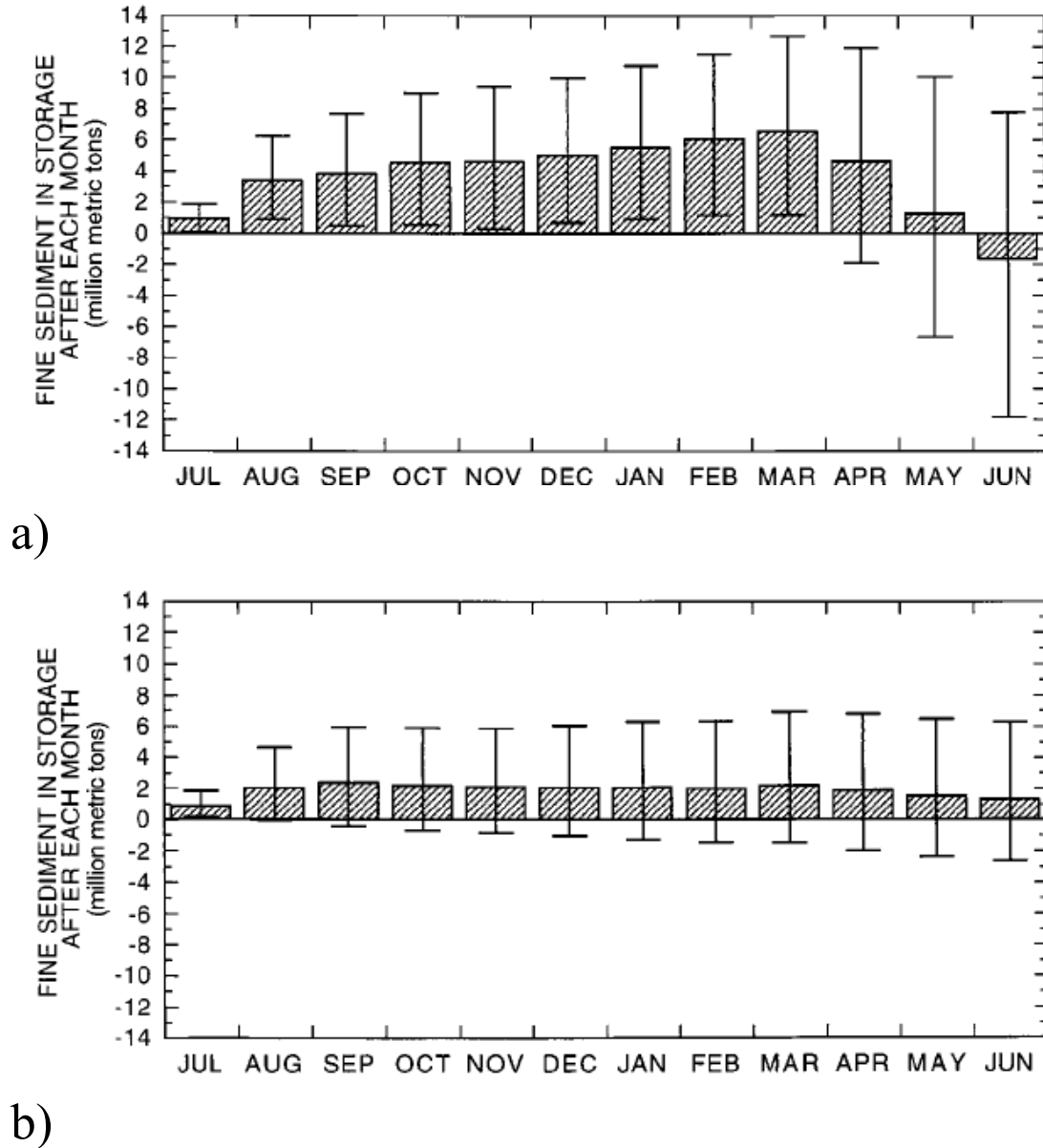


Figure 4. Amount of fine sediment storage in Marble Canyon and Upper Grand Canyon during the average pre-dam year (a) and the average post-dam year (b) (Topping et al., 2000)

GLEN CANYON DAM'S EFFECT ON SEDIMENT

There were two significant impacts of the closure of Glen Canyon Dam on the Colorado River. First, as explained in the previous chapter, the hydrology has been significantly altered with the late spring-early summer floods and the sediment-accumulating low flows during the rest of the year both virtually eliminated. Second, 81-85% of the pre-dam sediment yield at the Grand Canyon gage has been lost because of the dam's remarkable ability to trap sediment (Topping et al. 2000). The combination of these two impacts has created a very different river system. The reduction in sediment supply was larger than the reduction in the capacity of the river to transport sediment which caused the river to become supply-limited (Schmidt et al. 2004).

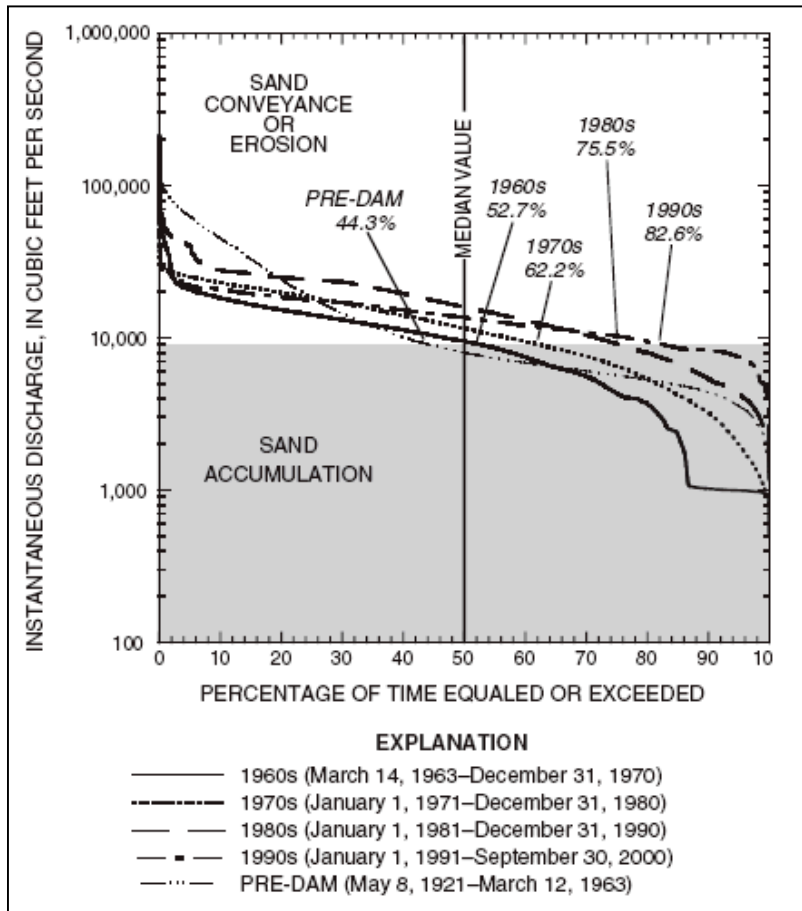


Figure 5. Flow-duration curves for the pre-dam flow record at the Lees Ferry gage and for the subsequent decades after the closure of Glen Canyon dam. (Topping et al., 2003)

The dam has also affected the seasonal differences in fine-sediment storage in the Grand Canyon (see Fig. 4). During the pre-dam era, rapid accumulation of fine-sediment in Marble

Canyon and Upper Grand Canyon occurred in July and August and remained in storage throughout the low-flow period of the year until March (Topping et al. 2000). Then, during the snowmelt floods occurring between April and June, this sediment storage was eroded away (Fig. 4a). For the post-dam era, this large seasonal change no longer takes place. Due to uncertainties in the sediment budget, sand cannot be shown to accumulate for more than 1 month or remain in storage for more than 2 months during the average post-dam year (Fig. 4b). Figure 4 also shows that no net erosion or accumulation can be shown to take place during both the pre-dam and post-dam eras due to sediment budget measurement uncertainties. These uncertainties are common in bedrock canyon reaches where storage is small compared to the overall sediment budget.

While there were significant accumulation and erosion events in the pre-dam sediment regime, only 44.3% of the time flow was above the sand conveyance or erosion threshold of approximately 9,000 cfs (255 cms) (Fig. 5). So more than half of the time, the capacity of the river to transport sediment was very small and sediment was accumulating within the Grand Canyon. In contrast, once Glen Canyon Dam was built, more than half of the time flow is above the sediment conveyance or erosion threshold where the capacity of the river to transport sediment is substantial. The time spent above that threshold actually increased substantially every decade after the closure of the dam due to the fact that the reservoir was not full until 1980 and due to management changes in the 1990's (Fig. 5).

So the sediment budget by Topping et al. (2000) suggests that no net erosion is taking place but the post-dam flow regime has been shown to be significantly more erosive than the pre-dam flow regime. One possible explanation for these seemingly contradictory conclusions is that the more erosive flow regime is acting more to redistribute the sand rather than causing net erosion. Another explanation may be that the sediment budget (which was only conducted in 1966-1970 for the post-dam era) does not reflect what is occurring currently in the canyons or that the measurement uncertainties were too large to detect slow but consistent rates of net erosion.

However, even if we assume the sediment budget is outdated, the redistribution of sand is definitely occurring. Since the sediment and flow regimes have been significantly altered due to the dam, the river channel is approaching a new state of equilibrium. This new channel shape is the result of the high elevation sand bars being replaced by low-elevation sand bars. The high-

elevation sand bars historically appeared above the current river stage fluctuations while the low-elevation bars exist within the river stage fluctuations.

The causes of sand bar erosion are mostly due to the flows with low suspended sediment concentrations that have the capacity to erode and transport sand away from the sand bars. Also, work done by Budhu and Gobin (1995) shows that seepage erosion can cause substantial erosion of sand bars during the daily ramp-down period provided by the dam. If the river stage is lowered faster than the water can drain from the sand bars, excess pore-water pressure can develop within the sand bar. In combination with excess pore-water pressure, seepage forces, and without the stabilizing water pressure provided by the river against the sand bar, slope failures can often occur (Budhu and Gobin 1995). The result of these slope failures can be a dramatic loss in the volume of sand bars.

The changing river channel shape has also resulted in the loss of backwaters, once formed by eddy currents associated with large flows. These currents scoured away fine sediment that were deposited in the backwater areas during the low-flow parts of the year. After the dam was built, these large flows occurred much less frequently and consequently, the backwater areas were quickly filled in with fine sediment. Losing the process of high elevation sand deposition due to the dam has also allowed vegetation to encroach onto sand bars that were once disturbed on an annual basis. The loss of these critical-habitat backwaters and the encroachment of vegetation are subjects of later chapters.

MANAGEMENT ATTEMPTS AT REDUCING SAND BAR EROSION

Starting in 1982 with the initiation of the Glen Canyon Environmental Studies (GCES), the managers of Glen Canyon Dam have made an (often unsuccessful) effort at attempting to reduce sand bar erosion in Marble and Grand Canyons. Despite conflicting studies in the 1970's and early 1980's about whether sediment was accumulating (the prevailing view until recently) or eroding from the Grand Canyon due to Glen Canyon Dam, most studies and anecdotal evidence showed that sand bars were being lost and subsequent ecosystem changes were taking place (Schmidt et al. 2004). When changes to Glen Canyon Dam power generation operations were proposed in 1980, the GCES became the first systematic effort to investigate the effects of proposed operations on downstream resources. Throughout the 1980's, much was learned about the sediment resources of the Grand Canyon thanks in part to the large flood in 1983. Before the

big flood, Beus et al. (1985) analyzed sand bar surveys and concluded, “On balance there was slightly more loss than gain suggesting a gradual depletion of beach sand from the terraces studied.” After the 1983 flood, Beus et al. (1985) became one of the first to suggest that “occasional high water ‘spills’” from Glen Canyon Dam could be used to maintain beaches.

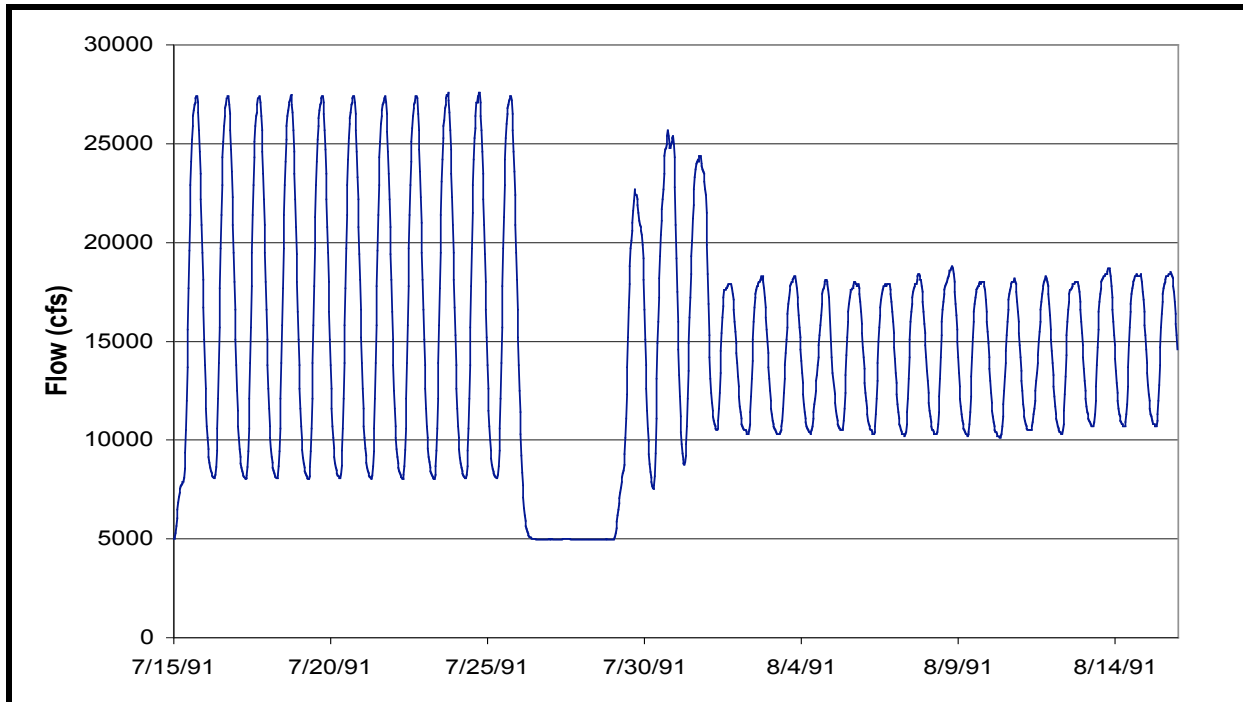


Figure 6. Streamflow at Lees Ferry gage on Colorado River during the 1991 transition to interim flows. (Data courtesy of Grand Canyon Monitoring and Research Center)

By 1989, substantial public concern from the initial findings of the GCES led to the initiation of the Environmental Impact Study that would last until 1996 when a Record of Decision was made on the Final Environmental Impact Statement (EIS). In 1990, modifications to Glen Canyon Dam operations as a research tool were made for the first time in the dam’s history (Patten et al. 2001). These research flows conducted in 1990-1991 consisted of three two-week steady-flow periods that would investigate the responses of river resources to different dam releases. These flows led to interim flows that began in August of 1991 (Fig. 6) and signified the first time that dam operations were modified to protect environmental resources at the expense of power revenues. The requirements of the interim flows are the following:

- Discharges no lower than 5,000 cfs (142 cms)
- Discharges no lower than 8,000 cfs (227 cms) during the day

- Discharges no greater than 20,000 cfs (566 cms)
- Maximum up-ramp rate: 2,500 cfs/hour (71 cms/hour)
- Maximum down-ramp rate: 2,500 cfs/hour (71 cms/hour)

They represent attempts to accumulate sand by reducing the maximum discharge and daily fluctuations and to reduce seepage erosion by decreasing the down-ramp rate of the dam releases. However, according to Figure 5, these interim flows of the 1990's actually increased the percentage of time that flow was above the conveyance/erosion threshold to 82.6%. Thus, the sand bars of the Grand Canyon continued to erode without the presence of large beach-building flows.

1996 RECORD OF DECISION AND EXPERIMENTAL FLOOD

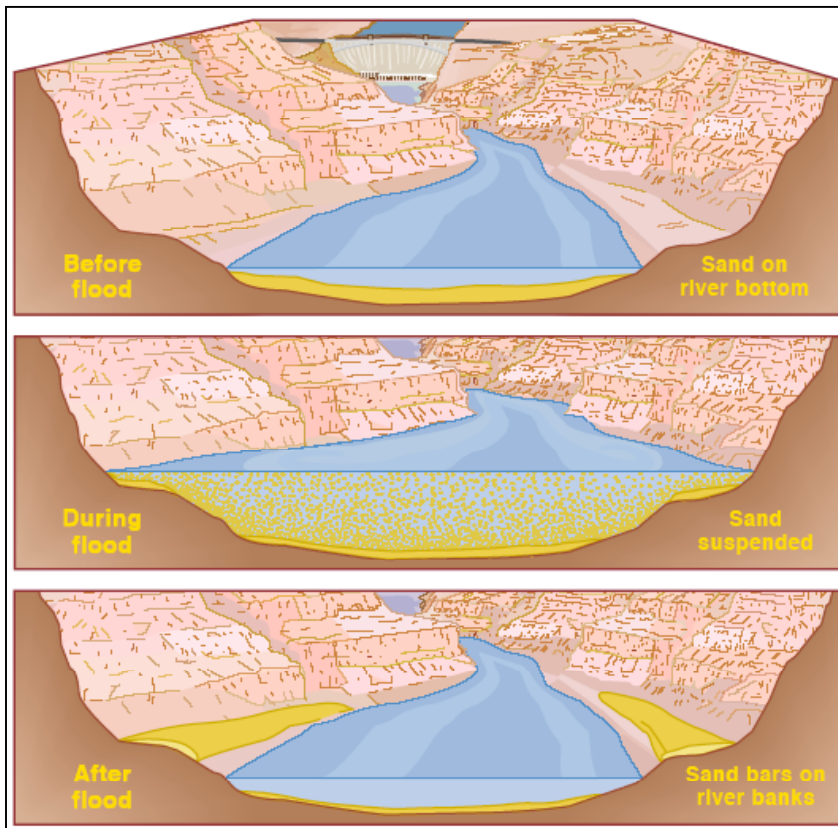


Figure 7. Diagram of the process of sand suspension and deposition predicted to occur during beach/habitat-building flows. (Anderson et al., 1996)

The Glen Canyon Dam Final EIS was completed in March of 1995 and presented several alternatives for managing dam operations. In the 1996 Record of Decision, the Secretary of Interior chose the preferred Modified Low Fluctuating Flow Alternative (MLFFA). The MLFFA requirements were very similar to the interim flow requirements except the maximum discharge was increased to 25,000 cfs, the maximum down-ramp rate was decreased to 1,500 cfs/hour, and the maximum up-ramp rate was increased to 4,000

cfs/hour. The MLFFA also included the use of Habitat Maintenance Flows (HMF) and

Beach/Habitat-Building Flows (BHBF). The HMFs would be approximately 32,000 cfs and occur on average once every year while the BHBFs would be approximately 40,000 cfs and occur on average every five years. The two hypotheses associated with the MLFFA were that 1) sediment would accumulate under normal dam operations over multiple years and 2) the BHBFs and HMFs would redistribute this accumulated sediment and rebuild sand bars (U.S. Department of Interior 1995). Figure 7 shows this predicted process of sand going into suspension and being deposited to rebuild sand bars along the channel margins.

The management of Glen Canyon Dam implemented the first BHBF in March of 1996 with a 7-day 45,000 cfs release. The idea that large amounts of sediment would be redistributed throughout the channel was quickly reinforced within the first few hours of the flood. Andrews et al. (1999) monitored five eddies and their sand bars during the flood and reported that sand bars aggraded and degraded by as much as 11.5 ft [3.5 m] within less than 24 hours. Despite this large variation, Hazel et al. (1999) monitored thirty-three study sites in fan-eddy complexes and showed that the flood caused widespread sand deposition at high elevations (10 to 16 ft [3 to 5 m] above the MLFFA minimum flow level). The average increase in volume of this high-elevation sand was 164%, the average increase in area was 67%, and the average increase in thickness was 2.1 ft [0.64 m] (Hazel et al. 1999).

The source of sand to these high elevations was predicted to be mostly from the channel bed according to the Final EIS (U.S. Department of Interior 1995). However, Rubin et al. (2002) points out that a sand budget conducted by Schmidt (1999) indicated that more than half of the sand deposited at higher elevations was cannibalized from the lower elevation sand bars rather than redistributed from the channel bed as originally hypothesized in the reach between Lees Ferry and the Little Colorado River. Downstream from the Little Colorado River, the channel bed became a larger source of sand for high elevation bars (Schmidt 1999). Thus, the channel bed still provided a large portion of the sand source but due to the limited sediment re-supply in upstream parts of the system, the lower elevation sand bars were more of a significant source than originally thought (Rubin et al. 1994).

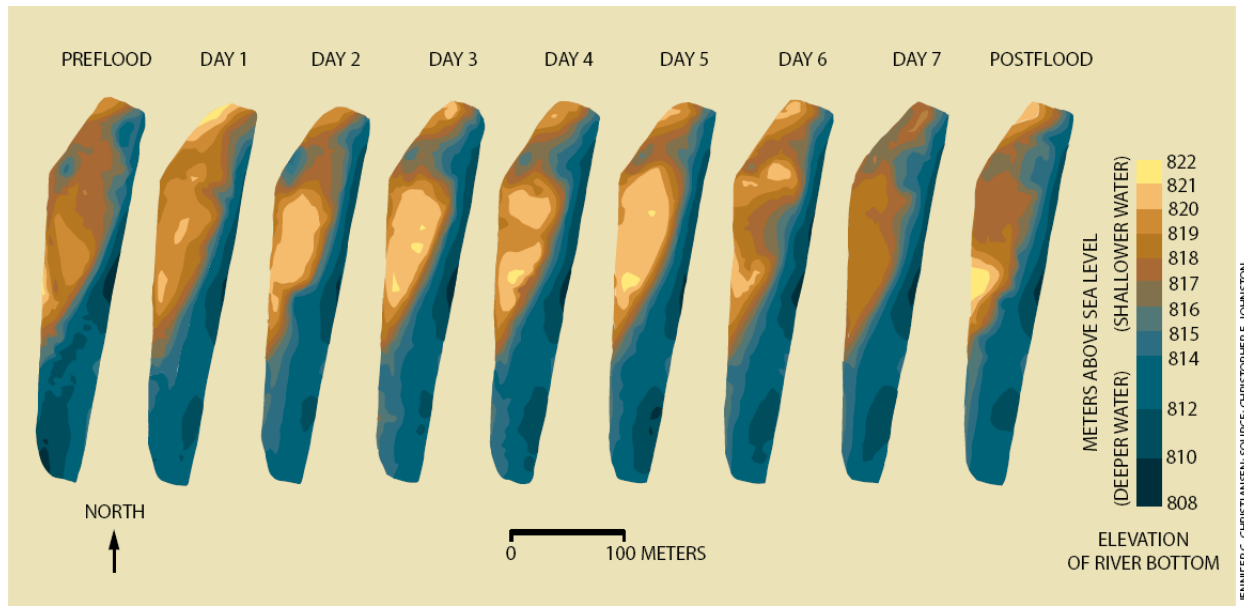


Figure 8. Sand bar evolution within an eddy before, during, and after the 1996 Experimental Flow showing the accumulation of sand within the first few days and the subsequent loss of sand back into the main channel during the last few days. (Collier et al., 1997)

This limited sediment re-supply was characterized by a decreasing concentration in suspended sediment as the flood progressed, as well as by sand bars that quickly aggraded and then eroded after the first few days (Fig. 8). Several studies indicated that even though the flood consisted of a constant flow for 7 days, the suspended sediment concentrations decreased throughout the entire Grand Canyon after the peak occurred on the first day or two (Schmidt 1999). This decrease is actually reminiscent of pre-dam floods since the Colorado River was, and still is, supply-limited. However, the Final EIS did not predict this sediment depletion because U.S. Department of Interior was under the impression that fine sediment was accumulating during the years prior to the experimental flood. This assumption also depended upon a constant relationship between suspended sediment concentration and flow, which was clearly not the case as these concentrations decreased in time during the constant flow (Topping et al. 1999).

Due to the major evidence of sediment-limitation presented by several studies (Topping et al. 1999, Schmidt 1999), researchers began to question the validity of the assumptions given in the Final EIS. In 2002, the research community finally agreed to reject the hypothesis that sand supplied by tributaries would accumulate over several years during normal dam operations and be able to be redistributed during experimental floods (Rubin et al. 2002). The revised

conceptual model was that tributary sand inputs were exported rapidly (weeks or months) from the channel during normal dam operations (Rubin et al. 2002). Another conclusion of Topping et al. (1999) was that the bed sediment was also significantly coarsened over the course of the flood which indicated a decrease in suspended sediment concentration. This coarser sediment also “armored” the channel by preventing more fine sediment to become suspended. Some researchers suggested that since the sediment supply decreased after the first few days of the flood, controlled floods should be of shorter duration so that the work of redistributing the sand is not lost by erosion after the sediment resources have dwindled (Schmidt 1999, Topping et al. 1999). These suggestions would spawn shorter duration Habitat Maintenance Flows (HMFs) in

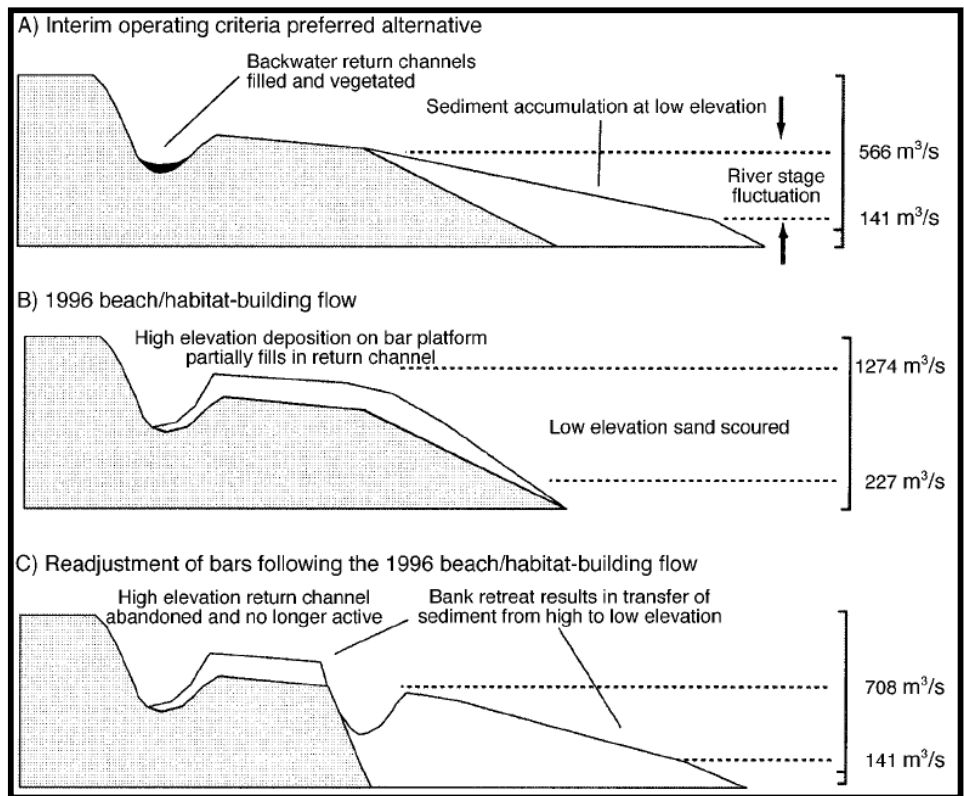


Figure 9. A diagram representing the processes of sediment deposition during the controlled flood and erosion afterwards. (Schmidt et al., 2001)

erosion rates (9% loss by volume each month) during the 5 months after the flood (Hazel et al. 1999). The erosion rate decreased to 2-4% per month in the next five-month period (Hazel et al. 1999). Figure 9 is a diagram representing the processes of sand bar deposition and the subsequent erosion associated with the controlled flood. Figure 10 shows the changes in areas of the low-elevation and high-elevation sand bars before and after the controlled flood.

1997 and 2000.

The monitoring effort also quickly recognized the instability associated with these new higher elevation sand bars as slope failures occurred within the river stage fluctuation zone after the flood. This instability was apparent by the large sand bar

1997 & 2000 HABITAT MAINTENANCE FLOWS (HMF)

The second form of experimental flow provided by the Modified Low Fluctuating Flow Alternative (MLFFA) was the Habitat Maintenance Flow (HMF). The first time an HMF was conducted was in November of 1997 after significant late-summer sediment inputs from the Paria River had partially accumulated in Marble Canyon. Unfortunately, as seen in Figure 10, this 2-day flow of a constant 31,000 cfs did not reverse or even affect the degrading trend in high-elevation sand bar area and only slightly increased the area of low-elevation sand bars in the Grand Canyon. According to Hazel et al. (2000), the reason for this ineffective result was due to the fact that “the stage change was not high enough to redistribute sand to areas where depositional sites were open”.

Despite this discouraging evidence, two more HMFs took place in 2000 (May and September). Both HMFs consisted of a constant 30,000 cfs flow for a duration of 4 days and did not correspond with tributary sediment inputs. As seen again in Figure 10, both HMFs in 2000 had little effect on the cumulative area of both high-elevation and low-elevation sand bars due to the fact that stage change was not high enough.

2002 PROPOSED EXPERIMENTAL FLOWS AND 2004 HIGH FLOW

In 2002, the management of Glen Canyon Dam proposed the addition of more experimental flows to the MLFFA arsenal as well as a “set of hydrological scenarios and

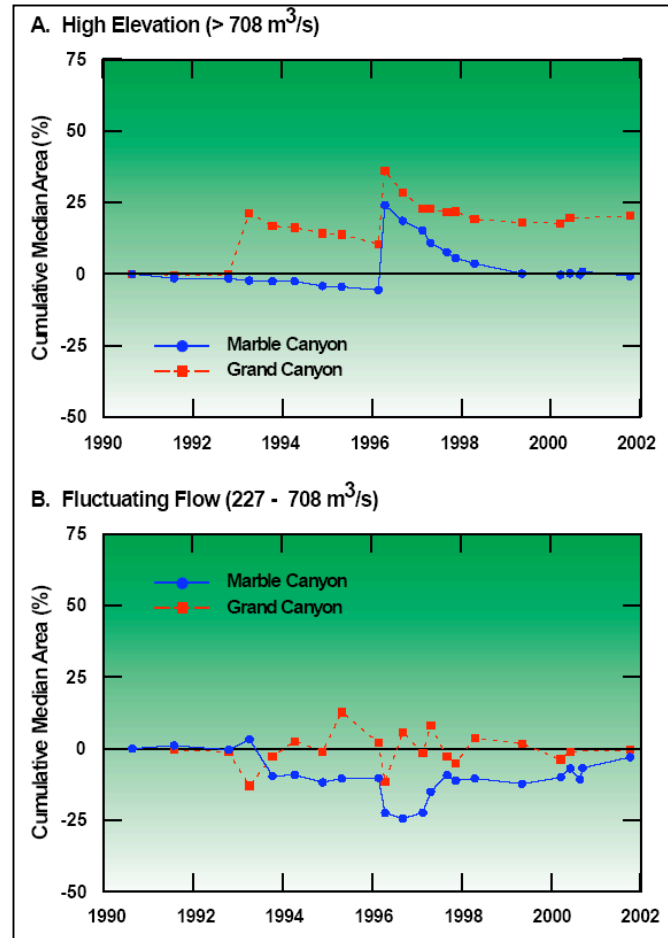


Figure 10. Cumulative mean sand bar area from September 1990 to October 2001. A) High Elevation sand bars B) Low Elevation sand bars. (Hazel et al., 2002)

experimental dam releases that are triggered by minimum sediment inputs to the Colorado River from tributaries” (U.S. Department of Interior 2002). The additional experimental flows consisted of:

- 8,000 cfs [225 cms] steady flows
- 6,500-9,000 cfs [185-255 cms] fluctuating flows
- 5,000-20,000 cfs [140-565 cms] fluctuating Non-Native Fish Suppression flows
- 31,000-33,000 cfs [880-935 cms] Habitat Maintenance Flow, and
- 42,000-45,000 cfs [1190-1275 cms] High Flow

The first two lower flows were designed to compete against each other with the flow having the best potential to accumulate fine sediment in the channel winning out after careful monitoring. The Non-Native Fish Suppression flows, beginning in 2003, occur every year in January through March. Normal MLFFA flows occur during the rest of the year unless specific sediment input scenarios develop at which point a HMF or High Flow would occur to beneficially redistribute these inputs.

The first High Flow took place in November of 2004 when 42,000 cfs was released for a duration of four days following necessary sediment inputs from the Paria River. Monitoring and data analysis from this flood is currently being undertaken and no definitive conclusions have been reached yet. However, at the Fall 2004 American Geophysical Union, Melis et al. mentioned that preliminary anecdotal evidence suggest that this most recent flood was less successful than the 1996 flood.

CONCLUSIONS & RECOMMENDATIONS

If any restoration strategy is to be successful, it must be recognized that the Colorado River below Glen Canyon Dam has been severely changed due mainly to the remarkable decrease in sediment supply. The natural flow regime has also been severely changed by significantly reducing high flows and decreasing low flows that once accumulate vast quantities of sand. However, even if the pre-dam flow regime was reinstated, this would result in a dramatic net loss of fine sediment due to scour by water with very low suspended sediment concentrations.

At first, the general hypothesis was that the sediment limitation was not as big of a problem as the reduced floods because sediment accumulated in Marble and Grand Canyons

under normal dam operations. This same hypothesis was echoed in the 1995 Glen Canyon Environmental Impact Statement and subsequent Record of Decision by recommending experimental floods to redistribute this accumulated sediment to the higher elevation sand bars. Recently, this hypothesis has been rejected and fine sediment has been shown to be exported from the Marble and Grand Canyons within the weeks or months following tributary sediment inputs (Rubin et al. 2002).

Without large controlled floods, the channel will tend towards an equilibrium condition with very little high elevation (exposed) sand bars while low elevation (underwater) sand bars would likely remain but be significantly smaller compared to pre-dam conditions. Even the 1996 Record of Decision recognized that without these floods, “any flow regime will result in continued loss of beach and backwater habitat” (U.S. Department of Interior 1996). However, large controlled floods are a double-edged sword because as they can build sand bars by redistributing sand from low elevations to high elevations, they are exporting vast amounts of sediment out of the system (Rubin et al. 2002). Therefore, it is a critical task to investigate the most effective and efficient way to utilize all fine sediment in the Marble and Grand Canyon systems to build sand bar habitat.

The large reduction in sediment supply due to the dam has dramatically changed where this fine sediment is stored in the channel. In the pre-dam era, there was usually substantial sand accumulation on the channel bed as well as some in the eddy areas (low-elevation sand bars) (Schmidt et al. 2004). In the post-dam era, the major storage site throughout the year is no longer on the channel bed but in the eddies where low-elevation sand bars are present. Post-dam floods are now primarily redistributing these low-elevation sand bars to higher elevations which produces an unstable bar configuration leading to high sand bar erosion rates immediately following these flood events. Therefore, there is now more effort to time the controlled floods with large tributary sediment inputs so that the channel bed consisting of this new sediment is a larger contributor to high-elevation sand bars than in previous post-dam floods. However, as Schmidt et al. (2004) points out, even with this management, the “fate of fine sediment deposits in the Colorado River ecosystem is bleak, because post-dam sediment transport is derived from a progressively declining bank account of fine sediment.” The duration of low flows that can accumulate fine sediment in the channel is just not long enough to provide a significantly large fine sediment source during controlled floods.

At this point in the adaptive management of Glen Canyon Dam, the best chance at conserving fine sediment resources is to time High Flows (not the ineffective HMFs) following large tributary sediment inputs as in the Fall 2004 controlled flood. In order to best accumulate these inputs on the channel bed, a constant flow of 8,000 cfs should be used immediately after the first detection of this sediment input until a sufficient supply has accumulated at which point the controlled flood can occur. Flows above approximately 10,000 cfs will quickly export tributary fine sediment inputs and should be avoided during this time. The latest sediment monitoring technology should be used to detect this tributary sediment input (most likely located on the Paria River tributary) in as close to a real-time fashion as possible. If these floods induced by tributary sediment inputs are as ineffective as the 1996 Experimental Flood at developing stable sand bars, the idea of sediment augmentation from the Glen Canyon reservoir bottom should be considered as an additional sediment source alternative.

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