Evaluation of Water Year 2011 Glen Canyon Dam Flow Release Scenarios on Downstream Sand Storage along the Colorado River in Arizona

By Scott A. Wright and Paul E. Grams

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
acre-foot (acre-ft)	1,233	cubic meter (m^3)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
ton per year (ton/yr)	0.9072	metric ton per year

SI to Inch/Pound

Multiply	By	To obtain
cubic meter (m^3)	0.0008107	acre-foot (acre-ft)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
metric ton per year	1.102	ton per year (ton/yr)

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Abstract

This report describes numerical modeling simulations of sand transport and sand budgets for reaches of the Colorado River below Glen Canyon Dam. Two hypothetical Water Year 2011 annual release volumes were each evaluated with six hypothetical operational scenarios. The six operational scenarios include the current operation, scenarios with modifications to the monthly distribution of releases, and scenarios with modifications to daily flow fluctuations. Uncertainties in model predictions were evaluated by conducting simulations with error estimates for tributary inputs and mainstem transport rates. The modeling results illustrate the dependence of sand transport rates and sand budgets on the annual release volumes as well as the within year operating rules. The six operational scenarios were ranked with respect to the predicted annual sand budgets for Marble Canyon and eastern Grand Canyon reaches. While the actual WY 2011 annual release volume and levels of tributary inputs are unknown, the hypothetical conditions simulated and reported herein provide reasonable comparisons between the operational scenarios, in a relative sense, that may be used by decision makers within the Glen Canyon Dam Adaptive Management Program.

Introduction

Physical characteristics of the riverine ecosystem of the Colorado River in Glen Canyon National Recreation Area and Grand Canyon National Park are affected by the existence and operations of Glen Canyon Dam (GCD) upstream (Schmidt and Graf, 1990; Wright and others, 2005; Hazel and others, 2006; Grams and others, 2007). The dam has blocked the upstream supply of sand and finer sediment since completion in 1963, and dam operations determine the transport capacity of the Colorado River, which affects the magnitude of sediment retention along the bed and banks versus the magnitude of sediment export downstream to Lake Mead. Sediment that is retained may be stored on the channel bed, along the channel margins, or in zones of lateral recirculating flow or eddies (Schmidt, 1990). Sediment within eddies, if deposited by high flows that are sufficiently greater than base flow, creates sandbars that are valued as recreational campsites (Kearsley and others, 1994), backwater aquatic habitat that may be used by native fish (Valdez and others, 2001), and substrate for riparian vegetation (Ralston, 2005). One of the goals of the Glen Canyon Dam Adaptive Management Program (GCDAMP) is to manage the dam to promote sand retention and sandbar deposition (Bureau of Reclamation, 2001). Monitoring sediment flux and sandbar size provides information on how dam operations have affected sand retention and storage. Numerical modeling tools developed and tested with the monitoring data are now available to provide managers with predictions on how future dam operations are likely to affect sediment retention and, thereby, sandbar characteristics.

Results from previous modeling and analyses have varied from predictions of persistent sand erosion (Laursen and others, 1976) to likely sand retention (Howard and Dolan, 1981; U.S. Department of the Interior, 1995). Most recently, a simplified modeling approach based on assumptions of steady dam releases and a stable suspended sand rating curve indicated that for these conditions, which would tend to maximize sediment retention, long-term increases in sandbar size were possible but not certain (Wright and others, 2008). The uncertainty associated with this model led to the development of a more sophisticated semi-empirical model that incorporates unsteady flow and a sand rating curve that shifts in response to the sand supply (Wright and others, in press).

Purpose and Scope

The purpose of this report is to document the application of the Wright and others (in press) model to a set of hypothetical scenarios for potential dam operations (that is, daily and monthly patterns) and annual release volumes in Water Year (WY) 2011. Model simulations predict sand export and sand budgets for three reaches, for six different dam operations scenarios each applied to two potential WY 2011 annual release volumes (for a total of 12 simulations). The modeled dam operation scenarios incorporate variables, such as patterns of daily flow fluctuation and the distribution of monthly release volumes. These scenarios derive either from previously implemented dam operations or dam operations proposed by members of the GDCAMP. The degree to which each of these scenarios is consistent with the body of legislation, agreements, and treaties, collectively known as the "law of the river," has not been evaluated and is beyond the scope of this technical report. Similarly, the annual release volumes that are modeled were chosen because they were considered to be most probable at the time this report was prepared (June 2010). Actual release volumes for WY 2011 are subject to change.

Physical Setting

The segment of the Colorado River considered for this modeling exercise extends from Lees Ferry, Arizona, downstream about 87 miles (fig. 1). Within this segment, the river is divided into three modeling reaches. Upper Marble Canyon extends from Lees Ferry to river-mile[1] (RM) 30, lower Marble Canyon extends from RM 30 to RM 61, and eastern Grand Canyon extends from RM 61 to RM 87. Sand is supplied to the study reach by the Paria River, which is just downstream from Lees Ferry, and by the Little Colorado River, which is just downstream from RM 61. Streamflow is monitored at each of the reach boundaries (Lees Ferry, RM 30, RM 61, and RM 87), and suspended-sediment concentration is monitored at 15-minute intervals at RM 30, RM 61, and RM 87 (Topping and others, 2010). For reporting of results herein, the two upstream reaches (upper and lower Marble Canyon) were combined, thus providing information on the entire reach between the two major tributaries (Marble Canyon).

[1] The river-mile convention has long been used as the standard reference system for locations along the Colorado River in Grand Canyon and was formalized in 2006 (U.S. Geological Survey, 2006). Lees Ferry is located 15.5 miles downstream from Glen Canyon Dam and 1 mile upstream from the mouth of the Paria River.

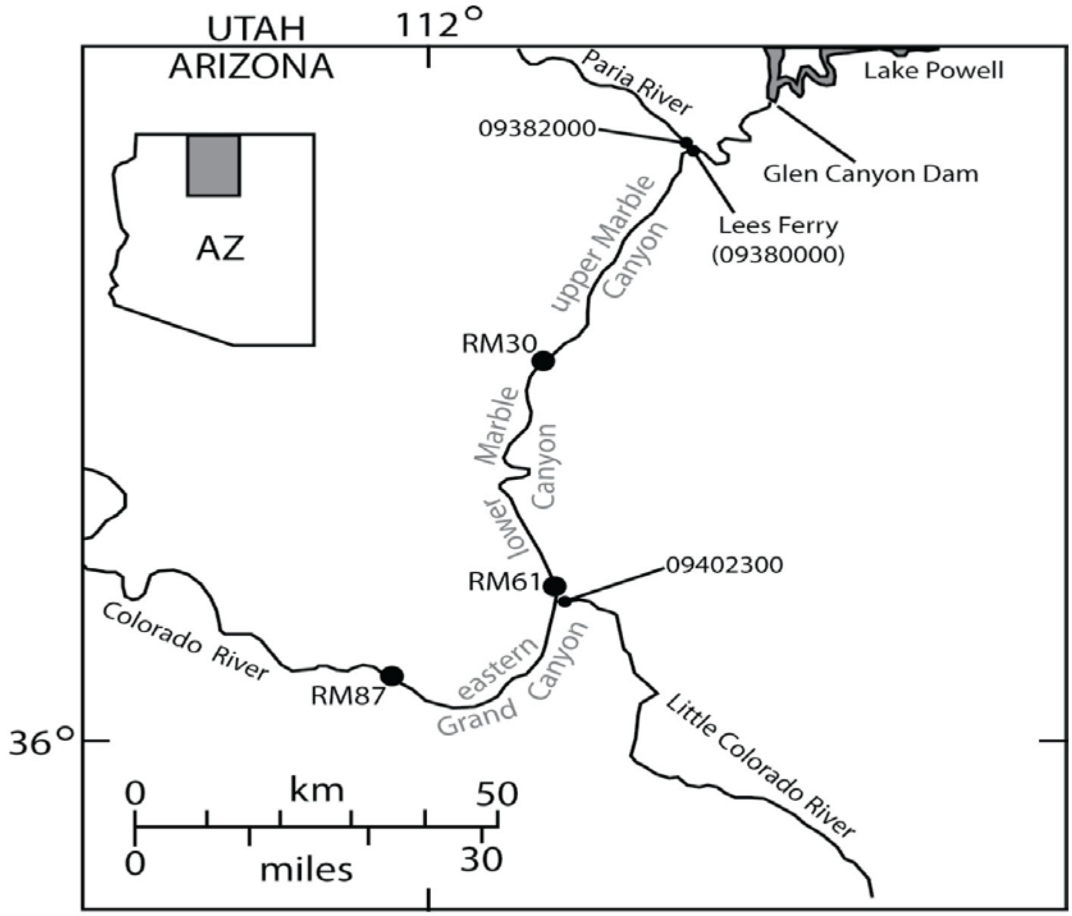


Figure 1. Colorado River below Glen Canyon Dam (GCD). Lees Ferry is designated river-mile (RM) 0 and is about 15.5 miles downstream from the dam. RM 30, RM 61, and RM 87 denote model nodes and are labeled according to river miles downstream from Lees Ferry. 8-digit numbers denote U.S. Geological Survey gaging stations referenced in the text.

Glen Canyon Dam Flow Release Scenarios

Six scenarios for GCD hourly release hydrographs were identified through discussions with the GCDAMP Technical Work Group. For each of the six hourly release scenarios, two annual release volumes were evaluated, that is, two possibilities for the total volume of water to be released in WY 2011 (for a total of 12 simulations). Based on the April 2010 24-month study from the Bureau of Reclamation (http://www.usbr.gov/uc/water/crsp/studies/24Month_04.pdf, accessed May 4, 2010), the most probable annual release volume was 11.0 million acre-feet (MAF). For comparative purposes, we also evaluated an annual release volume of 8.23 MAF because this volume has been the most common release volume over the past decade during multi-year drought conditions (8 of 9 water years from 2001 to 2009, based on data from Lees Ferry, U.S. Geological Survey station 09380000). Figure 2*A* shows the expected pattern of monthly release volumes for current operations, known as Modified Low Fluctuating Flows (U.S. Department of the Interior, 1995) for the two annual release volumes. The pattern of monthly volumes for 11.0 MAF is based on the April 2010 24-month study, while the pattern for 8.23 MAF is based on historical data and available synthetic hydrographs, discussed in more detail below:

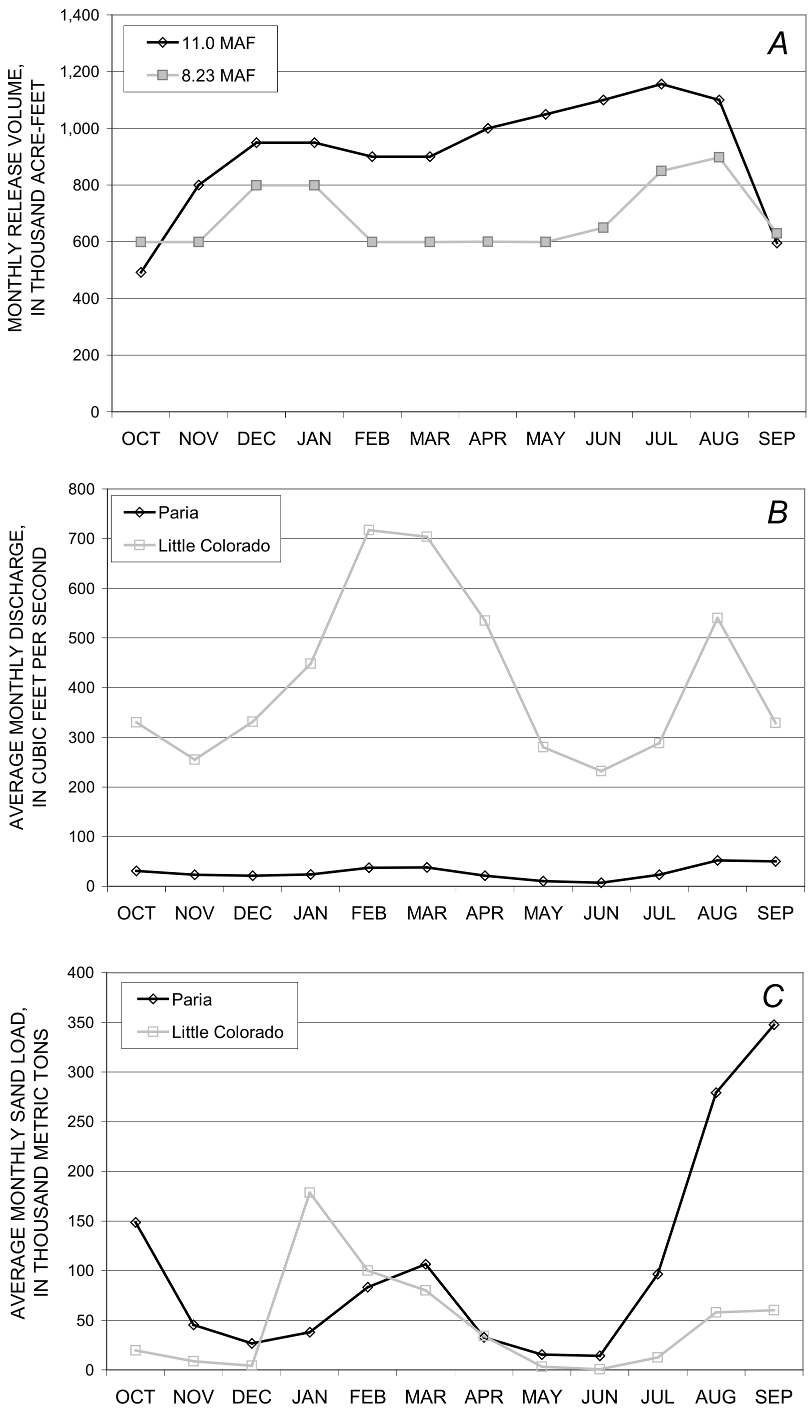
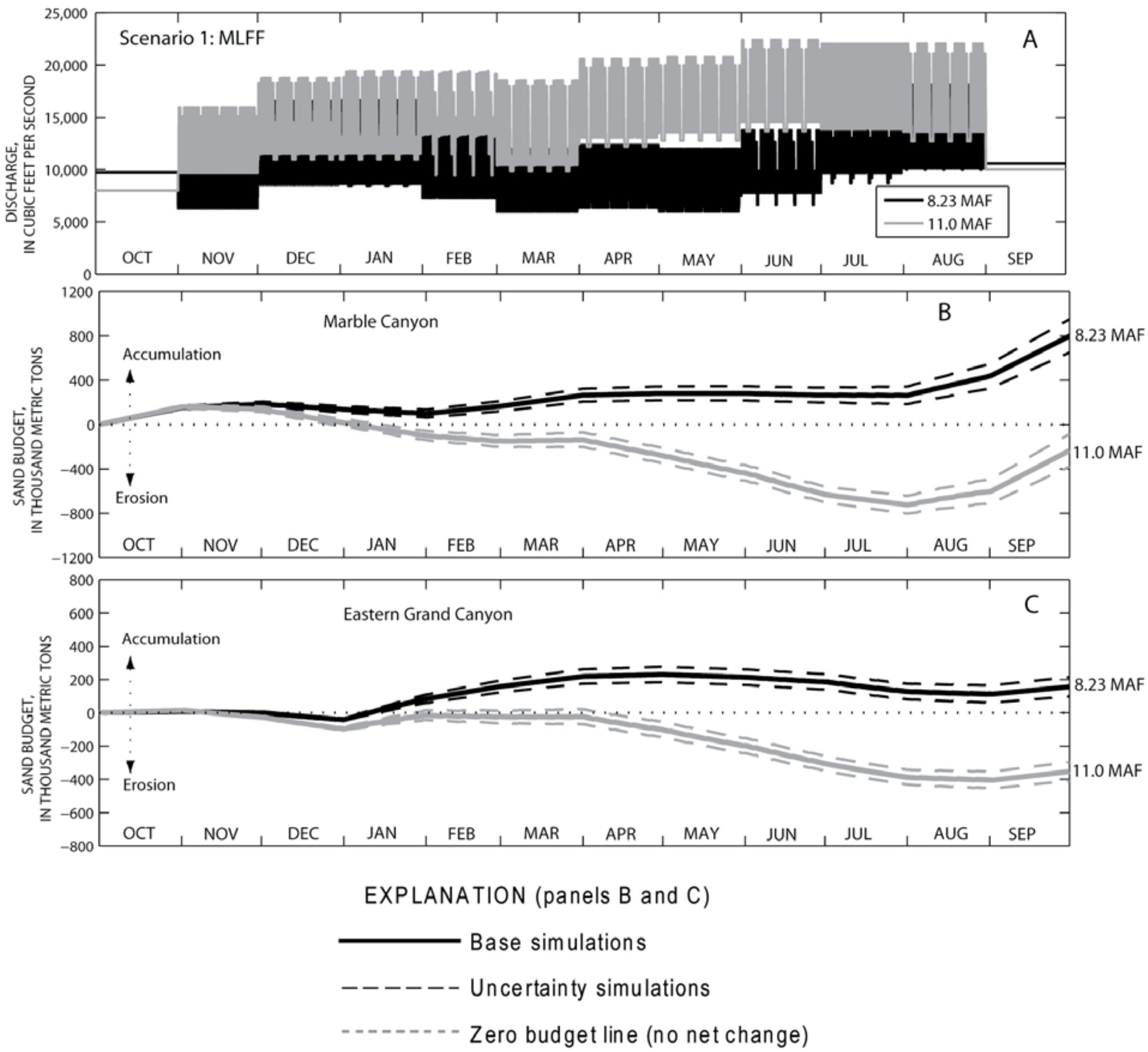


Figure 2. Monthly release volumes for the two modeled annual release volumes for Modified Low Fluctuating Flows (MLFF) operations and major tributary average monthly flow and sand inputs. *A*, Monthly Glen Canyon Dam release volumes, B, Average monthly Paria and Little Colorado River discharges. *C*, Average monthly Paria and Little Colorado River sand loads. MAF, million acre-feet

Six operational scenarios were identified for release patterns for a given annual release volume, that is, for how the water is distributed on monthly, daily, and hourly bases. For reference, the release hydrographs for each scenario are shown as the top panel (*A*) in figures 3–8; the data sources are discussed in detail below.

1) Modified Low Fluctuating Flows (MLFF) – This is the current operational regime as selected in the 1995 Environmental Impact Statement and record-of-decision for the operation of Glen Canyon Dam (U.S. Department of the Interior, 1995) (fig. 3).
2) Steady Daily Flows (SDF) – This scenario eliminates fluctuations in releases that occur under MLFF on a daily basis, but maintains the MLFF pattern of monthly volume releases (fig. 4).
3) Equal Monthly Volumes (EMV) – This scenario maintains the daily fluctuations of MLFF but replaces the pattern of monthly volume releases with an equal volume for each month (fig. 5).
4) Steady Year Round (SYR) – This scenario eliminates both daily fluctuations and monthly volume changes resulting in a single steady flow all year (fig. 6).
5) Seasonally Adjusted Steady (SAS) – This scenario eliminates daily fluctuations and revises the MLFF monthly volumes to a pattern with the highest monthly volumes in May–June and lowest volumes in Aug–Dec (U.S. Department of the Interior, 1995) (fig. 7).
6) Increased Daily Range and Down Ramp (IDR) – This scenario increases the MLFF daily ranges in discharge (up to 12,000 cubic feet per second [cfs] compared with 8,000 cfs) and down ramp rates (up to 4,000 cfs/hr compared with 1,500 cfs/hr) (fig. 8).



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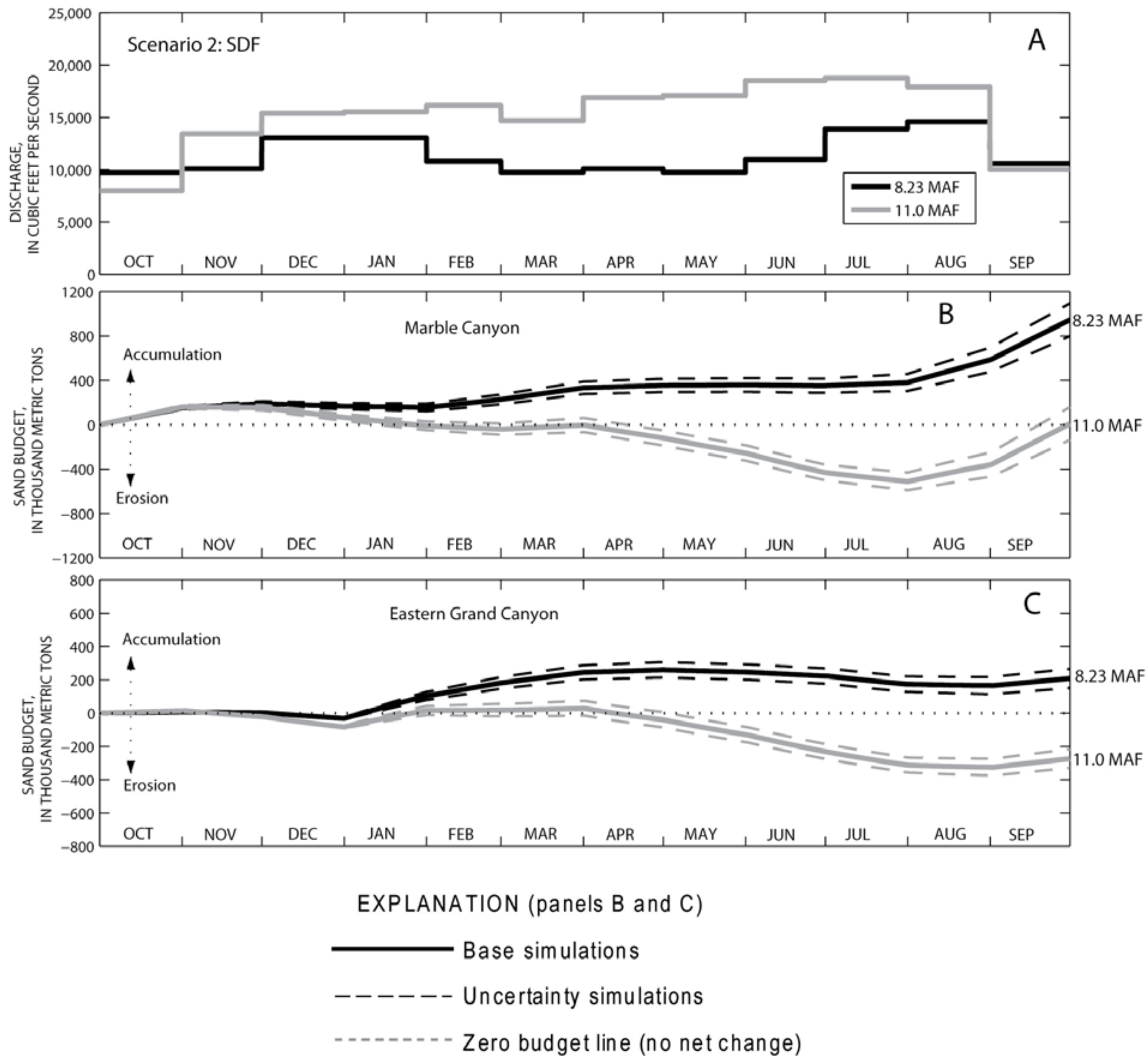

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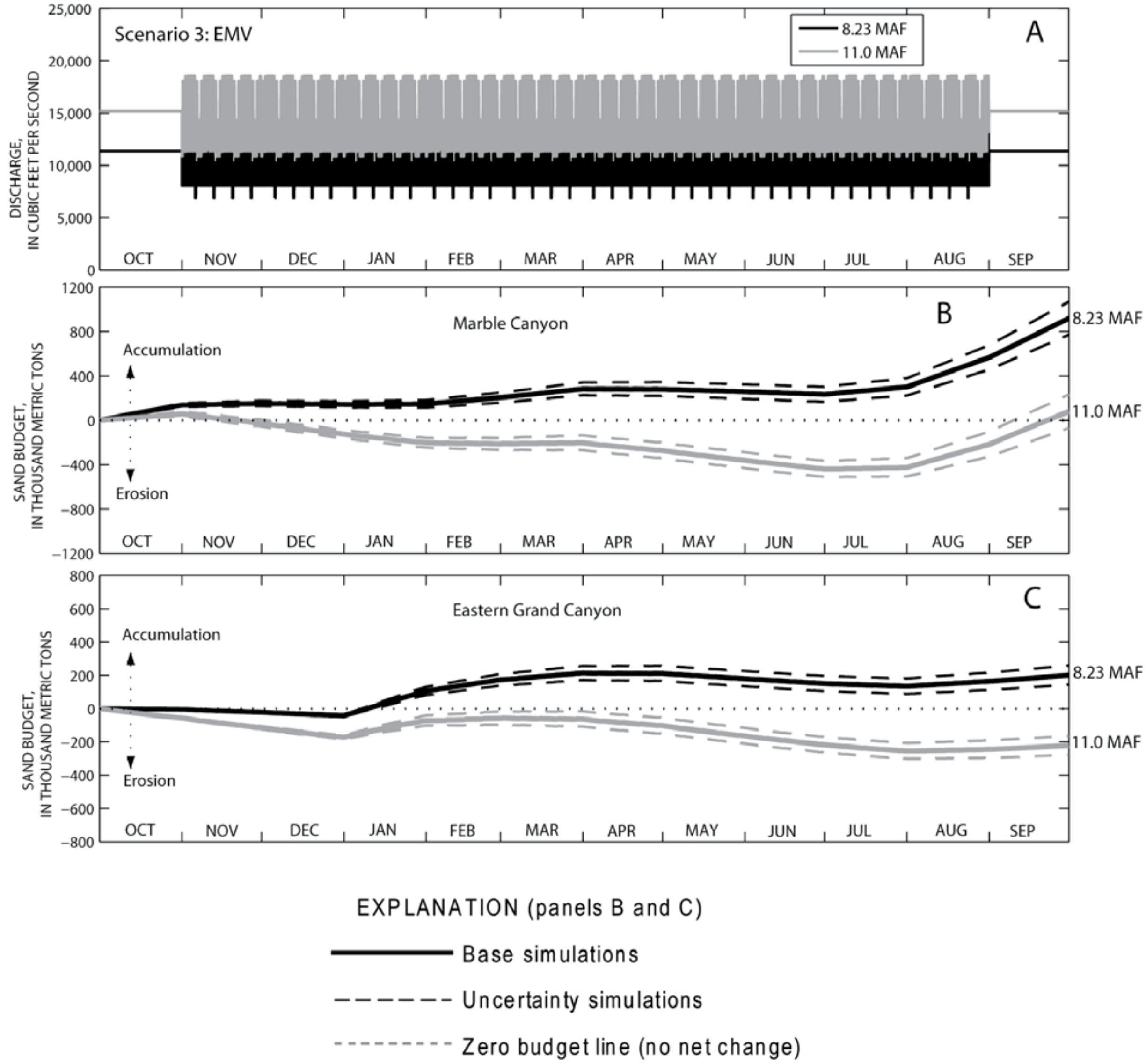

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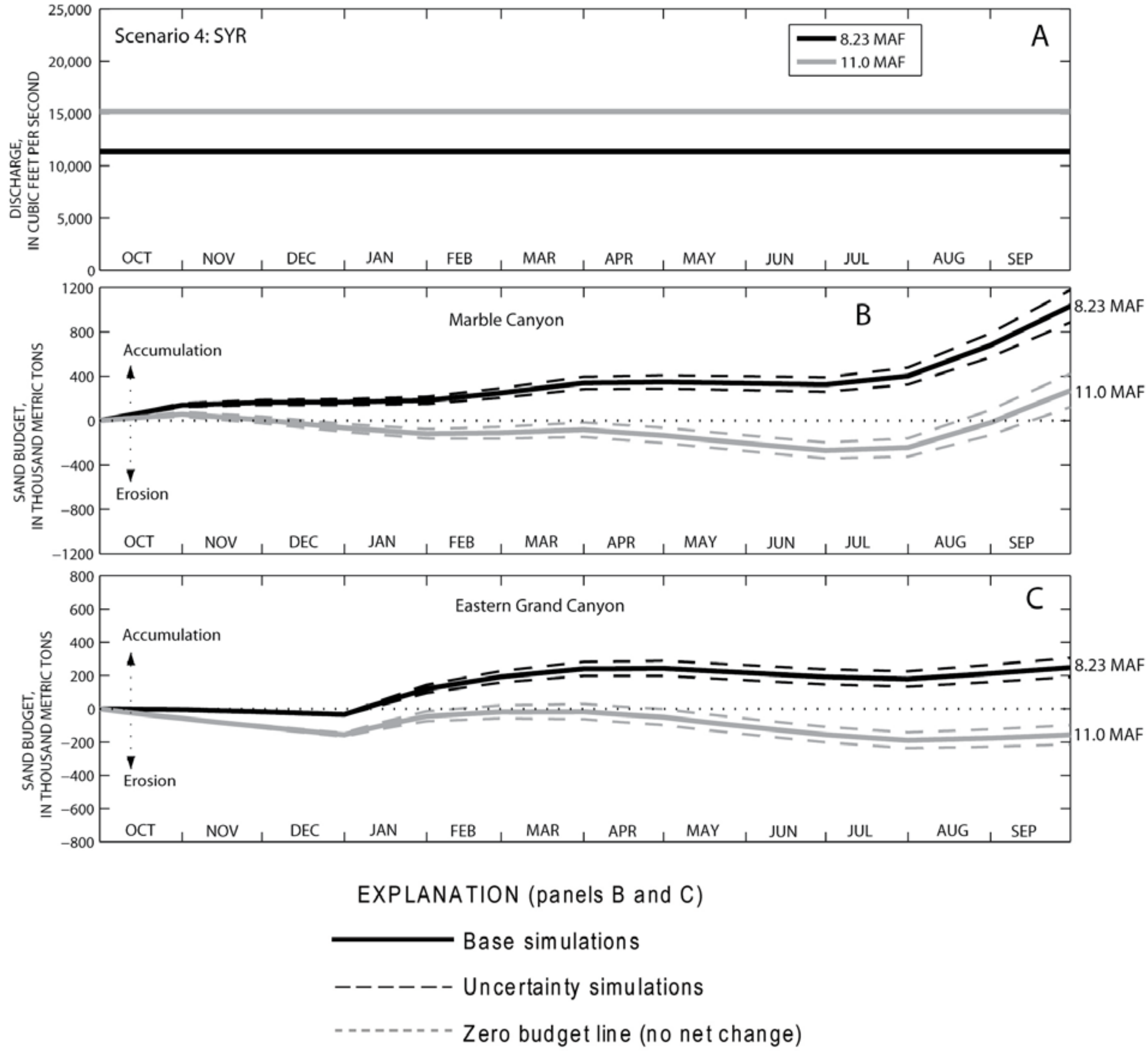

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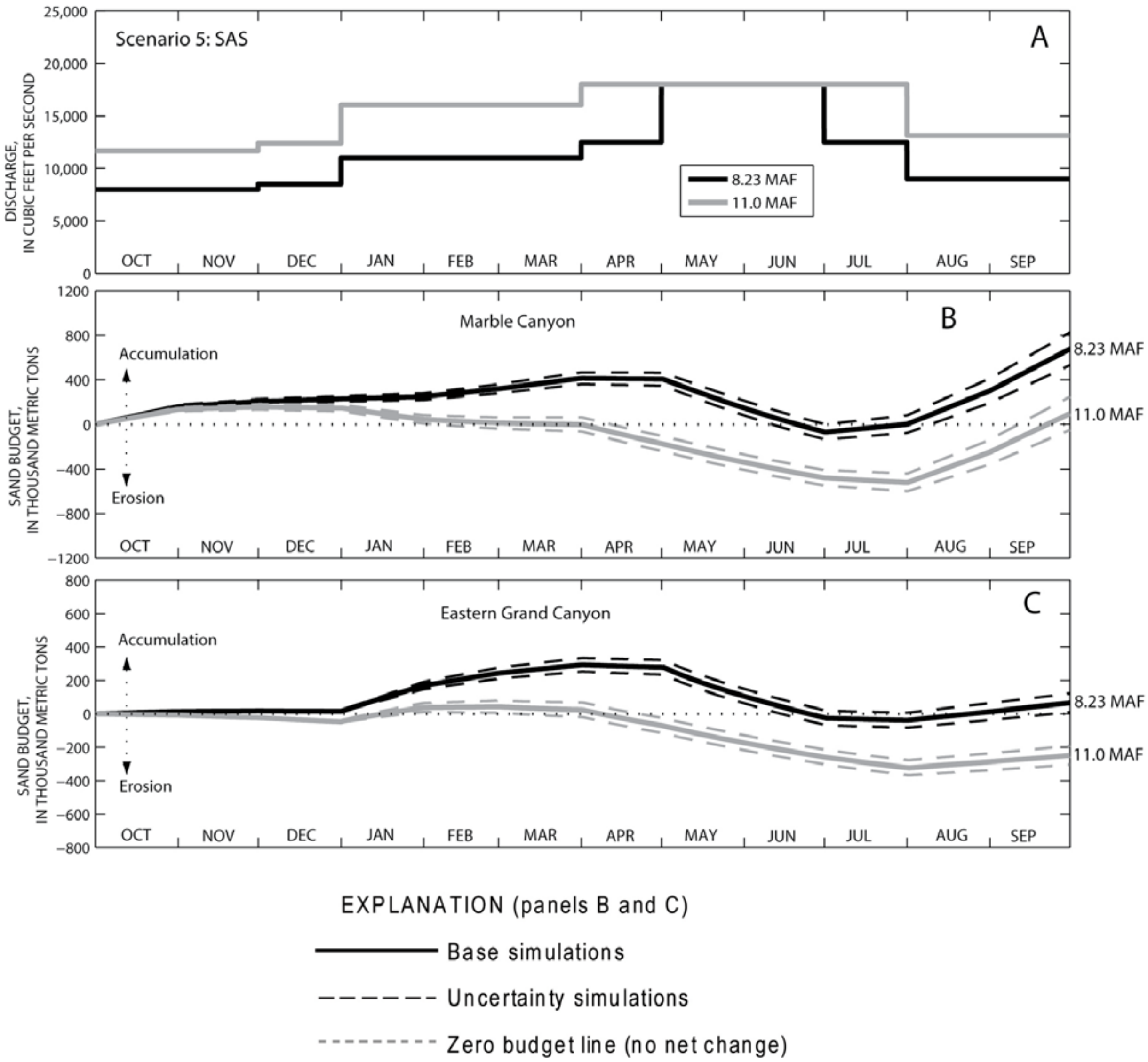

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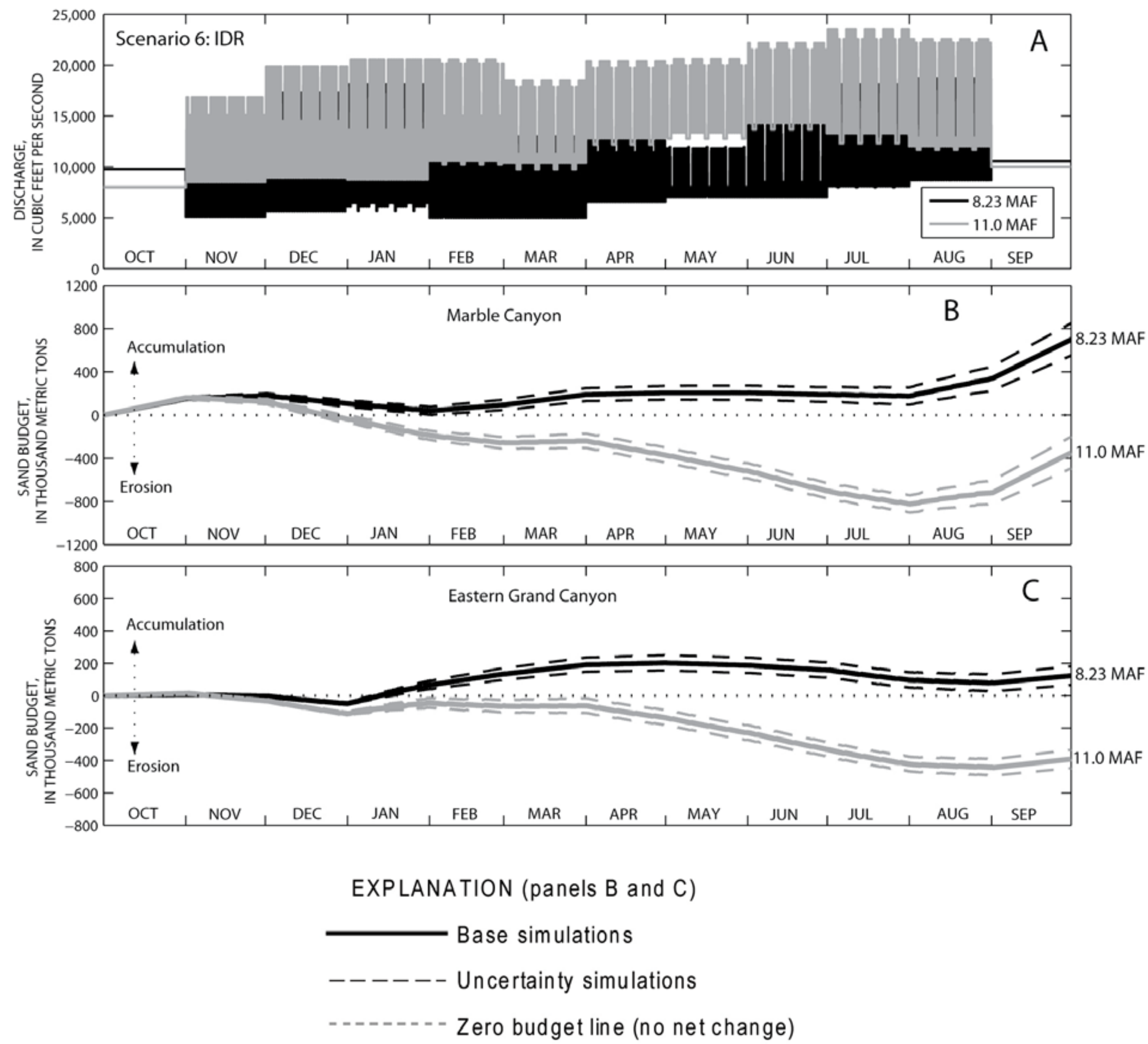

Figure 8. Glen Canyon Dam (GCD) flow releases and model results for Increased Daily Range and Down Ramp (IDR) operations at 8.23 and 11.0 MAF annual release volumes. *A*, GCD hourly hydrograph. *B*, Modeled sand budget for Marble Canyon. *C*, Modeled sand budget for eastern Grand Canyon. MAF, million acre-feet

The modeling simulations required hourly release hydrographs for each operational scenario and annual release volume. These were derived primarily from information that was generated in support of an experimental options assessment conducted by the Grand Canyon Monitoring and Research Center in 2006 (U.S. Geological Survey, 2006). For the 2006 assessment, hourly release hydrographs were generated by Western Area Power Administration for several operational scenarios for three 10-year periods with annual release volumes representative of dry, average, and wet conditions. Information from these hydrographs was used to construct the WY 2011 hydrographs for each of the six scenarios as follows. For MLFF, the 8.23 MAF hydrograph was taken directly from the hydrographs generated for the 2006 assessment; for 11.0 MAF, each month was matched with a similar volume month from the 2006 assessment hydrographs and then scaled so that the volumes matched exactly (fig. 3*A*). The scaling consisted of adjusting all flows in a month by a constant factor; typically, a month was available with a volume within about 5 percent of the desired volume such that the need for scaling was minimal. For SDF, the monthly volumes are the same as MLFF, but for each month, the MLFF hourly flows were averaged to yield a steady flow for each month (fig. 4*A*). For EMV, the monthly volumes are constant throughout the year and the hourly hydrographs were taken from the MLLF month with the volume that most closely matched this constant monthly volume (fig. 5*A*). For SYR, the hydrographs are simply constant flows for the entire year that yield the desired annual volumes (fig. 6*A*). The SAS hydrographs were generated based on information from the 1995 EIS for operation of Glen Canyon Dam (U.S. Department of the Interior, 1995); the 8.23 MAF annual release volume hydrograph was based on the minimum releases provided in the EIS Summary table and the 11.0 MAF annual release volume scales the minimum releases in each month to achieve the higher volumes while imposing a maximum release of 18,000 cfs (fig. 7*A*). Finally, the IDR scenario was evaluated in the 2006 assessment as scenario “A Variation” (U.S. Geological Survey, 2006), and the hydrographs (fig. 8*A*) were derived from that analysis in the same manner as the MLFF hydrographs were derived. In addition, all release hydrographs incorporate steady flows during the months of September and October as dictated by the Final Environmental Assessment for Experimental Releases from Glen Canyon Dam, Arizona, 2008 through 2012 (U.S. Department of the Interior, 2008).

Modeling Approach

The modeling simulations were performed using the Wiele and Smith (1996) model for routing the GCD flow releases downstream and the Wright and others (in press) model for routing sand and computing sand budgets for the various scenarios. The flow model requires release hydrographs and major tributary flow hydrographs as inputs. Streamflows from the Paria River (U.S. Geological Survey station 09382000) and Little Colorado River (U.S. Geological Survey station 09402300) were included using average monthly flows (fig. 2*B*) for their periods of record. While average monthly tributary flows were used for the flow routing, instantaneous tributary flows were used to estimate the tributary sand inputs (methods described in detail below, fig. 2*C*). For each scenario, the hourly release hydrographs described above were routed downstream and results were output at RM 30, RM 61, and RM 87 to be used as input to the sand routing model, as described below.

The Wright and others (in press) sand routing model computes sand fluxes at the computational nodes shown in figure 1 (RM 30, RM 61, and RM 87). The model computes sand concentrations for narrow particle size ranges and includes bed sorting algorithms to simulate the fining and winnowing characteristic of sand supply-limited rivers, such as the Colorado below Glen Canyon Dam. The sand routing model was calibrated and validated using sand transport monitoring data from 2003–2009 as described by Wright and others (in press). Required model inputs are flow hydrographs at the three computational nodes as well as time series of sand inputs from the Paria and Little Colorado Rivers (sand transport at the upstream boundary, Lees Ferry, is assumed to be zero in the model as per Wright and others, in press). The flow hydrographs were provided by the flow model as described above. The tributary inputs were modeled in a similar fashion as for the flow routing, that is, average monthly sand loads were used as boundary conditions (fig. 2*C*). While this approach does not incorporate the episodic nature of tributary flooding, it provides the correct long-term seasonal distributions and average annual inputs, making it a reasonable approach for comparing alternative flow release scenarios. The average monthly sand inputs were derived from long-term records of tributary sand loads provided by the USGS Grand Canyon Monitoring and Research Center (David Topping, U.S. Geological Survey, unpub. data). These long-term records were developed using a combination of measurements (flow and sediment concentration at the gages cited above, using standard USGS methods) and models (Topping, 1997; Topping and others, 2010). The particle size distributions used for the tributaries were the same as those used by Wright and others (in press). Finally, the sand routing model requires specification of the initial bed sand thicknesses and particle size distribution for each reach. These were specified as the values at the end of the validation simulations (March 2009) described by Wright and others (in press) as follows: sand thicknesses equal to 0.45, 0.48, and 0.56 m and median particle sizes equal to 0.35, 0.32, and 0.30 mm for upper Marble Canyon, lower Marble Canyon, and eastern Grand Canyon, respectively. These conditions were chosen because they are the most recent estimates of bed conditions in the reaches. It is not possible to know the bed conditions on Oct 1, 2010 (the beginning of the simulations) because tributary inputs cannot be forecasted accurately. Also, Wright and others (in press) showed that the sand routing model is not particularly sensitive to the initial bed conditions for the sensitivity range studied therein.

Uncertainties in the model results were evaluated by conducting simulations with estimated errors incorporated into the boundary conditions (tributary inputs) and model calculations (sand transport rates). Following the methods used by Topping and others (2010) for constructing error bars for sand budgets based on high-resolution monitoring data, the tributary inputs were varied by ±10 percent and the sand transport rates were varied by ±5 percent. That is, for each scenario, two additional simulations were performed: 1) tributary inputs increased by 10 percent and sand transport rates decreased by 5 percent, providing an upper uncertainty bound; and 2) tributary inputs decreased by 10 percent and sand transport rates increased by 5 percent, providing a lower uncertainty bound. This technique is particularly appropriate here because the sand routing model was calibrated to sand transport measurements with comparable error estimates. It is noted that these uncertainty bounds are most useful for evaluating whether there is net accumulation or erosion for a given scenario. For comparing scenarios to each other, it is important to only compare simulations with the same boundary conditions and model parameters. For example, it would not be appropriate to compare one operating scenario with tributary inputs increased by 10% with a different operating scenario with tributary inputs decreased by 10%.

Results

The sand routing model predicts sand concentrations at the three computational nodes shown in figure 1 (RM 30, RM 61, RM 87). The sand concentrations were combined with the flows at these locations to compute sand fluxes, and the sand fluxes were then used to construct sand budgets for the three reaches bounded by the computational nodes (flux is assumed to be zero past Lees Ferry). For this report, the two Marble Canyon reaches were combined for sand budgeting purposes. The sand budgets are simply a cumulative accounting of sand inputs to a reach minus sand export from a reach; thus, a positive sand budget indicates net sand accumulation within the reach and a negative sand budget indicates net sand erosion within the reach.

The primary results of the simulations are shown in the series of figures 3–8. Each figure represents a different operational scenario and consists of three panels. The top panel shows the hourly release hydrographs for the given operational scenario for both the 8.23 and the 11.0 MAF annual volumes. The middle panel shows the modeled cumulative sand budgets for Marble Canyon, again for 8.23 and 11.0 MAF, including the uncertainty envelopes. The bottom panel shows the simulated sand budgets for the eastern Grand Canyon reach.

The model results show some expected trends that are common to most of the operational scenarios. First, the higher annual release volume (11.0 MAF) consistently leads to more sand export and thus less sand in the reaches projected at the end of WY 2011. The sand budgets are also seen to reflect variations in flow releases (patterns and volumes) and tributary inputs throughout the year. For example, the Marble Canyon sand budgets tend toward accumulation during August and September when Paria sand inputs are greatest (fig. 2*C*). An example of the impact of flow volume on the sand budgets is apparent in the results for SAS (fig. 7), where it is seen that extended periods of relatively high flows in the spring drive the sand budgets substantially in the negative direction (that is, erosion). The dashed lines define the modeling uncertainty envelopes and allow for determination of the sign of the sand budget for each scenario at the end of WY 2011 (that is, for determination of a positive or negative sand budget, the uncertainty envelope must not span zero).

In order to compare the scenarios more directly, annual sand budgets, including the uncertainty envelopes, were computed for each simulation. The annual sand budgets are equivalent to the cumulative sand budgets shown in figures 3–8 at the end of WY 2011. These results are shown in figures 9 and 10; in these figures, the horizontal lines represent the “base” simulations (that is, without uncertainty estimates) and the vertical lines denote the range based on the uncertainty simulations.

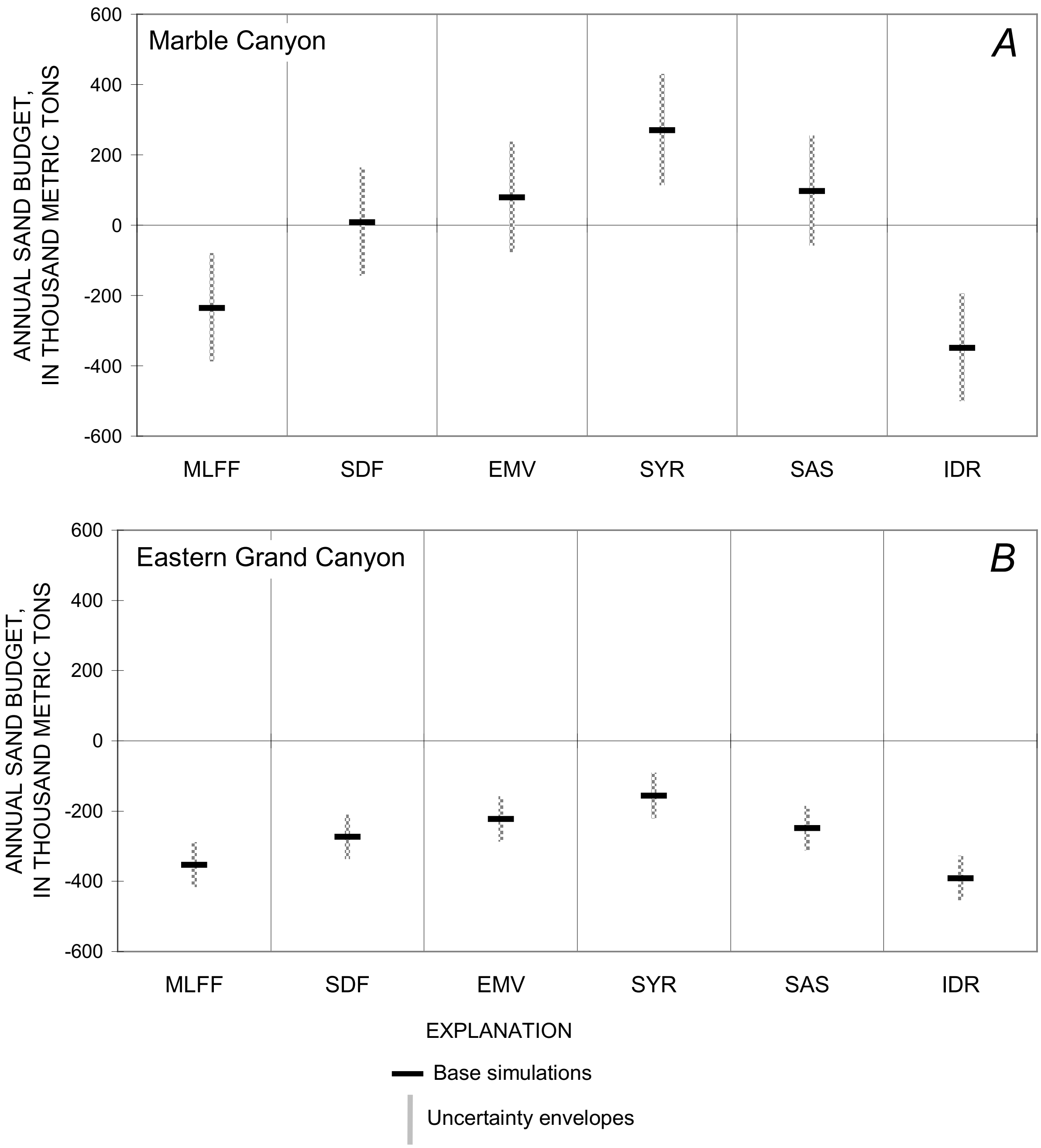

Figure 9. Modeled annual sand budgets for the 11.0 million acre-foot annual hydrologic scenario. *A*, Sand budget for Marble Canyon. *B*, Sand budget for eastern Grand Canyon. Vertical lines denote range based on uncertainty simulations.

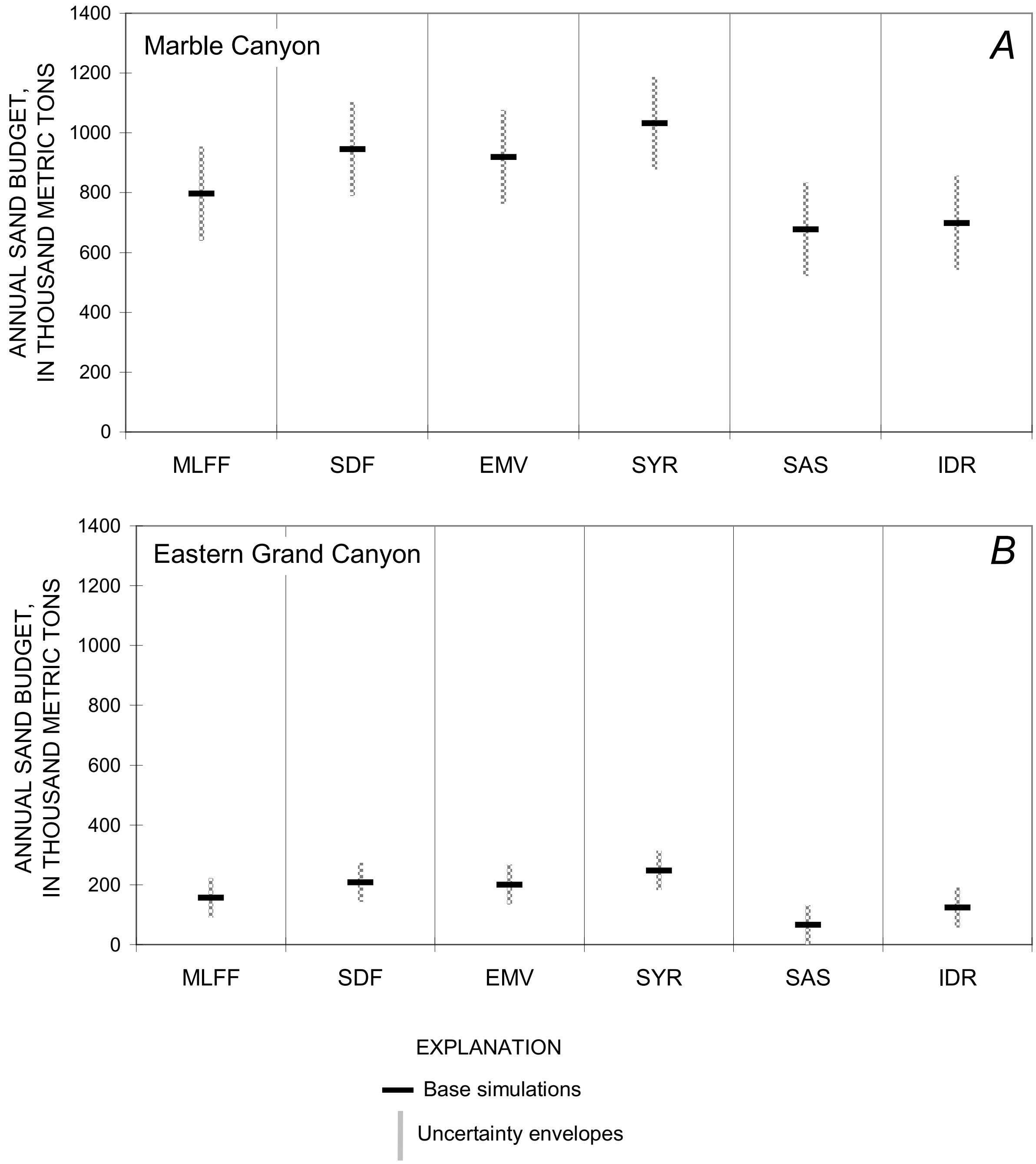

Figure 10. Modeled annual sand budgets for the 8.23 million acre-foot annual hydrologic scenario. *A*, Sand budget for Marble Canyon. *B*, Sand budget for eastern Grand Canyon. Vertical lines denote range based on uncertainty simulations.

For the 11.0 MAF annual release volume for Marble Canyon (fig. 9*A*), only one scenario, SYR (steady year round flows), results in a positive sand budget (that is, an uncertainty envelope entirely above zero indicating net sand accumulation). Two scenarios, MLFF and IDR, result in negative sand budgets (that is, uncertainty envelopes entirely below zero indicating net sand erosion), and three scenarios, SDF, EMV, and SAS, result in neutral sand budgets (that is, uncertainty envelopes span zero). For this release volume in the eastern Grand Canyon reach (fig. 9*B*), all of the scenarios resulted in negative sand budgets based on the model simulations. The differences in the results between the Marble and eastern Grand Canyon reaches are primarily due to differences in tributary inputs to each reach. That is, the Paria River supplies about 1.23 million metric tons to Marble Canyon, whereas the Little Colorado River supplies about 0.56 million metric tons to eastern Grand Canyon. Also, because the Paria inputs are greatest in the months of August and September (fig. 2*C*), near the end of the simulations, this sand may not have had sufficient time to move through the Marble Canyon reaches and into eastern Grand Canyon. This issue could be avoided in future analyses by conducting modeling simulations over multiple water years using a range of annual release volumes in order to evaluate the longer-term response of sand budgets to different operational scenarios.

The results for 8.23 MAF (fig. 10) annual volume, when compared to the 11.0 MAF volume results, illustrate the strong influence that annual release volume has on the simulated sand budgets. All scenarios resulted in positive sand budgets (that is, net accumulation) for Marble and Grand Canyon reaches for an 8.23 MAF annual release volume. This is perhaps not surprising given that 8.23 MAF is well below the long-term annual flow volume for the Colorado (10.8 MAF based on the period of record for the Colorado River at Lees Ferry, Arizona, U.S. Geological Survey station 09380000) and that average annual tributary sand inputs were used in the modeling scenarios. This combination of below average annual release volume and average tributary sand inputs is conducive to sand accumulation in the reaches below the Paria River (Topping and others, 2010). This combination may not be unusual because annual release volumes and tributary inputs tend to be uncorrelated since annual volumes are driven by upper basin snowpack conditions, whereas tributary inputs are primarily dependent on summer/fall monsoon rainfall. The simulated annual sand budgets for each scenario are compared numerically in the following section.

Summary and Discussion

The annual sand budget results described in the previous section are summarized in table 1 (11.0 MAF) and table 2 (8.23 MAF) for both the Marble Canyon and Grand Canyon reaches. For each annual release volume and reach, the operational scenarios are ranked 1 through 6 on the basis of the simulated annual sand budgets, with a rank of 1 denoting the scenario with the most sand in the reach at the end of WY 2011 and a rank of 6 denoting the scenario with the least sand. Tables 1 and 2 also report the sign of the sand budget at the end of WY 2011 with consideration of the estimated uncertainty envelopes; that is, for a sand budget to be non-neutral (positive or negative), both uncertainty bounds must have the same sign. The numbers reported in the tables are for the base simulations (no adjustment for uncertainty), which are the appropriate results for comparing the operational scenarios with each other.

Table 1. Modeled sand budgets for 11.0 million acre-foot annual release volume

Rank	Scenario	Annual sand budget (Tmt[1])	Sign (includes uncertainty)	Rank	Scenario	Annual sand budget (Tmt)	Sign (includes uncertainty)
Marble Canyon				**Grand Canyon**			
1	SYR	+270	Positive	1	SYR	-157	Negative
2	SAS	+97	Neutral	2	EMV	-223	Negative
3	EMV	+79	Neutral	3	SAS	-249	Negative
4	SDF	+8	Neutral	4	SDF	-274	Negative
5	MLFF	-235	Negative	5	MLFF	-354	Negative
6	IDR	-349	Negative	6	IDR	-391	Negative

[1] Tmt – thousand metric tons.

Table 2. Modeled sand budgets for 8.23 million acre-foot annual release volume

Rank	Scenario	Annual sand budget (Tmt)	Sign (includes uncertainty)	Rank	Scenario	Annual sand budget (Tmt)	Sign (includes uncertainty)
Marble Canyon				**Grand Canyon**			
1	SYR	+1,032	Positive	1	SYR	+248	Positive
2	SDF	+945	Positive	2	SDF	+208	Positive
3	EMV	+919	Positive	3	EMV	+200	Positive
4	MLFF	+796	Positive	4	MLFF	+156	Positive
5	IDR	+699	Positive	5	IDR	+123	Positive
6	SAS	+677	Positive	6	SAS	+65	Positive

The first observation from the tables is that the SYR scenario is consistently ranked 1 in terms of the annual sand budgets and is the only operation that results in a positive Marble Canyon sand budget for 11.0 MAF (table 1, fig. *9A*). This ranking is an expected result and is consistent with the choice by Wright and others (2008) to evaluate this scenario as the optimal flow regime for building and maintaining sandbars below Glen Canyon Dam. The nonlinear relationship between sand transport and water discharge (with exponent greater than one) dictates that a steady flow will transport less sand than an equivalent-volume fluctuating flow, and thus a steady year round flow yields the least sand export. For the 11.0 MAF simulations, the MLFF and IDR operations consistently ranked 5 and 6, owing to the fact that the other four scenarios all constrain the MLFF fluctuations to some degree (either monthly variations or daily fluctuations are constrained). MLFF ranks higher than IDR because IDR relaxes the MLFF constraints and allows for increased fluctuations and increased down ramp rates (which allow for longer peaks within each day). The SDF operational scenario ranks 4 for both reaches. The SAS and EMV operations rank 2 and 3 and the order is swapped for the two reaches; however, these operations produce quite similar results for this annual release volume.

The results and rankings for the 8.23 MAF annual volume are substantially different from the 11.0 MAF results, the only similarity being that SYR is ranked 1 (tables 1, 2). For this annual volume, the SAS operation ranks 6 for both reaches, whereas for 11.0 MAF, this operation ranked 2 or 3, depending on the reach. This difference results from the 18,000 cfs maximum release imposed by SAS. For all other scenarios, the 11.0 MAF annual volume results in higher peak flows that substantially increase sand transport and export rates. MLFF and IDR rank above SAS at positions 4 and 5, again with MLFF resulting in more sand in both reaches than IDR. Finally, SDF and EMV yield similar results for 8.23 MAF, with SDF ranked 2 and EMV ranked 3 for both reaches.

Finally, it is noted that these simulations should not be considered absolute predictions of the sand budgets below Glen Canyon Dam for WY 2011. It is unknown what the actual annual release volume and tributary inputs will be. Also, the initial conditions with respect to sand in the reaches are unknown. Rather, these simulations provide realistic estimates of the sand budgets for the hypothetical initial and boundary conditions simulated, as well as comparisons of the various operational scenarios, in a relative sense, that may be used by decision makers within the GCDAMP.

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