The State of the Colorado River Ecosystem in Grand Canyon

A Report of the Grand Canyon Monitoring and Research Center 1991-2004

Edited by Steven P. Gloss, Jeffrey E. Lovich, and Theodore S. Melis

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This report is a scientific product of the U.S. Geological Survey. As such, it will be an important element in informing the policy dialogue for decisionmakers and stakeholders involved with or interested in operations of Glen Canyon Dam and the protection of downstream resources of Grand Canyon National Park. Like all scientific documents, however, it will be only one element of the policy dialogue. Ultimately, many other factors will also be considered by decisionmakers when they formulate official policy governing the operation of Glen Canyon Dam.

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Chapter 1

Influence of Glen Canyon Dam Operations on Downstream Sand Resources of the Colorado River in Grand Canyon

Scott A. Wright

Theodore S. Melis

David J. Topping

David M. Rubin

Introduction

The closure of Glen Canyon Dam and the beginning of flow regulation of the Colorado River through Grand Canyon in 1963 all but eliminated the mainstem sand supply to Grand Canyon and substantially altered the seasonal pattern of flows in the Colorado River. Dam-induced changes in both sand supply and flow have altered the sedimentary processes that create and maintain sandbars and related habitats, resulting in smaller and coarser grained deposits throughout the ecosystem.

From the perspective of river management, the ecological implications associated with such changes are not well understood and are the focus of ongoing integrated science studies. The effects of Glen Canyon Dam operations on fine-sediment resources (i.e., sand and finer material), particularly the erosion and restoration of sandbars, are of interest because sandbars are a fundamental element of the Colorado River's geomorphic framework and the landscape of Grand Canyon (see Webb, 1996; Webb and others, 2002). Sandbars are also of interest in terms of the essential role fine-sediment resources play in other ecosystem processes (U.S. Department of the Interior, 1995). For example, emergent sandbars create terrestrial habitats for riparian vegetation and associated fauna. Similarly, sandbars create areas of stagnant or low-velocity flow that may be used as rearing habitat by the endangered humpback chub (*Gila cypha*) and other native fish. Recreational river runners and other backcountry visitors frequently use sandbars as campsites. Finally, abundant sand and silt deposits near and above the elevation of typical predam floods contain archeological resources and protect those resources from weathering and erosion.

Conservation of Grand Canyon's fine-sediment resources is a primary environmental goal of the Glen Canyon Dam Adaptive Management Program. Despite this fact, the dam's hydroelectric powerplant operation under the Record of Decision (U.S. Department of the Interior, 1996) continues to erode the limited fine-sediment deposits that exist downstream. Changes in the abundance, distribution, size, and composition of sandbars began to occur under the no action period (historical operations) of dam operation from 1963 through 1991. Sandbar erosion continued despite changes in the operation of the dam that resulted from the implementation of the interim operating criteria in 1991 and the modified low fluctuating flow (MLFF) alternative in

1996. The MLFF was the preferred alternative identified in the 1995 Operation of Glen Canyon Dam Final Environmental Impact Statement (EIS) and was selected in the Record of Decision (U.S. Department of the Interior, 1996).

The U.S. Geological Survey's (USGS) Grand Canyon Monitoring and Research Center and its cooperators have conducted extensive monitoring and research on fine-sediment transport and sandbar evolution in Grand Canyon. This chapter presents a summary of the results of studies since the 1970s, as well as conclusions derived from recent syntheses of streamflow, sediment transport, and geomorphic data from 1921 to 2004, including recent sediment budgets. The effects of the MLFF operating alternative at Glen Canyon Dam (1996–2004) on fine-sediment transport and sandbars are examined in the context of these historical data. Finally, options identified by sediment scientists for testing alternative operations aimed at more effective conservation of fine-sediment resources are discussed.

Background

Predam Sediment-transport Processes

As described by Rubin and others (2002), sandbars below Glen Canyon Dam in Marble and Grand Canyons are maintained by fine sediment that is transported by the Colorado River through the ecosystem. As sand is carried through these bedrock canyons by the river, some of it is deposited along channel margins and along shorelines within hundreds of eddies, thus building sandbars. The eddy areas, which are typically located immediately downstream from channel constrictions created by tributary debris fans, are susceptible to fine-sediment deposition because the flow tends to recirculate and be of lower velocity than the flow in the main channel. Using historical sediment-transport records from the Lees Ferry (RM 0) and Grand Canyon (RM 87) gages, Laursen and others (1976) and later Topping and others (2000b) identified that before closure of Glen Canyon Dam, sand would accumulate in the Colorado River channel during late summer, fall, and winter. Annual accumulation of sand in the channel during predam years apparently resulted from large sediment inputs from tributaries that occurred during periods of seasonal low flows in the main channel of the Colorado River. Following these periods of sand enrichment in the main channel, spring snowmelt floods would erode the accumulated sand from the channel and transport it out of the canyon, along the way depositing some of the sand in the low-energy eddy areas and thus leading to the building of the high-elevation sandbars. Following the spring replenishment of sandbars, some of this sand would in turn be redistributed to even higher elevations by winds (Topping and others, 2000b). On an annual basis, the inputs of sand to the system would approximately balance the export, maintaining equilibrium in background sand storage in the eddies.

Effects of Lake Powell on Sand Transport

Before the closure of Glen Canyon Dam in 1963, approximately 25 million tons (23 million Mg) of sand passed the Lees Ferry stream gage annually. With the addition of 1.7 million tons (1.5 million Mg) of sand from the Paria River, which joins the Colorado River just downstream from Lees Ferry, the total predam annual sand supply to Marble Canyon reached about 27 million tons (24 million Mg). At the end of Marble Canyon, the Little Colorado River joins the Colorado River and contributed, on average, about 1.9 million tons (1.7 million Mg) to the annual sand supply. Thus, the total predam sand supply to Grand Canyon, from the Colorado River upstream from Lees Ferry and with the Paria and Little Colorado Rivers combined, was approximately 29 million tons (26 million Mg).

Today, because Lake Powell traps all of the sediment upstream from Glen Canyon Dam, the Paria River is the primary source of sand to Marble Canyon, supplying approximately 6% of predam sand levels. In the case of Grand Canyon, Glen Canyon Dam has reduced its sand supply to primarily the contributions of the Paria and Little Colorado Rivers. Other lesser tributaries also contribute a small amount of sand to Grand Canyon, with an estimated cumulative supply that is approximately 10% to 20% of the mean annual load provided by the Paria River. Taken together, the contributions of sand from various sources provide Grand Canyon with approximately 16% of its predam sand levels. The findings presented here are drawn from Topping and others (2000b) and Webb and others (2000); readers interested in more details on the predam and postdam sediment budgets for Marble and Grand Canyons should consult these reports.

Effects of Dam Operations on Flow Frequency and Duration

Changes in the flow regime of the Colorado River since construction of Glen Canyon Dam have also been dramatic in terms of seasonal variability, as well as in terms of daily fluctuations that occur because of "peaking" hydroelectric power generation. Dam operations have altered seasonal variability by eliminating long-duration flood flows that occurred during the spring snowmelt and short-duration flood flows that occurred during the late summer and early fall thunderstorm season, as well as the very low flows that occurred during summer, fall, and winter. With regard to the highest flows, dam operations have reduced the 2-yr recurrence interval flood (i.e., the flood that occurs every other year on average) from 85,000 cubic feet per second (cfs) during the predam period to 31,500 cfs during the postdam period. In the predam era, discharge exceeded 9,000 cfs only 44.3% of the time, while in the postdam era this percentage has gradually increased by decade, from 52.7% in the 1960s to 82.6% in the 1990s. This decrease in the duration of low flows has important implications for sediment transport because Topping and others (2000b) showed that flows less than about 9,000 cfs result in accumulation of tributary sand inputs in the Marble Canyon and Grand Canyon reaches of the river, whereas flows above this generally lead to transport of new sand inputs through these reaches or erosion of sand from these reaches.

Dam operations have introduced large daily variations in discharge to generate hydroelectric power that tracks daily peaks in demand throughout the Western United States. Also, because peak energy demand varies seasonally in the West, with peak demand occurring in midsummer and winter, the month-to-month flow pattern related to dam operation is substantially different from natural, predam, seasonal patterns. Highest discharges in the river now occur during the two seasons when predam discharge had typically been the lowest, midsummer and winter. Furthermore, daily patterns of flow in the river have been altered by dam operations. For example, during the predam period the median daily range in discharge was only 524 cfs, whereas in the postdam era the median daily range increased to 8,580 cfs, a value greater than the predam median discharge. Before dam operation, the daily range in discharge exceeded 10,000 cfs only about 1% of all days; postdam, the daily discharge range exceeded 10,000 cfs on 43% of all days.

Initially, operation of the dam's powerplant was characterized mostly by unconstrained daily fluctuations that were designed to optimize electrical generation around peak daily demand, which had patterns that also varied on a monthly timescale related to seasonal changes in energy demand. From 1963 through 1991, these operations typically caused the Colorado River's discharge to fluctuate on a daily basis from less than 5,000 cfs to near powerplant capacity of about 31,000 cfs. These so-called "no action" daily operations (because they were considered the no action alternative in the EIS) were first altered in 1990 to facilitate experimental release patterns implemented through July 1991 as part of field investigations associated with the EIS on dam operations. The experimental flows of 1990–91 were then followed by "interim operating criteria" from August 1991 until October 1996, when Secretary of the Interior Bruce Babbitt implemented current Record of Decision dam operations. Implementation of the interim operating criteria in 1991, as well as the MLFF in 1996, constrained the change in discharge over any 24-h period to 5,000; 6,000; or 8,000 cfs, depending on the monthly volume-release schedule specified in the annual operating plan for the Colorado River Storage Project. The flow history of the Colorado River into Grand Canyon as measured at the Lees Ferry gaging station is shown in figure 1. These flow data illustrate a transformation of the Colorado River from a fluvial ecosystem with significant seasonal variability in the predam era to a postdam river ecosystem with little seasonal variability and substantial daily fluctuations.

Another important aspect of the MLFF operation is the schedule of monthly release volumes in relation to the seasonality of sediment inputs. Because of energy demand and hydropower economics, monthly release volumes are highest during months with high demand, including those in late summer. Historically, however, the late summer months were characterized by low mainstem flows and the highest tributary inputs, leading to sediment accumulation during the predam era. Postdam, high summer releases coincide with tributary inputs, leading to rapid export instead of accumulation. Therefore, not only has the sand supply been drastically reduced through the impoundment of Lake Powell, but the seasonal timing of low and high flows has also been both highly compressed and significantly shifted to later periods of the year that coincide with tributary sand inputs. The information in this section was taken from Topping and others (2003); readers with further interest in the Colorado River's hydrology, both before and after the dam was closed, should consult this report.

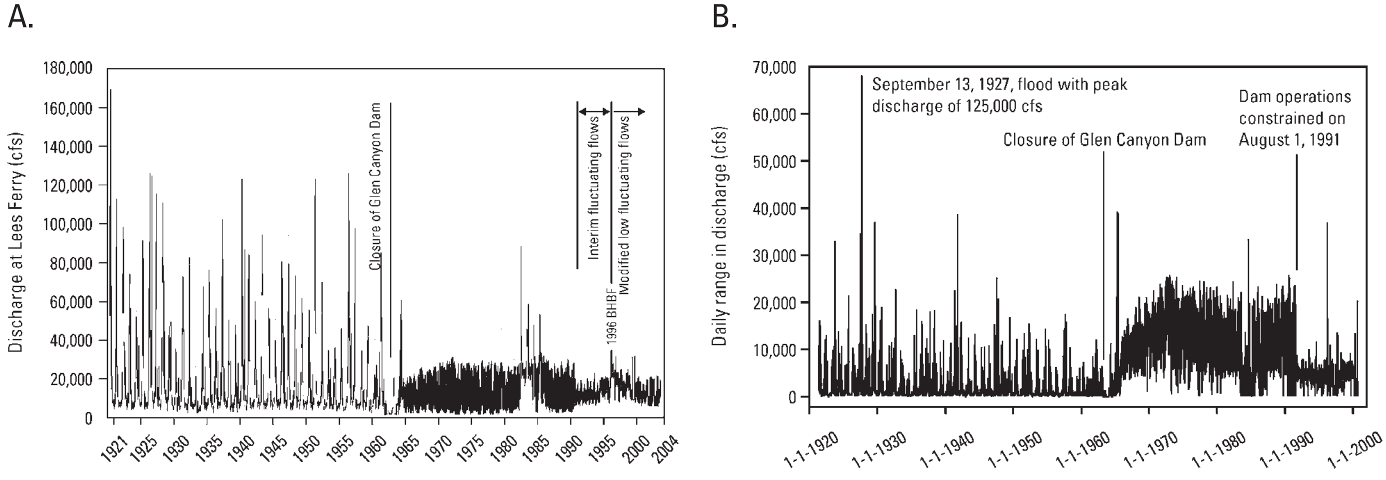

Figure 1. Instantaneous discharge (A) and daily range in discharge (B) in cubic feet per second of the Colorado River at Lees Ferry (RM 0) between 1921 and 2004 (modified from Topping and others, 2003). Before construction of Glen Canyon Dam, the annual peak flow routinely exceeded 100,000 cfs. Dam operations during the period from 1963 through 1990 were characterized by daily fluctuations from typically less than 5,000 cfs to near powerplant capacity, or about 31,000 cfs, and included the record wet period of the mid-1980s, which resulted in the use of the spillways in 1983 for emergency releases exceeding about 90,000 cfs. Interim operating criteria, which constrained daily release fluctuations, began in 1991 and were followed by the modified low fluctuating flow operating alternative that was implemented as part of the Secretary of the Interior’s Record of Decision (ROD) in 1996 (BHBF = beach/habitat-building flow).

Status and Trends of Fine Sediment Below Glen Canyon Dam

Changes in sand supply and flow regime downstream from a dam affect the geomorphology of the downstream channel. When a dam traps sand and releases clear water, this clear water is often termed “hungry” because it still has the capacity to transport an amount of sand and gravel proportional to the flow and will erode the downstream channel and banks in order to satisfy its appetite with respect to sediment transport. On the basis of resurveys of historical cross-sections upstream from Lees Ferry, approximately 20 million tons (18 million Mg) of material—gravel and fine sediment, including sand—have been eroded from the first 15 mi (24 km) of the Colorado River downstream from the dam, an area referred to in this report as the Lees Ferry reach (Grams and others, 2004). The amount of material removed is equivalent to a 6 to 10 ft (2–3 m) drop in channel elevation averaged over the entire reach. Most of this sediment was removed by daily, high-release dam operations designed to scour the channel of the Colorado River below the powerplant during April–June 1965 (fig. 1). Daily suspended-sediment measurements made by the USGS at the Lees Ferry and Grand Canyon gaging stations indicated that these high flows in 1965 eroded 4.4 million tons (4.0 million Mg) of fine sediment (mostly sand) from the Lees Ferry reach and 18 million tons (16 million Mg) of fine sediment (mostly sand) from Marble and upper Grand Canyons. Channel scour was anticipated below the dam during its design and was later needed to optimize energy generation within the operating range of the hydroelectric powerplant (Grams and others, 2004). Typical dam releases today do not result in much erosion from the Lees Ferry reach, and as a result very little fine sediment is transported downstream to Marble and upper Grand Canyons.

Despite the fact that its contributing drainage area is approximately 18 times smaller than that of the Little Colorado River, the single largest sand supplier to the reaches below Glen Canyon from 1990 through 2004 was the Paria River. Farther downstream in Marble and upper Grand Canyons, the fate of fine-sediment deposits is dependent upon the long-term balance between inputs to the system (i.e., tributary supply) and exports from the system (i.e., mainstem sediment-transport rates). Although sand inputs have been greatly reduced by the closure and operation of Glen Canyon Dam, the annual mainstem transport—and thus export—has also most likely been reduced because of the elimination of the highest flood flows. As a result, two possibilities exist for the postdam fine-sediment balance downstream from the Paria River. First, if the supply from the Paria River and other lesser Marble Canyon tributaries exceeds the postdam transport rate on an annual basis, then new sand inputs would accumulate in the channel and in low-elevation portions of eddies over multiple years. Such accumulated sand supplies would then be available at any time for redistribution to higher elevation sandbars through release of periodic controlled floods (i.e., beach/habitat-building flows in the EIS; hereafter BHBF) from Glen Canyon Dam. This scenario was the conclusion reached by Howard and Dolan (1981), Andrews (1990, 1991), Smillie and others (1993), and the EIS study team (U.S. Department of the Interior, 1995) for the MLFF alternative, leading to its implementation in 1996. Howard and Dolan (1981) reached their conclusion by using an estimate for the sand contribution from the lesser tributaries that is now regarded to be about a factor of four too high (Topping and others, 2000b; Webb and others, 2000). Andrews (1990, 1991) and Smillie and others (1993) reached their conclusions by using stable sand-transport relationships, also called “rating curves.” A stable sand-transport rating curve exists where there is a unique value for sand concentration for any given flow. This approach invokes the assumption that the upstream sand supply is in equilibrium with transport capacity. The methods and data used to reach the conclusion in the EIS are discussed further in the following section.

Alternatively, if the annual mainstem transport rate (export) exceeds tributary supply (input), then systematic long-term erosion of fine sediment from the channel would be expected. In fact, this second scenario was originally predicted by Dolan and others (1974) and Laursen and others (1976) on the basis of their early sediment-transport studies related to effects of Glen Canyon Dam on downstream resources. In order for high-flow releases to be effective at restoring and maintaining sandbars under this second scenario, controlled floods would need to be strategically timed to coincide with or immediately follow tributary sand inputs. These early studies predated the concept of using controlled floods to restore eroded sandbars; hence, their estimates of sand transport in the postdam era could only result in net export of new sand inputs and continued erosion of existing sandbars of predam origin. More recent evidence presented in the following section further supports the conclusion that this second scenario prevails under the current reoperating strategy and that this situation is leading to systematic, long-term erosion of fine sediment from the channel bed and eddies of Marble and Grand Canyons. On the basis of existing data, it is still uncertain whether or not strategically timed managed floods can restore and maintain eroded sandbars by using only the limited and infrequent tributary-derived sand that enters the river below the dam.

Recent Findings

The Paradigm of Sand Transport and Storage Used in the 1995 Environmental Impact Statement

The EIS concluded that sand would accumulate over multiyear timescales in the channel of the Colorado River in Marble and upper Grand Canyons during MLFF powerplant releases in all but the highest release years (U.S. Department of the Interior, 1995). The basis for this conclusion was the assumption that the relationship between the water discharge and sand transport in the Colorado River did not change substantially over time. This assumption was used because sediment-transport data collected in the postdam Colorado River were sparse.

Prior to the early 1970s, suspended-sediment concentration was measured on a daily basis at the three USGS gaging stations that are critical to constructing a sand budget for Marble and Grand Canyons: the Paria River at Lees Ferry, the Little Colorado River at Cameron, and the Colorado River near Grand Canyon. The sediment sampling program at the Colorado River near Grand Canyon gaging station began in October 1925; the daily sediment sampling programs at the Paria and Little Colorado Rivers began in October 1947. The Little Colorado River sediment record was discontinued on September 30, 1970; the Colorado River sediment record at the Grand Canyon gaging station was discontinued on September 30, 1972; and the Paria River sediment record was discontinued on September 30, 1976. Thus, the only postdam period of overlap between these stations that could be used to construct a sand budget was the period from closure of the dam in March 1963 through September 30, 1970. Furthermore, no postdam sand-transport data were collected within Marble Canyon during this early period.

To fill this data gap, the USGS began a program of quasi-daily sediment sampling on the major tributaries to the Colorado River (that is, the Paria River, the Little Colorado River, and Kanab Creek) and at five locations on the mainstem Colorado River in Marble and Grand Canyons (Garrett and others, 1993). On the tributaries, this program extended from July through December 1983. On the mainstem, this program included the periods from July through December 1983 and October 1985 through January 1986. All suspended-sediment samples collected under this program were analyzed for grain size to allow use in constructing sand budgets.

The sand budget for the Colorado River in Marble and Grand Canyons used in the EIS was constructed by Randle and Pemberton (1987) and Pemberton (1987). For tributary sand input, they constructed stable sand-rating curves by using all of the historical and 1983 data from the Paria River, the Little Colorado River, and Kanab Creek. They also included an estimate for the sand supply from the lesser tributaries. Pemberton (1987) developed stable sand-transport rating curves at the five mainstem locations based on the USGS 1983–86 data, and the EIS states, "The sand transport equations of Randle and Pemberton (1987) and Pemberton (1987) were used for these computations" (U.S. Department of the Interior, 1995, p. 95) in reference to the sediment budget presented in figure III-15 of the EIS (and reproduced here as fig. 2). Therefore, the EIS sediment budget was based on the assumption of stable sand-transport rating curves. Results of recent studies presented in the following section suggest that this assumption is incorrect for the Colorado River below Glen Canyon Dam.

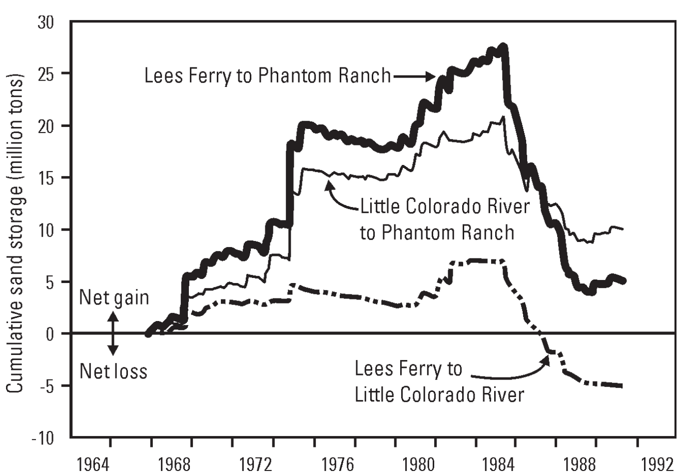

Figure 2. Reproduction of figure III-15 from the final environmental impact statement (EIS) (U.S. Department of the Interior, 1995), which shows the sand budget as computed by Randle and Pemberton (1987). Recent studies refute the conclusion of the EIS that sand accumulates on the bed of the Colorado River over multiple years under normal dam operations. (Phantom Ranch is the location of the Grand Canyon gage.)

Studies Since 1996 That Refute the Environmental Impact Statement Findings

Research and monitoring conducted during and after the 1996 BHBF experiment, also known as the 1996 controlled flood, have led to several findings that refute the EIS predictions for sand conservation and suggest that the implementation of this strategy has not led to sustainable restoration and maintenance of sandbars in either Marble or Grand Canyon. Instead, the canyons' sandbars continue to erode (figs. 3–6). The primary results of several of these studies are briefly summarized below:

- Rubin and others (1998) and Topping and others (1999) showed that the sand supply during the 1996 BHBF was not as great as was assumed before the experiment and that the sand on the bed of the river and in suspension coarsened dramatically as the upstream supply of sand decreased over time during this flood. This process led to flood deposits that coarsened vertically upward (i.e., inversely graded deposits).

- Topping and others (2000a) demonstrated that the grain size of sand on the bed of the Colorado River can change by over a factor of four as functions of tributary resupply of finer sand and higher dam releases that winnow the bed and that this factor-of-four change in bed-sand grain size corresponds to a change of two orders of magnitude in the concentration of sand in suspension (for the same discharge of water). Identification of this dynamic process precludes the use of stable sand-transport relationships in the Colorado River, thus invalidating the approach used to construct the sand budget in the EIS. Topping and others (2000a) also showed that Randle and Pemberton (1987) incorrectly predicted sand accumulation in the Colorado River because the data they used to verify their modeled stable sand-export relationships were from periods in the mid-1980s, when sand in the river was anomalously coarse and sand-transport rates were anomalously low following prolonged releases above powerplant capacity between 1983 and 1986.

- Rubin and Topping (2001) showed that sand transport in the postdam Colorado River in Grand Canyon is regulated by both the discharge of water and the grain size of the sand available for transport in suspension. This information also

A.

B.

Figure 3. Repeat photographs of Tapeats Creek at the Colorado River, Grand Canyon (RM 133.8, right shore). A. (July 1952) This view downstream from below the mouth of Tapeats Creek shows a large sandbar with few rocks or boulders exposed. This sandbar was frequently used for layovers during river trips in the 1950s (Kent Frost, courtesy of the photographer). B. (March 27, 2003) Large rocks and boulders are now exposed because of severe beach erosion. New sand was deposited here during the 1996 beach/habitat-building flow but was quickly removed. This camp is no longer used, which creates a problem for river runners who want to visit Tapeats Creek (J. Janssen, stake 2676, courtesy of the Desert Laboratory Collection of Repeat Photography). (Figure after Webb and others, 2002.)

A.

March 13, 1994

B.

March 25, 1996

C.

April 4, 1996

D.

April 19, 1998

E.

June 17, 2000

F.

September 11, 2000

Figure 4. Time series of repeat photographs of sandbars along the left shore of the Colorado River near RM 44.5 (Eminence Break) illustrating deposition on the sandbar during the 1996 beach/habitat-building flow (March 26–April 2; high flow occurred between photographs B and C) and subsequent erosion since April 1996. Images provided by Northern Arizona University, Department of Geology in cooperation with the U.S. Geological Survey.

contradicts the approach of the EIS, where it was assumed that sand transport was regulated only by the discharge of water.

- Topping and others (2000b) showed through their analysis of the 1965–70 daily sediment-transport data collected by USGS that, under normal powerplant flows, newly input tributary sand is exported past the Grand Canyon gaging station within several months. Their analysis of predam data indicated that, prior to closure of Glen Canyon Dam, sand would accumulate in Marble and upper Grand Canyons only during the 9 mo of the year when discharges were typically lower than about 9,000 cfs.

- Measurements of the channel bed indicate that tributary sand, which is typically much finer than the sand on the bed of the Colorado River, accumulates on the bed for only a short time before being eroded and transported out of the canyon under normal MLFF dam operations (Topping and others, 2000a).

- Since August 1999, detailed suspended-sediment transport measurements have been collected at the Paria and Little Colorado Rivers to document inputs and at the USGS gaging stations above the mouth of the Little Colorado River and near Grand Canyon to document export. Initially, these quasi-daily measurements were made by using only conventional USGS methodologies to obtain cross-sectionally integrated samples of suspended-sediment concentration and grain size (methods described in Edwards and Glysson, 1999). Because substantial and rapid (within a day) changes that are due to tributary inputs can occur in suspended-sediment concentration and grain size, emerging technologies for continuous monitoring of suspended-sediment concentration and grain size were tested and implemented beginning in 2001. These technologies include acoustic backscatter and laser-diffraction methods and are described in detail in Melis and others (2004) and Topping and others (2004). The detailed sediment-transport measurements allow for the ability to construct sediment budgets based on continuous data instead of on rating curves, a very important distinction from the EIS approach of using a limited data set. These data show that the overall mass balance of sand (input minus export) continues to be negative (fig. 7), as originally predicted by Laursen and

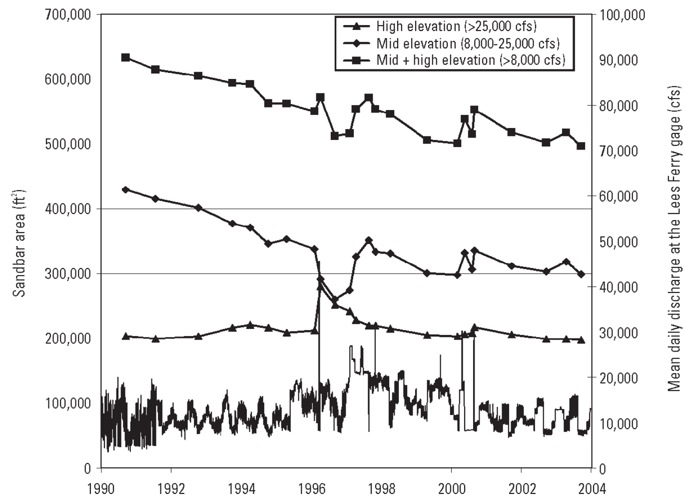

Figure 6. Changes in sandbar size (total surface area) are shown for 14 long-term sandbar study sites between the Lees Ferry and Grand Canyon gages (RM 0 to RM 87). Area of bars exposed above water discharges of 8,000 cfs decreased by 22% from 1991 to 2004. The 1996 beach/habitat-building flow resulted in a net transfer of sand from mid elevations to high elevations (modified from Rubin and others, 2002).

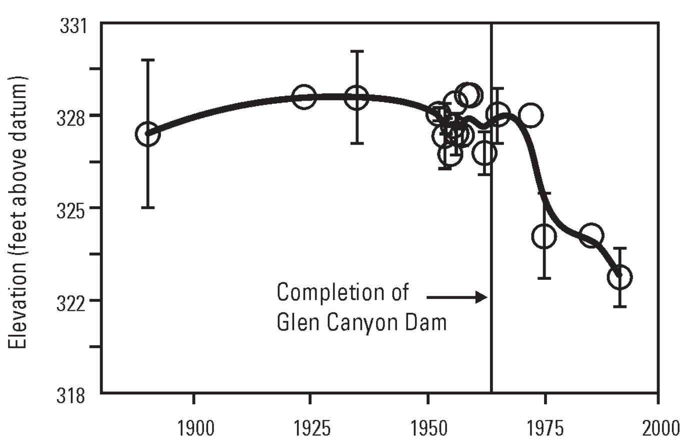

Figure 5. A decrease in elevation of the sandbar surface is seen at Jackass Creek camp located along the left shore of the Colorado River, 23 mi (37 km) downstream of Glen Canyon Dam. Elevations were determined by examining oblique and aerial photographs of the site and by field survey of the elevation and the former sand surface at its contact with large talus blocks. This graph shows the elevations near one prominent talus block that was inundated by predam mean annual floods, but since the dam was completed, the talus block has been inundated infrequently (modified from Rubin and others, 2002).

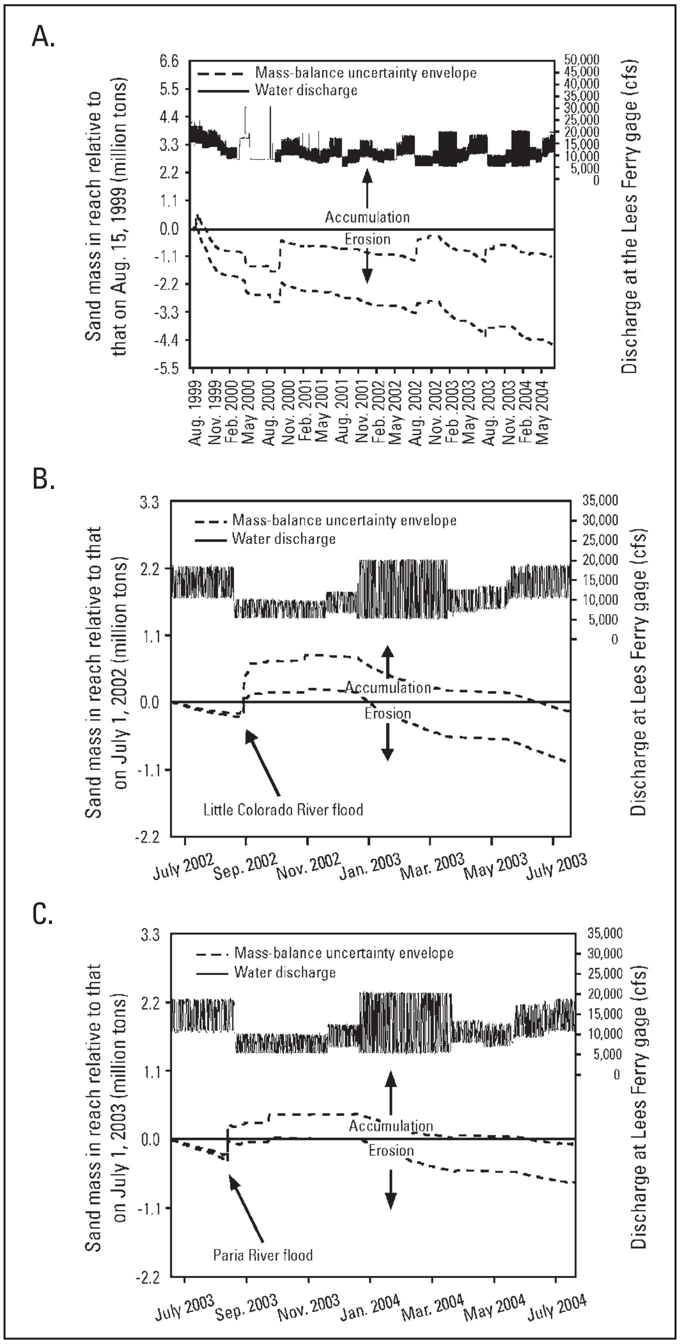

Figure 7. Mass balance of sand between Lees Ferry and Grand Canyon gages from August 1999 through July 2004 (A) and separately for sediment years (July–June) 2003 (B) and 2004 (C). Mass balance is computed by subtracting measured, mainstem suspended-sand export (10% uncertainty) from estimated and measured sand inputs from the Paria River (20% uncertainty) and Little Colorado River (30% uncertainty), as well as from estimated inputs from numerous lesser tributaries (50% uncertainty). The measurements illustrate the rapid export of tributary inputs by high dam releases and the continued overall loss of sand from Grand Canyon under the modified low fluctuating flow (MLFF) alternative, even during the drought-hydrology, minimum-volume release years of 2003 and 2004 (modified and updated from Rubin and others, 2002).

others (1976). Most significantly, the sand mass balance remained negative during water years 2000 through 2004, despite 5 consecutive years in which minimal release volumes (8.23 million acre-feet (10,148 million m^3)) from Lake Powell occurred during prolonged drought in the upper Colorado River Basin. These measurements and calculations of sand transport also show that tributary inputs are typically transported downstream and out of the canyon within a few months under typical Record of Decision operations (Rubin and others, 2002).

- Repeat topographic mapping of sandbars (Hazel and others, 1999) showed that the 1996 BHBF did increase the surface area of high-elevation sandbars, but more than half of the sand deposited at higher elevations was taken from the lower portions of the sandbars (Schmidt, 1999) rather than being derived from tributary sand supplies accumulated on the channel bed, as originally hypothesized in the 1995 EIS.

- Repeated surveys of channel cross-sections (Flynn and Hornewer, 2003) revealed erosion at 55 of the 57 locations between 1991 and 1999, even though daily operations were constrained during the time series of repeat measurements.

- Schmidt and others (2004) conducted geomorphic mapping from air photos and land surveys for the predam and postdam periods. They estimated the loss of sand to be about 25% of the area typically exposed at base flow in predam photographs, but estimates range from 0% to 55% depending on study reach and method of analysis. Their studies further suggested that loss of the sandbar area continued at a relatively steady rate between 1983 and 2002, despite constraints on daily operations imposed after 1991.

Importance of Continuous Long-term Sediment-transport Data

Because of a lack of continuous data on sediment inputs and export that would have allowed for a sediment budget based on measured data, the EIS study team used stable sand-transport rating curves. Stable rating curves assume that for any given flow there is a single value for the corresponding sand concentration and, therefore, a predictable sand-transport rate related to flows released from Glen Canyon Dam. The recent studies reported above, however, have demonstrated that in the postdam Colorado River the relationship between flow and sand transport is not stable but instead shifts quickly and substantially relative to the grain size of sand on the bed of the river (which is controlled by tributary inputs and mainstem flows). Rubin and Topping (2001) and Rubin and others (2002) showed that the grain size of the sand in the regulated Colorado River ecosystem depends greatly on the recent history of tributary activity. For example, during low tributary flow periods the only source of sand to the mainstem Colorado River is that on the channel bed and in eddies, and that sand tends to be much coarser than tributary-delivered sand because of the winnowing of the finer sizes. When tributaries are flooding and delivering large quantities of fine sand (fig. 8), however, the supply is no longer limited to the coarser channel bed sand, resulting in much higher mainstem sand concentrations and, hence, greatly increased suspended-sediment export for any given flow released from the dam.

Because sand transport cannot be predicted based on discharge alone, sediment budgets for the Colorado River in Grand Canyon can only be constructed based on measurements of sand transport at a frequency great enough to capture changes in concentration and grain size resulting from tributary inputs. Fundamentally, the conclusions drawn by the EIS team, which are not supported by the more recent data, resulted from a lack of continuous data in the postdam era; that is, if daily records had been continued beyond 1972 and into the EIS period, then the fine-sediment budget would have been constructed based on these data rather than on stable rating curves. Recent sediment budgets suggest that under this scenario the conclusions of the EIS would have been different and possibly would have led to a different strategy for operation of Glen Canyon Dam in 1996. Though it is somewhat costly to collect long-term, high-frequency sediment-transport records, in this case it may have prevented 13 yr of dam operations that have continued to erode sandbars from Grand Canyon.

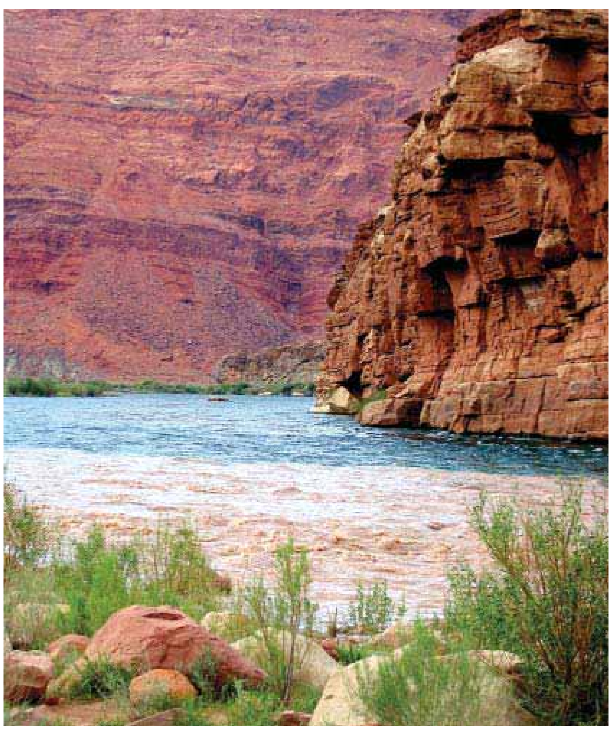

Figure 8. Looking upstream into Glen Canyon from the Paria River confluence with the main channel Colorado River during a Paria River flood. Tributary inputs of sand, such as the one pictured, now encounter clear Colorado River water because Lake Powell traps incoming fine sediment. The Paria River is the primary source of sand to Marble Canyon but is only about 6% of the predam sand supply (photograph by Scott A. Wright, U.S. Geological Survey).

Current Experimental Plan for Fine Sediment

Because recent research has shown that sand does not accumulate on the river bed in Marble and Grand Canyons under normal Record of Decision dam operations, scientists have recently proposed two possible field tests of dam operating options that might more effectively conserve limited, downstream sand resources. One approach is to implement floods immediately following large tributary inputs that commonly occur in late summer and early fall. A second approach is to follow tributary sand-input events with low flows, in order to limit export and retain most of the sand input, until flooding can be implemented. This approach would require a change in the pattern of monthly release volumes and associated dam operations because July and August releases of recent drought years still resulted in half of the sand introduced by a tributary flood being exported within days or weeks (Rubin and others, 2002).

In September 2002, the U.S. Department of the Interior (2002) approved implementation of the second approach described above. Under this plan, changes in dam operations and restoration floods are linked to triggering thresholds based on sand inputs from the Paria River and lesser Marble Canyon tributaries and retention of sand in Marble and Grand Canyons. For example, the "autumn sediment input" scenario described in the 2002 environmental assessment (EA) (U.S. Department of the Interior, 2002) defined a sequence of events related to sand inputs and retention that would trigger a 2-d, 42,000–45,000-cfs experimental high flow in the following January (fig. 9). Significant sand inputs to Marble Canyon that exceeded the triggering threshold for an experimental high flow occurred during September–November 2004. Instead of constraining operations through December (a winter, peak-demand month) in order to retain sand in Marble Canyon as laid out in the 2002 EA, a supplemental EA was prepared that allowed for a hybrid of the first and second approaches to be tested and evaluated. Approval of the supplemental EA paved the way for the experimental high flow that began on Sunday, November 21, 2004, when the Bureau of Reclamation opened the bypass tubes of Glen Canyon Dam for 90 h. The peak high flows ran for 2.5 d (60 h) at about 41,000 cfs. Scientists will evaluate data collected during and after the high-flow event to determine whether or not this strategy succeeded in enlarging existing beaches and sandbars.

Other dam operation scenarios may be more effective at retaining tributary inputs, such as Record of Decision operations modified such that equal volumes of water are released from the dam each month. Alternatively, a scenario of seasonally adjusted steady flows, which was an alternative in the EIS process, may be effective. Because of the severely reduced sand supply, however, even during periods of minimum release requirements of 8.23 million acre-feet (10,148 million m^3) per year the possibility exists that no operational scenario will result in management objectives being achieved for restoring sandbars, simply because of the volume of water that must be released on an annual basis. If so, other, more effective alternatives for restoring and maintaining sandbars and related habitats may need to be evaluated.

Sediment augmentation, one possible alternative, was eliminated during the development of the EIS, partly because of the belief that sandbars could be restored and maintained by constraining the hourly ramping rates and range of daily dam operations and partly because of concerns about contamination of sediment upstream in Lake Powell (Graf, 1985). Addition of sediment—continuously, seasonally, or perhaps only during floods—may offer greater powerplant operating flexibility and therefore may cost less than further restrictions on annual dam operations. To this end, the feasibility of mechanically transporting fine sediment around Glen Canyon Dam and introducing it into the Colorado River below the dam is currently being investigated.

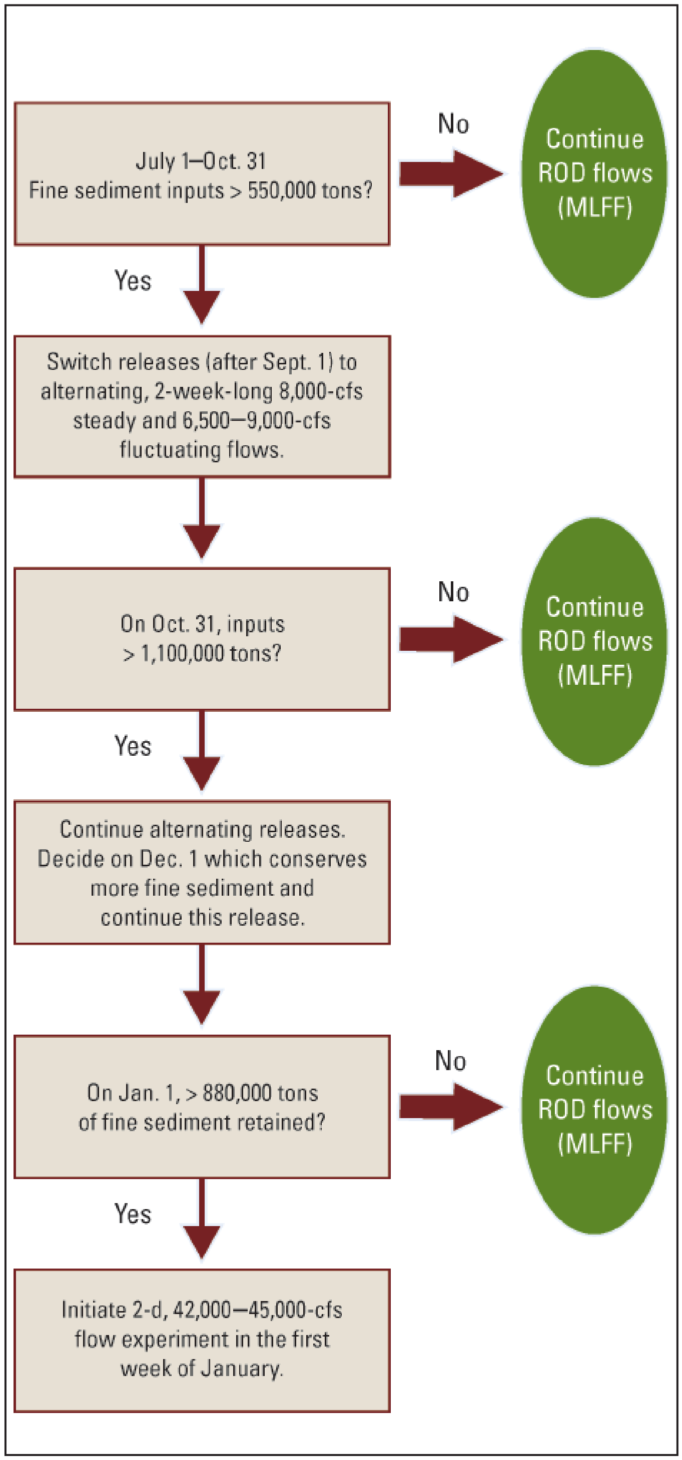

Figure 9. Sequence of events established in the autumn sediment input scenario in an environmental assessment by U.S. Department of the Interior (2002) related to fine-sediment inputs and retention to trigger a 2-d, 42,000–45,000-cfs experimental high flow in January. If fine-sediment inputs do not reach specified levels, then modified low fluctuating flow (MLFF) operations, as specified in the Record of Decision (ROD) (U.S. Department of the Interior, 1996), are continued.

Discussion and Future Research Needs

Extensive research and monitoring of fine-sediment transport and sandbars since the completion of the EIS have resulted in a better understanding of the geomorphology of the Colorado River in Marble and Grand Canyons and of the effects of the operations of Glen Canyon Dam on the river's downstream resources. Probably the single most important finding of this research and monitoring is that postdam mainstem sand transport exceeds the postdam supply of sand from tributaries on a seasonal to annual basis, such that the postdam river is in an annual fine-sediment deficit (i.e., export exceeds input). This sediment deficit has resulted in a consistent downstream pattern of erosion of channel and sandbar deposits from Marble and Grand Canyons despite restrictions on daily powerplant fluctuations required by the implementation of the MLFF alternative.

The finding of an annual sediment deficit directly contradicts the critical EIS assumption that sand will accumulate on the bed of the Colorado River over multiple years under the MLFF operating alternative (and minimum annual volume releases) and has important implications for the potential success of managing tributary sediment inputs. It is also worth noting that the EIS conclusion resulted fundamentally from a lack of long-term records for tributary sand supply and mainstem sand-transport rates, illustrating the importance of long-term data sets in river management. A continuous sediment budget for the Colorado River in Grand Canyon since construction of Glen Canyon Dam, based on high-frequency measurements, likely would have resulted in a different EIS conclusion about fine-sediment dynamics below the dam, one that may have prevented the continued erosion of sandbars between 1991 and 2004.

A second important finding of recent research and monitoring efforts is that during the 1996 BHBF the primary source of sand for building high-elevation sandbars was the low-elevation portion of the sandbars instead of the channel bed as hypothesized in the EIS. This scenario of building high-elevation sandbars at the expense of the low-elevation portions was repeated during the powerplant capacity flow in September 2000 (Hazel and others, in press). This process of sandbar building is supported by the finding of an absence of multiyear accumulation on the channel bed: sand cannot be transported from the bed to high-elevation sandbars because there is typically little sand available on the channel bed.

Neither of these two findings supports the EIS hypotheses, but they have led scientists and managers to reassess the management strategy for sand resources within Grand Canyon. An emerging paradigm is the need to strategically time high-flow releases in order to take advantage of sporadic tributary sediment inputs, a scenario that requires greater flexibility in the annual operating plan for the dam with respect to both hydroelectric power generation and economic cost. Only immediately after these inputs is significant sand available on the channel bed for transfer to high-elevation sandbars through high-flow releases. Alternatively, dam releases may be constrained following inputs for a period of time until a high flow can be released from the dam; however, during extended periods of above-average upper Colorado River Basin hydrology and high storage in Lake Powell, constraining daily operations may not be possible (see fig. 1, 1995 through 1998). In the absence of high-flow releases strategically timed to redistribute tributary inputs to high-elevation sandbars, the inputs are exported from Grand Canyon in a period of weeks or months under normal dam operations, leading to continued long-term erosion of sandbars.

In November 2004, this paradigm of strategically timed, high-flow releases was tested for the first time on the Colorado River. Scientists are in the process of evaluating the results of this experiment. The findings will be critical for the long-term management of fine-sediment resources and sandbars in Grand Canyon. If a management approach of strategically timed, high-flow releases, triggered by tributary inputs, is to be followed, then further research will be required to define the appropriate triggering criteria and to develop high-flow hydrographs (peaks and durations) that may optimize deposition of tributary sand inputs within eddies while minimizing export during controlled flood peaks.

If strategically timed, high-flow releases are deemed inadequate for meeting the management objectives for Grand Canyon sandbars, then alternative approaches must be considered, such as further restraints on daily powerplant operations, changes in monthly volume release patterns, or sediment augmentation.

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Contact Information:

Scott A. Wright
Hydrologist
U.S. Department of the Interior
U.S. Geological Survey
Southwest Biological Science Center
Flagstaff, AZ
sawright@usgs.gov

Theodore S. Melis
Physical Scientist
U.S. Department of the Interior
U.S. Geological Survey
Southwest Biological Science Center
Flagstaff, AZ
tmelis@usgs.gov

David J. Topping
Research Hydrologist
U.S. Department of the Interior
U.S. Geological Survey
Water Resources Discipline, National Research Program
Denver, CO
dtopping@usgs.gov

David M. Rubin
Geologist
U.S. Department of the Interior
U.S. Geological Survey
Pacific Science Center
Santa Cruz, CA
drubin@usgs.gov

Jeff Sorensen, Arizona Game and Fish Department

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