COLORADO RIVER SAND BUDGET:

LEES FERRY TO LITTLE COLORADO RIVER

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INTRODUCTION

Historically, the pre-dam Colorado River in the Grand Canyon was characterized by enormous sediment-laden spring floods, and low flows during most of the remaining year. During periods of low discharge and low sediment transport, sediments were stored on the river bed and as sandbars along the river margins. Sandbars were deposited, principally in eddy zones, during periods of high discharge, and subsequently eroded as spring floods receded. Over periods of years a "dynamic mass balance" existed between the delivery of sediments to the Grand Canyon, the storage of sediments within the canyon, and the export of sediments out of the canyon.

The construction and operation of Glen Canyon Dam located in northeastern Arizona (Figure 1) has altered the natural flow and sediment transport of the Colorado River in the Grand Canyon. The natural unimodal spring runoff peak has been replaced by a series of lesser and more frequent peak discharges that are intentionally sized and timed for the production of hydroelectric power. Additionally, there have been dramatic reductions both in the amount of sediment input to the Grand Canyon and in the capacity of the river to transport bed-sized sediments (sand-size and larger sediments) through the canyon. Virtually all sediment formerly delivered to the canyon by the Colorado River is now trapped behind Glen Canyon Dam. The Paria River and the Little Colorado Rivers, located approximately 15 and 80 miles downstream from the dam, respectively, are now the primary sources of sediment to the Colorado River in Grand Canyon. Of particular concern to river managers is the effect of dam operations on the balance of sand-sized sediments stored along the river, especially as sandbars along the river margins. This is because sandbars are critical to maintaining the river's riparian and near-shore aquatic habitats. They also are widely used by river recreationers as camp sites.

The effects of alternative water release patterns from Glen Canyon Dam on downstream natural, cultural and recreational resources, including sediment resources, presently are the subject of an Environmental Impact Statement (EIS) being prepared by the U.S. Bureau of Reclamation (BuRec) in cooperation with other federal and state agencies and affected indian tribes. During the preparation of the EIS, the Secretary of Interior has directed that "interim flow" operating criteria be implemented at Glen Canyon Dam to minimize adverse effects of daily flow fluctuations on downstream resources. The BuRec also is overseeing the Glen Canyon Environmental Studies (GCES) Program, which is charged with conducting research and monitoring in support of the information needs of the EIS process. Numerous studies of sand transport and storage in the Grand Canyon are being conducted as part of the GCES Program. This analysis was conducted as part of the GCES Program in order to support the development of interim flow criteria.

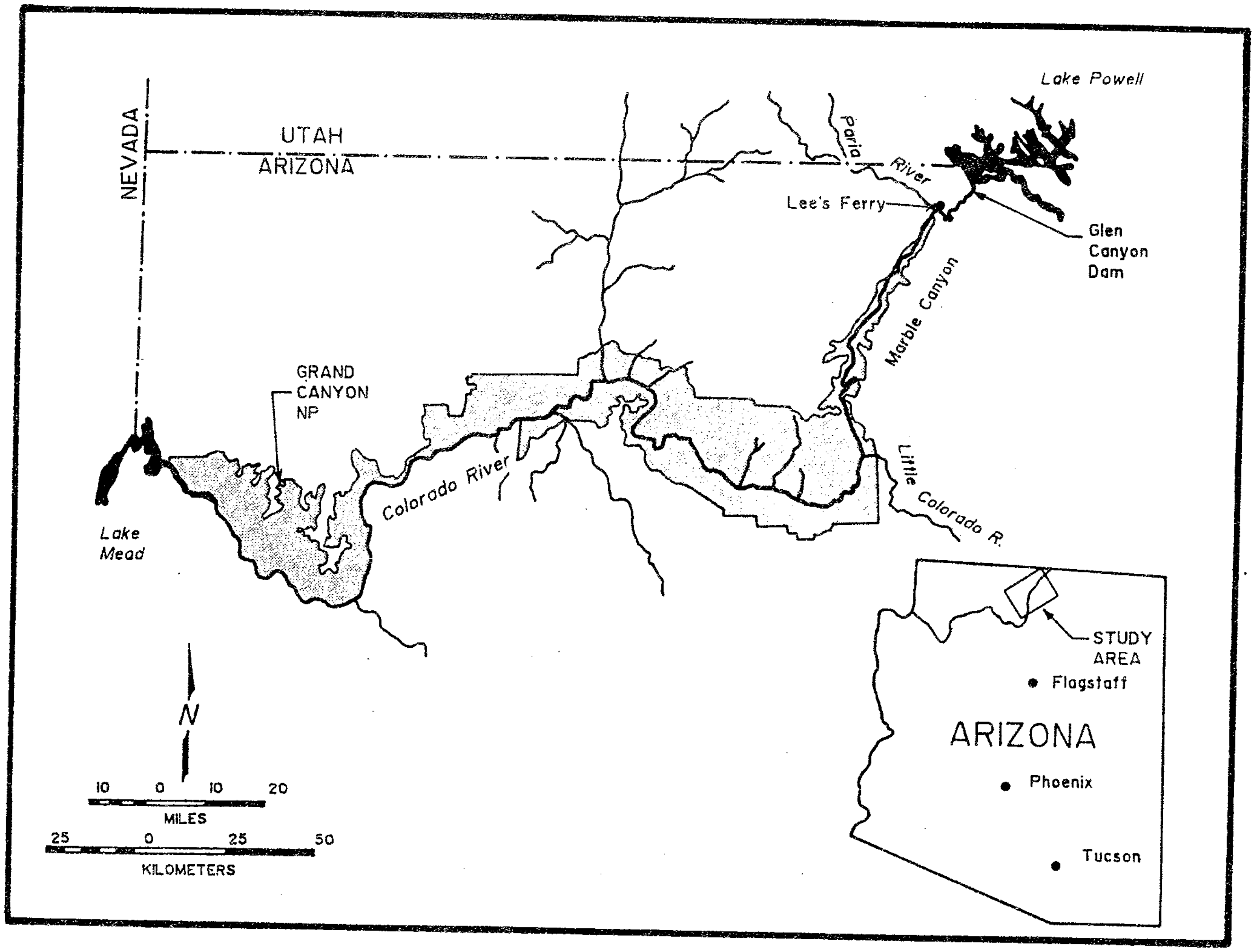

Figure 1. Location map and study reach.

OBJECTIVE

The objective of this analysis is to demonstrate an approach to sand balance analysis in the Grand Canyon. We will determine how annual variations in sand input from the Paria River affect the balance of river-stored sand in the Colorado River between the Paria and Little Colorado Rivers under alternative conditions of annual sand transport capacity in the Colorado River. It will be shown that flow fluctuations and corresponding sand transport in the Colorado River can be managed to achieve a balance with long-term average annual sand inputs from the Paria River. However, it will further be shown that the variability in annual tributary sand inputs means that even under conditions of long-term sediment balance, there will inevitably be periods of fairly substantial deficits in river-stored sand. The implications of this analysis for dam operations are discussed. Specifically, the implications of six hypothetical flow release patterns from Glen Canyon Dam on annual sand transport are evaluated. The reach between Paria River and Little Colorado River is the focus of this analysis, because this reach is most susceptible to management-induced reductions in sand storage.

Objectives for sediment management along the Colorado River in the Grand Canyon were developed by the Grand Canyon National Park as part of its river management planning process. Those objectives are: 1) to maintain a positive sand balance, and 2) to maintain the range of morphologic features associated the temporary storage of sand in the river system (e.g., sandbar deposits, high-flow terrace deposits, return channels, etc.).

BACKGROUND

Flow Fluctuations and Sand Transport

Andrews has determined elsewhere that sand transport, Qs (in tons/day), by the Colorado River in the Grand Canyon can be estimated by the relationship

$$Qs = 2.84 \times 10^{-12} Qw^{3.53} \quad (1)$$

where Qw is stream discharge in cubic feet per second (cfs) (E. Andrews, U.S. Geological Survey, pers. com., 1992). This power function relationship means that sand transport through the Grand Canyon can be minimized for any given annual release by releasing water at a constant rate. As flow fluctuations are introduced to the system (both the range of fluctuation and the period of time during which flows are higher than the annual mean) annual sand transport rates increase. If annual sand transport is increased by highly fluctuating flows above a certain amount, a long-term reduction of stored sand will result in the subject river reach.

When the amount of stored river sand is decreased, there is less sand available for deposition in backwaters and eddies, less sand available to "nourish" beaches during periods of high flow (flows in excess of normal operations), and a greater likelihood that the bases of margin deposits (including beaches) will be eroded. Because tributary sand inputs are highly variable on an annual basis, simply managing main channel sand transport to achieve a balance with long-term (mean) sand inputs will not avoid reoccurring (and sometimes fairly large) periods of deficit in river-stored sand. This situation will be further described and quantified in the analysis which follows.

Ramping Rates, Stage Fluctuations and Beach Erosion

While flow fluctuations influence sediment conditions in the Grand Canyon through their effect on sand balances in the Colorado River, stage fluctuations and ramping rates also influence sediment conditions through their effect on the stability and morphology of sediment margin deposits, including beaches (Bhudu 1992; Werrell et al. 1992). This analysis deals only with the effects of flow fluctuations on sand balances, and is not concerned with sandbar deposition and erosion induced by fluctuating flows.

METHODS

Mean daily flow and suspended sediment transport data are available for the Paria River at Lees Ferry streamgage for the 1949-1976 period. Daily sediment loads were summed to determine annual sediment yields for each year of record (Figure 2). Sand loads were approximated by assuming that 20 percent of the total suspended sediment load was sand and that 20 percent of the total sand load occurred as unmeasured bedload (Randle et al. 1991). The derived values for Paria River sand transport used to plot annual sand inputs to the Colorado River were plotted over time, and summary statistics were generated (annual means, annual medians, and sand-flux duration curves).

To describe the effects of annual variations in sand input on the balance of stored sand in the Colorado River, three alternative annual sand transport rates were assumed for the Colorado River (565,000 tons/yr, 790,000 tons/yr, and 1,000,000 tons/yr) and tributary sand inputs which corresponded to the measured inputs for the 28-year period of record on the Paria River. All changes in stored river sand were expressed as deviations from 1948 amounts (where the 1948 deviation was defined as zero). The low Colorado River transport rate equates to the median annual sand input from the Paria River; the medium transport rate corresponds to the mean annual sand input from the Paria River; and the high sand transport rate corresponds to approximately the 30 percent transport rate on the Paria River sand flux duration curve (Figure 3).

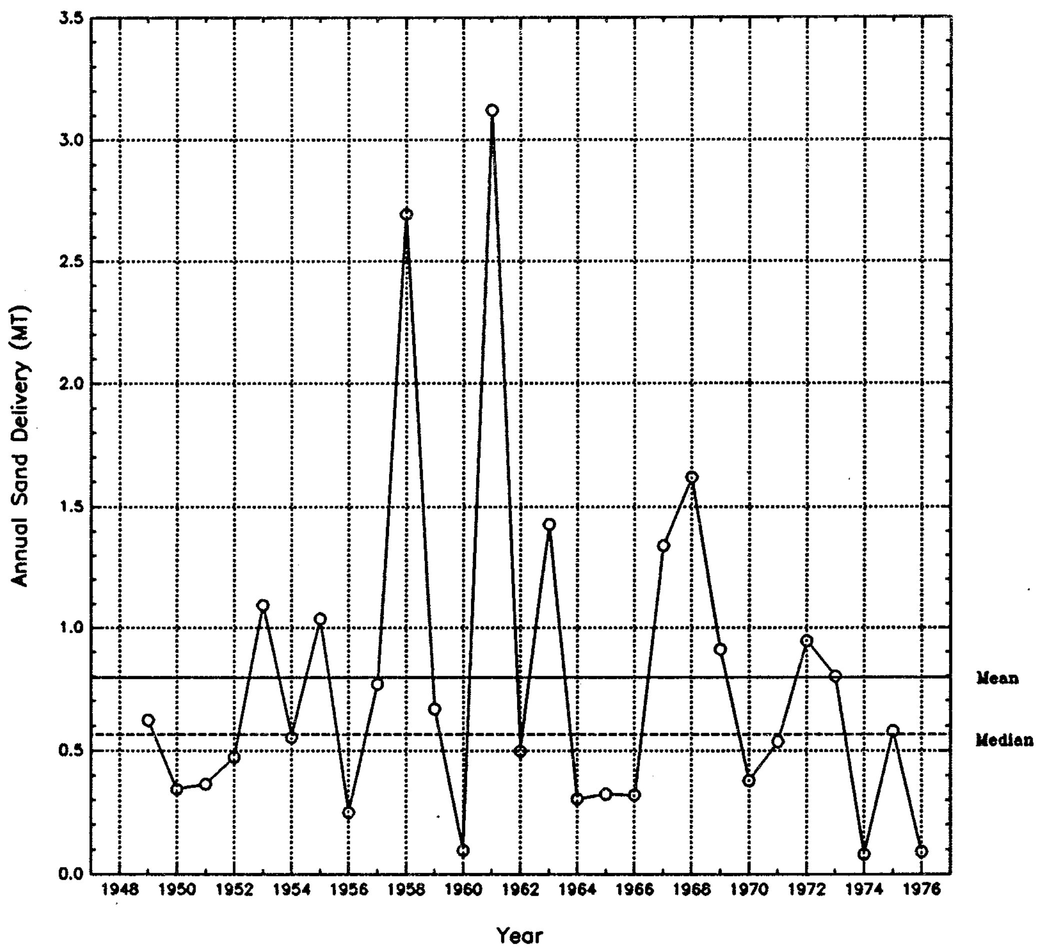

Figure 2. Sand delivery from the Paria River into the Colorado River (1948-1975).

Finally, to evaluate the effects of alternative dam operations on main-channel sand transport, a computer program was developed which calculated annual flow-duration curves for alternative operations and applied the sand transport function in Equation 1, to calculate annual sand transport for alternative daily flow patterns (this program has a user-interface which permits alternative sand-transport functions to be evaluated).

RESULTS

The distribution of annual sand inputs from the Paria River to the Colorado River is positively skewed. Thus, the mean annual sand input (790,000 tons) is considerably larger than the median annual sand input (565,000 tons) (Figure 2). A constant year-around release of 11,200 cfs from Glen Canyon Dam would result in approximately 200,000 tons/year of sand transport in the Colorado River. This mean flow release corresponds to a "minimum" release volume from Glen Canyon Dam as permitted by a compact between the upper and lower Colorado River Basin states. This value is far less than the mean annual supply from the Paria River and corresponds to approximately the 87 percent rate on the sand flux duration curve (i.e., 87 percent of the time, annual sand input equals or exceeds 200,000 tons).

At the other end of the spectrum, nearly 1.5 millions tons/year of sand is predicted to be transported with a daily fluctuating flow of 3000 to 30,000 cfs (this regime also averages 11,200 cfs). This magnitude of transport is far in excess of the mean annual supply from the Paria. These results are very significant because they strongly suggests that given a long term mean flow in the Colorado River of 11,200 cfs, it is possible to operate the Glen Canyon Dam in a manner that will result in surplus, deficit, or balance of sediment transport relative to supply.

In examining the effects of annual sand input variations on the balance of river-stored sediment in the Colorado River, several interesting points can be observed (Figure 4). First, if the sand transport capacity of the Colorado River is set to equate exactly to the long term average annual input of sand from the Paria River, fluctuations in river-stored sand occur, even though a long-term balance is achieved. In fact, for the simulated period of record, there was an 11-year period (1949-1960) of deficit in stored river sand. The maximum deficit during this period was about 2.1 million tons of sand. This deficit equates to approximately three times the annual mean input from the Paria River, or approximately four times the median sand input from the Paria River. Following this period of sand deficit, there was approximately a 15-year period of stored sand surplus. Over a longer period of record, continued periods of deficit and surplus would continue to occur. Over any relatively short time period (several years) there is a fairly high probability that managing for a balance with *mean* sediment inputs might result in a substantial sand deficit in the reach between the Paria and Little Colorado Rivers.

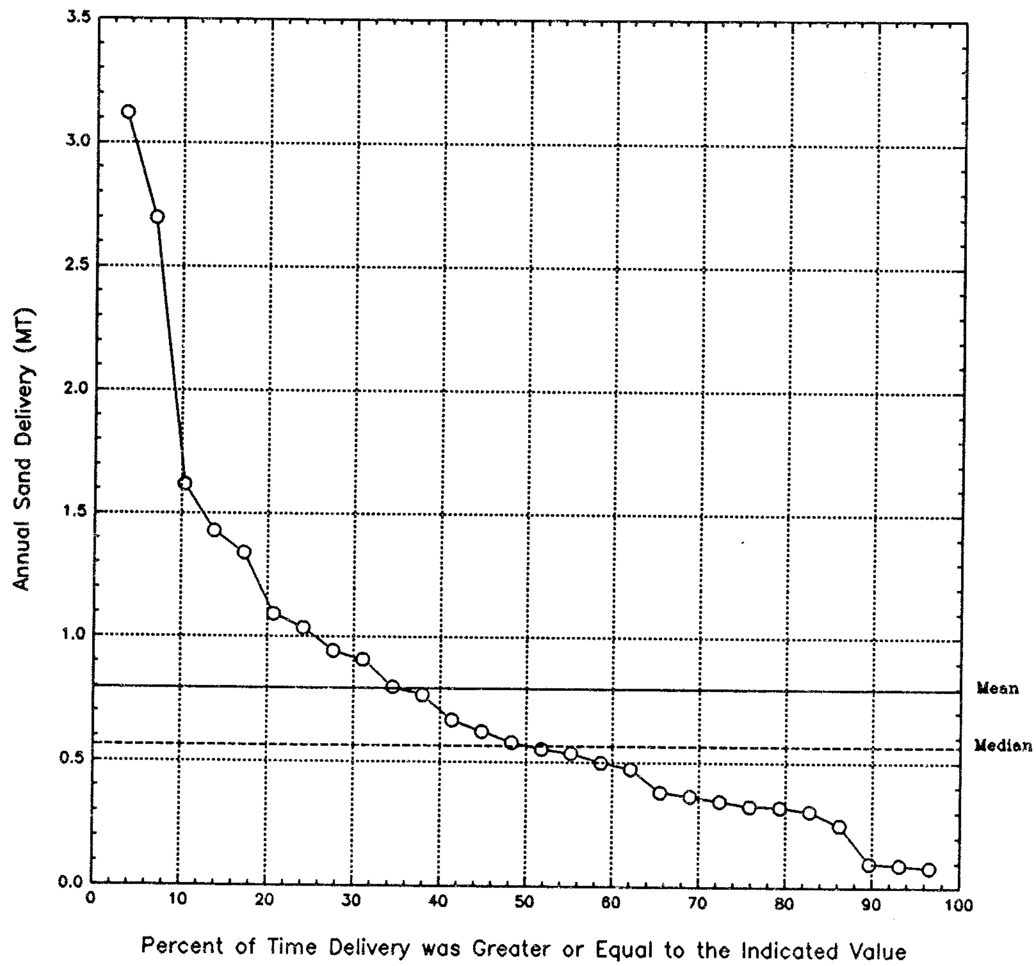

Figure 3. Paria River sand-flux duration curve.

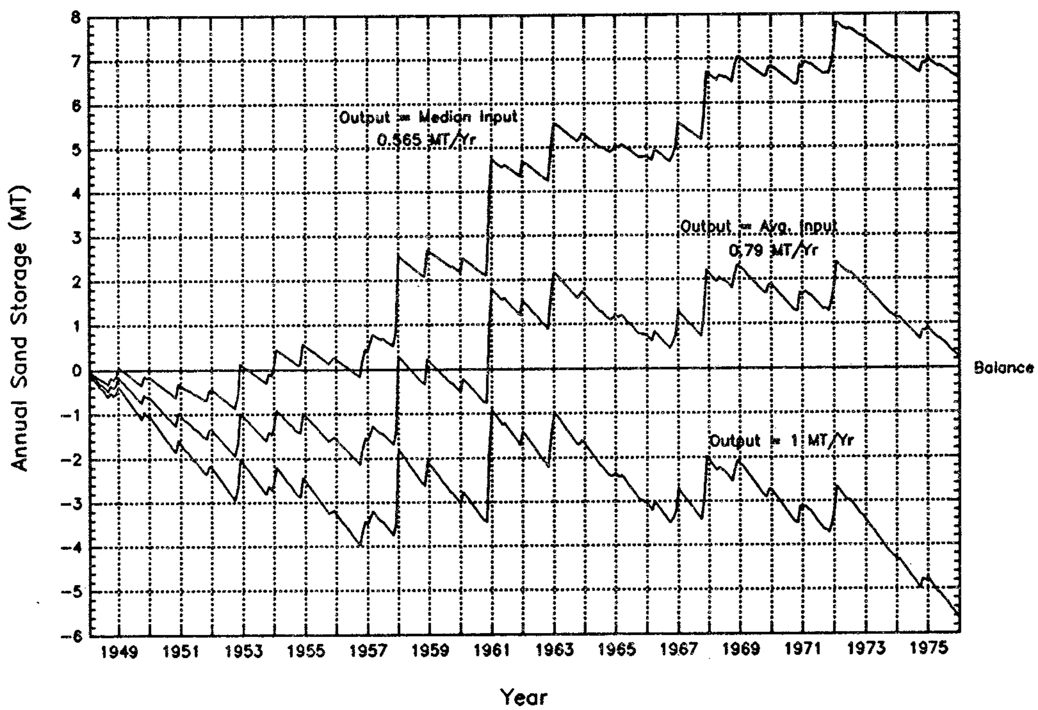

Figure 4. Sand budget for the Colorado River: sand storage cumulative surplus/deficit.

Of course, if main channel transport capacities are less than the long-term mean sand inputs, there will be less chance for short-term periods of sand-storage deficits and there will be a long-term trend towards sand accumulation. Conversely, if sand transport rates in the Colorado River are greater than the mean sand inputs from tributaries, there will be a long-term trend of sand depletion from storage.

Effects of Alternative Dam Operations on Main Channel Sand Transport

To illustrate how alternative dam release regimes affect main channel sand transport, and thus the long-term balance of sand in the subject river reach, six different hypothetical release regimes were modelled, including the two cases previously mentioned (Table 1). In all cases, the maximum discharge was maintained for four hours daily. Discharges were distributed over the rest of the period to minimize daily ramping rates and to achieve the required water delivery volume on a monthly and annual (11,200 cfs) basis. The results suggest that when fluctuations exceed roughly 18,000 to 20,000 cfs daily, long-term sand deficits will occur in the subject river reach.

DISCUSSION AND RECOMMENDATIONS

This analysis does not enable us to predict whether any particular operating regime for Glen Canyon Dam will cause significant short-term deficits in Colorado River sand storage in the Paria River to Little Colorado River reach. Furthermore, a longer simulation period would have produced a much wider range in the amount and duration of fluctuations in sand storage. However, it does suggest that if Colorado River sand transport is managed to achieve a balance with long-term average annual sand inputs, periods of sand storage deficit of some magnitude and duration, as well as periods of surplus, are likely to occur. We recommend that specific alternatives developed as part of the EIS process be analyzed for sand balance implications using methods similar to those presented in this paper. This action, of course, will require detailed information on the effects of various alternatives on the actual long-term operation of Glen Canyon Dam.

We caution that the analysis presented in this study does not consider that over the long term, spills from Glen Canyon Dam will occur resulting in potentially large-scale depletions of sand from the Paria River to Little Colorado River reach. Therefore, periodic or even modest long-term sand accumulations in storage are of less concern than periodic depletions from storage. In fact, given both the unpredictability of spills, and the need for periodic sandbar nourishment above the normal flow zone, it may be wise policy to manage for modest long-term accumulations of sand in river storage. In this case, there would be some rationale for

Release Pattern	Tons of Sand/year*
Steady, year-round flows	204,000
Daily Fluctuations:	
8,000-13,000 cfs	218,000
5,000 - 20,000	470,000
5,000-25,000	821,000
3,000-30,000	1,470,000
5,000 - 20,000 (11.5 months) 31,500 (2-weeks; to build sandbars)	716,000

* Mean Annual Sand Input (Paria River): 790,000 tons/year

$$Qs = 2.84 \times 10^{-12} Qw^{3.53}$$

All daily peaks were held for four hours.

Table 1. Sand transport examples.

managing flows to achieve sand transport capacities less than the long-term mean annual sand input for this critical river reach, and using periods of sand surplus as times to generate "sandbar building" flows (or to provide "insurance" against spills).

Finally, this analysis does not attempt to place significance on any particular level or duration of stored-sand depletions, although additional work may permit such an analysis to be made. This would further contribute to determining if temporary sand depletions associated with managing flows to achieve a long-term sediment balance should be a concern to resource management and protection agencies.

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William Hansen and Marshall Flug of the National Park Service, and Jim Wilson of the U.S. Geological Survey provided thorough and constructive reviews of an earlier draft of this manuscript.

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