TWG Webinar/Conference Call
June 21, 2010

Conducting: Paul Grams, GCMRC **Convened:** 1 p.m. (MDT)

TWG Members/Alternates:

Mary Barger, WAPA
Cliff Barrett, UAMPS
Marianne Crawford, USBR
Kerry Christensen, Hualapai Tribe
Jerry Cox, Grand Canyon River Guides
Bill Davis, CREDA
Chris Harris, Colorado River Board of California
Norm Henderson, NPS/GLCA
Rick Johnson, Grand Canyon Trust
John Jordan, Federation of Fly Fishers
Robert King, Utah Division of Water Resources
Dennis Kubly, USBR
Bill Stewart, AGFD
Jason Thiriot, Colorado River Commission/Nevada
Clayton Palmer, WAPA
Mike Yeatts, Hopi Tribe

Other Participants:

Glenn Bennett, USGS/GCMRC
Jane Bird, Upper Colorado River Commission
Lori Caramanian, DOI
Mary Daugherty, USGS/GCMRC
Paul Grams, USGS/GCMRC
John Hamill, USGS/GCMRC
Leslie James, CREDA
Ted Melis, GCMRC/USGS
Bruce Moore, Southern Nevada Water Authority
Jack Schmidt, Utah State University
Patti Aaron, USBR
Scott Wright, USGS (Sacramento)

Webinar Support: Mary Daugherty

Meeting Recorder: Linda Whetton

Introduction. John said this information request came up through the TWG via a number of different avenues, most recently the last TWG meeting where there was a request from a variety of TWG members to assess the effects of various different types of dam operations on sediment conservation in Marble and Grand Canyon. There was some dialogue with the Secretary's Designee about the scope of the work that GCMRC was going to do and ultimately they were given the go-ahead to provide the analysis which should be helpful in forming the TWG's discussion of the 2011 hydrograph.

Modeling Results. Scott Wright gave a PowerPoint presentation, "Briefing Subject" (***Attachment A***) and said the Open File Report (***Attachment B***) would provide more information. He also referenced another Open File Report, "An Approach for Modeling Sediment Budgets in Supply-limited Rivers" (***Attachment C***). Since he has talked about the modeling done in several meetings, he would only focus on the results. He said two release volumes, the first being 8.23 maf and the reason for doing that was because it has been the most common release volume over the last decade so it seemed reasonable to do that. With the new equalization guidelines in place, they looked at the April 24-month study, which was the most current study they had while they were developing the scenarios to model. At that time the projected volume was a 11.0 maf due to the need to do equalization between the two main reservoirs (Lake Powell and Lake Mead). They solicited input from the TWG several months ago and compiled the responses they received and developed the list of operations: 1

1. MMLF = Modified Low Fluctuating Flow
2. SDF = Steady Daily Flows. This operation is the same as MLFF in terms of the monthly distribution of the volume but it does not have any daily fluctuations so steady flows for each month and then the monthly volume changes through the year.
3. EMV = Equal Monthly Volume. This is the opposite of #2 where it maintains the MLFF daily fluctuations so the flows still fluctuates up and down every day, but the monthly volumes are changed so there is an equal volume in each months so getting rid of the MLFF distribution of monthly volumes but maintaining the daily fluctuations.
4. SYR = Steady Year-round Flow. This is a steady flow for the whole year. They've looked at this before and this is a useful one to do just from the standpoint of providing an upper bound, basically as good as you can do for sand conservation with the dam there and providing the other scenarios too.

5. SAS = Seasonally Adjusted Steady Flow. For this they used the description of the 1995 EIS where it was also analyzed.
6. IDR = Increased Daily Range and downramp. This was the option A Variation that came from the 2006 assessment. It increases the daily range over what is currently allowed by MLFF up to 10,000 or 12,000 cfs per day and also increases the downramp rate in certain months up to 4,000 cfs per hour.

In 2-5, flows are further constrained to fluctuate MLFF on a daily basis or on a monthly so they all have some element of a more steady hydrograph. Number 6 is the lone scenario that increases the degree of fluctuation from MLFF.

Q*: I thought there was also a scenario requested that was going to look at pre-ROD? (James)*
A*: We had to draw the line somewhere as far as getting to too many scenarios. The one step closer with the increased daily range was the interim step towards something with more fluctuations than MLFF. (Grams)*
Q*: Just so I understand these, item 6 has more flexibility but all the others are less flexible that current operations, correct? (James)*
A*: Correct. (Grams)*

Scott said the way they constructed the hydrographs was for MLFF the 8.23 MAF scenario was taken directly from the 2006 options that were developed by Reclamation and Western. For the 11.0 MAF, they used that information and then for each month looked for a volume that was similar for that month within those 30 years of early hydrographs that had been generated and then those were matched up. They didn't match up perfectly so they would just scale them a little bit to get the monthly volume correct. All of the hydrographs used were basically derived from those early hydrographs for the 2006 assessment.

Q*: When you say the 2006 assessment, that's the LTEP analysis that was done? (Johnson)*
A*: I don't think it was considered LTEP. Ted could probably offer a better reason for how that happened but there was an assessment of five different scenarios for resource response. I don't think it was LTEP but was pre-LTEP. Is that right, Ted? (Wright)*
R*: That was the so-called Science Planning Group (SPG) option assessment. It was released to the TWG in October 2006 and preceded the announcement for the so-called LTEP in the Federal Register. (Melis)*

Q*: What's the period of record for the tributary inputs? (Henderson)*
A*: For the Paria it goes all the way back to the 1920's. There is more data in more recent times. As for the Little Colorado, we went back to the late 1980's. For the Paria we ended up using the same period of record as the LCR so it's about 20+ years of record to get the averages. (Wright)*

Scott reviewed the plots for Marble Canyon at 11.0 MAF and 8.23 MAF and then for Eastern Grand Canyon at 11.0 MAF and 8.23 MAF.

Q*: Can you give a quick definition of the uncertainty envelope? (Johnson)*
A*: We used the same definitions that Topping uses for the mass balance so we varied the tributary inputs by +/- 10% and we varied the mainstem, the predicted transport rates, for the model in the mainstem by +/- 5%. The upper uncertainty would be if the tributary inputs were 10% more than we thought and the mainstem transport was 5% less so more inputs, less exports that uses the upper bound and vice versa for the lower bound. (Wright)*

Q*: Why would you characterize 8.23 MAF as below average annual volumes because in the last 10 years, it's been about 8.0 and for the foreseeable future except if we get some decent inputs? (King)*
A*: It depends on how you would define the average for this basin. Certainly that hasn't been the case over the last 10 years but if you look at the longer record, the average is between 10.5 – 11 MAF. That's the number that gets used for allocations and the like. (Wright)*
R*: It isn't for allocations. An 8.23 MAF is probably closer to what the average is going to be in the future. (King)*
C*: It doesn't matter too much here for this discussion. That is really important for trying to manage sand in the system because less water, which obviously isn't good for some things, is actually a good thing for sand resources in the canyon. Whenever you have average inputs and 8.23 MAF or something around that, that tends to result in accumulation in Marble Canyon. (Wright)*

He provided the following summary points:

- Since we don't know what the 2011 annual volume and tributary inputs will be, the results should be viewed in a relative sense (i.e., against each other)
- SYR consistently ranks 1st in terms of sand retention and provides an upper bound for comparison
- SDF and EMV yield similar results indicating more sand retention than MLFF, EMV is slightly better for 11.0 MAF while SDF is slightly better for 8.23 MAF
- SAS ranks high for 11.0 MAF (2nd or 3rd depending on reach), but ranks 6th for 8.23 MAF. This is because the maximum flow (18,000 cfs) is imposed and the same for both volumes.
- IDR consistently ranks just below MLFF for sand retention.

Q*: Bob Mussetter had wanted to participate in this call but couldn't, however, one of the questions he has asked in the past or a clarification. These are the only two reaches that you guys have looked at and wonder if the modeling has the capability to look at the same scenarios for some of the lower reaches? (James)*
A*: Not as currently constructed. The reason for that is just a data limitation essentially. The model definitely need the data for calibration and we could extend downstream. It's easy enough to add reaches but that requires data on tributary inputs as well as mainstem transport in those reaches. I think Dave Topping is working toward providing that information but it's not something that has happened yet. I don't think he's on the call otherwise he could update us on where he's at. I think the mainstem monitoring is coming close to what we need. I'm not sure where he is with the tributary work. (Wright)*
C*: I appreciate that because I think it's really to clarify the report is only covering these reaches and not implications that it's for the entire mainstem. (James)*
Q*: What portion of the river corridor would this be covering? (Henderson)*
A*: It covers from Mile 0 to Mile 88, Lee Ferry to Phantom Ranch. (Wright)*
Q*: Have you run any simulations with the HFE thrown in? (Christensen)*
A*: No. (Wright)*
Q*: Could you run that simulation to calculate the amount of sand augmentation necessary to have a positive benefit under all conditions? (King)*
A*: Yes, that can be done. The key there would be specifying when it would come in and whether it would be a constant trickle or like a slug because that makes a difference in how it ends up getting transported. That would be very easy to do. (Wright)*
Q*: Does the paper get into the actual numeric comparisons between all the alternatives as far as percentages? (Henderson)*
A*: Yes. (Wright)*
Q*: You said you haven't done ___ with an HFE but I presume you could do it, right? (Johnson)*
A*: You would need to know the hydrograph and then you'd need to know how to redistribute that volume through the rest of the year. It's not as easy as sand augmentation, but it could be done. (Wright)*
Q*: At Saguaro Lake you presented the high, low, and average sediment inputs, but you have the inputs coming in at different times or was the average input that you showed at Saguaro Lake the same as what you shown here? (Johnson)*
A*: I think for those we had everything dumping in the first 10 days of the simulation. I didn't really like that but it made more sense to have it distributed using the historical information that we do have. (Wright)*
Q*: I'm trying to get a sense of scale here. These volumes, the differences, and the different scenarios – are they like totally overwhelmed if you did throw an HFE in there? I mean it wouldn't really matter given you did an HFE. (Christensen)*
A*: It would definitely matter. I think for the floods that were conducted in 2004 and 2008 the sand export mass during those events – it depends on the event and the site. They were on the order of half a million to 800,000 metric tons for the 60-hour peak and so the volumes go back to Marble Canyon for 8.23 MAF. You're talking retention of 800,000 up to 1 million and so export during a flood for those conditions would be more than 50% of what you retained. (Wright)*
C*: And integrating this model with an HFE is part of what we're talking about is work that would go into the development of the HFE protocol. That's why this was done separately without an HFE but that will be considered. (Grams)*
Q*: I appreciate that you said this modeling allows a person to make a relative ranking. This operation from a sediment budget point of view is better than that operation and it's better by a lot. I believe that the Bureau can't operate this way because what you've presumed here is perfect for knowledge about how much volume is going to be released from Glen Canyon Dam and that never happens. I've made a couple of suggestions but I'm a little bit at a loss to understand the reluctance that you didn't include in your forecast and modeling. So why aren't you doing that? (Palmer)*

***A**: So the idea would be to somehow change the volumes through the year as you're going? I see where you're coming from on that. You're right, the forecast does change through the year but I think for comparing these operations, I don't think that would really make any difference because in the long run if you change the forecast, that would change the volumes and the changes would be the same for all the different scenarios that you're looking at. The simplest way to do simulations and rank the scenarios is to assume the forecast is right and run the scenarios that way. If you start trying to incorporate the forecast error, 1) it's not clear to me how you would do that, and 2) I don't think all the extra work that would be required to do that is warranted. I don't think it would change the result in terms of the rankings of the alternatives. I think you could make the same argument about the tributaries. We're using the average tributary inputs. Someone could argue that you have to use every scenario imaginable for the tributary inputs and pretty much anything can happen, but to do that would be incredibly complicated from the standpoint of doing the simulations and I just don't think that it would be effecting the bottom line in the results and it would just be a lot of work so not much bang for the buck. (Wright)*

***Q**: This has already been done and you must have looked at the 2006 SPG options report. In that, the forecast was included and came out with the monthly volumes that would pertain to this. When you say it's a lot of work, well, it's already been done. Secondly, I've pointed out a couple of times that when you start the year with a presumption of 8.23 MAF and you end up the year with equalization flows, you actually do things like have equal monthly volumes, have greater volumes and therefore greater fluctuations across the four summer months than MLFF does. It seems to me that since you end up with greater volumes and greater fluctuations under an equal monthly flow during the summertime, that it could easily change the relative ranking of the two. (Palmer)*

***Q**: That's if the forecast is off in one direction, but what if it's off in the other direction? (Wright)*

***A**: Yes exactly, but stop for just a second. If the forecast is off in one direction, then you're saying it's possible but the relative ranking of equal monthly volumes vis-á-vis MLFF could change. That's all I need you to do is acknowledge that it's possible the relative ranking of these operations could change if forecast errors included in your analysis. (Palmer)*

***C**: If you change the volume, then the rankings change. (Wright)*

***R**: That's what I'm saying. You've retorted to my comment by saying, "look we haven't done it because we think it will be more work and it won't change relative rankings." As far as I can tell, it has quite a potential to change relative rankings of some of those operational scenarios. (Palmer)*

***R**: I can't disagree with that. All I would say is that these are the scenarios that we think are the most probable and use the most realistic boundary conditions for the modeling. (Wright)*

***C**: And you've seen several e-mails from me suggesting that if you don't know whether an 8.23 MAF or an 11 MAF at the end of year is going to start out that way in the beginning of the year. It's easy to do and incorporate the monthly volumes and include an error forecast and see that you get hourly hydrological inputs you need to run your model. I don't understand why you don't use those for the sake of this. (Palmer)*

***Q**: How many scenarios would you have to run then for forecast error because there could be an infinite number of ways that the error could go. (Wright)*

***A**: Let's suppose there is an infinite number and let's suppose you divided the infinite number of errors into a normal distribution and took the upper and lower core tile. At least you'd be able to know whether forecast error significantly altered the relative ranking of these operational scenarios for sediment distribution. The way you're doing it now you're going to leave us with a single conclusion that it's the core knowledge and people are going to take that and say "I see that the relative ranking error for this scenario above or below this other one." They won't be able to separate a sensitivity analysis which could significantly change a relative ranking. (Palmer)*

***R**: I disagree with that it would significantly change the relative rankings. (Wright)*

***C**: This model applies the model to an annual volumes equitably across all the scenarios analyzed. So if you chop that up finer, you're going to get the same results. (Grams)*

***R**: Not given the information I've sent you which shows you that it's possible to start out the year with a presumption about annual volume, use MLFF, and then compare it to equal monthly volume. You'd end up with summer releases where the equal monthly volumes actually has greater volumes than MLFF and therefore greater fluctuations over a four-month summer period. That's the period in which you're getting the Paria inputs and so given the way you've set up the model, it's possible that the relative ranking between MLFF and equalized monthly volume would change in Marble Canyon. (Palmer)*

***C**: I think it would be helpful to see something about some scenarios about how the Bureau might distribute monthly volumes under a couple different forecast error scenarios because right now it's pretty much anything. You're saying that anything would be possible. The reality is that 8.23 MAF has been a very, very common release and this is targeted towards what I think is the most likely and average condition. (Grams)*

***R**: 8.23 MAF, for example, was released in 2009 but the Bureau started off with a presumption that 10.5 MAF was going to be released and they modified their monthly volumes to accommodate what they thought was going to be a higher release year. And the Bureau did this for 10 years under five scenarios for the 2006 report. If you want to know how the Bureau would distribute monthly volumes for a 10-year period, including forecast error, you could*

look at the 2006 option report which I've referred you to. The only reason I keep bringing this up Paul is because it was a surprise to everybody when the Bureau prepared the hydrology for the 2006 option report that things like seasonally adjusted steady flows and equalized monthly volumes didn't look anything like that once you incorporated the forecast error. (Palmer)
***Q**: Scott, you've used the average monthly inputs from the Paria and the LCR and obviously that's not usually how it works every year. Usually you get either one or maybe two blips somewhere along that line. Is it just the amount of sediment that comes in or is it the timing – will it change the relative merits of this based on when the input comes in? (Henderson)*
***Q**: Can I ask a clarifying question because I have a similar question. I think what Norm is asking and what I want to know is does it matter if it all comes in at one time during the month or if it's spread equally throughout the month? Is that right? (Johnson)*
***Q**: Well, sort of. The way the graph is there are some big months and then there's some small months and you're basically saying inputs come in every month almost and what I'm saying is that's not reality. Reality is usually they come in – any particular year they'll come in one time or maybe two times but usually one big impulse or are these numbers here, is the base load too or is this the actual pulses that come in? (Henderson)*
***A**: This illustrates a similar thing to what Clayton is pointing out is that these simulations are not reality. There are some assumptions built in to the boundary conditions and so for the tributaries typically such as the Paria, the floods happen in a day or two and that's when all the sand comes in. The bottom line is we don't know when that's going to happen in 2011. We could do every possible scenario and look at the variability of all the distribution. That's the most vigorous way to do it. The bottom line is that there wasn't time to do that for this for one thing and I just don't think that is worth all the effort to get these relative comparisons. (Wright)*
***Q**: Do you think the comparison would basically be the same no matter when the sediment came in? It's not like well I don't think you should put all the sediment coming in May. We know that doesn't happen. We've got the seasonal, the monthly distribution, the way it has happened historically and the difference is that we don't have – we've got X amount coming in October. That might come in in one day, but we don't know what day that will be so we're just distributing over the month. I think it makes sense to do that for simulations like this to keep that simple and as long as you're using the same boundary conditions for all the scenarios that you're comparing, you get a valid comparison between those scenarios. (Wright)*
***Q**: I was just thinking that in terms of the whole ecosystem approach that we're going to be looking at at some point and knowing the information that came out of the workshop at Saguaro Ranch, the request to do this for the pre-ROD might be really important since they were saying that pre-ROD, that the HBC was doing better and the RBT was doing worse. If you wanted the data to work on the full ecosystem approach, it sounds like we should also have that run. (Barger)*
***A**: That's something that could be done. It's not going to be in this report. It could be done at a later date I guess. It seemed unrealistic to me that those results would be that useful given the current situation but maybe for the reasons you outlined it would be worth doing that. (Wright)*
***Q**: I guess for curiosity I would like to see that, but I would imagine that it's going to be much worse than any of the other alternatives that are here. Is there any way it could be better than any of the alternatives? (Johnson)*
***A**: I'll say no. I'd be shocked given the way that's what built into – the way we did these simulations if we did it similarly for a 30 to 30,000 cfs fluctuation. I'm sure that would result in more export than any of these other ones. (Wright)*
***Q**: I was just thinking to have comparable data for whatever they're looking for on the fish stuff, it might be good to have it otherwise you're just guessing. (Barger)*

Paul asked if there were any more questions. Rick told him that he appreciated all the information that GCMRC prepared and that he felt it was really useful.

Conference Call ended at 2:12 p.m. (MDT)

Attachment A

Briefing subject

Wright, S.A., and Grams, P.E., in press, Evaluation of Water Year 2011 Glen Canyon Dam Flow Release Scenarios on Downstream Sand Storage along the Colorado River: *U.S. Geological Survey Open-File Report*

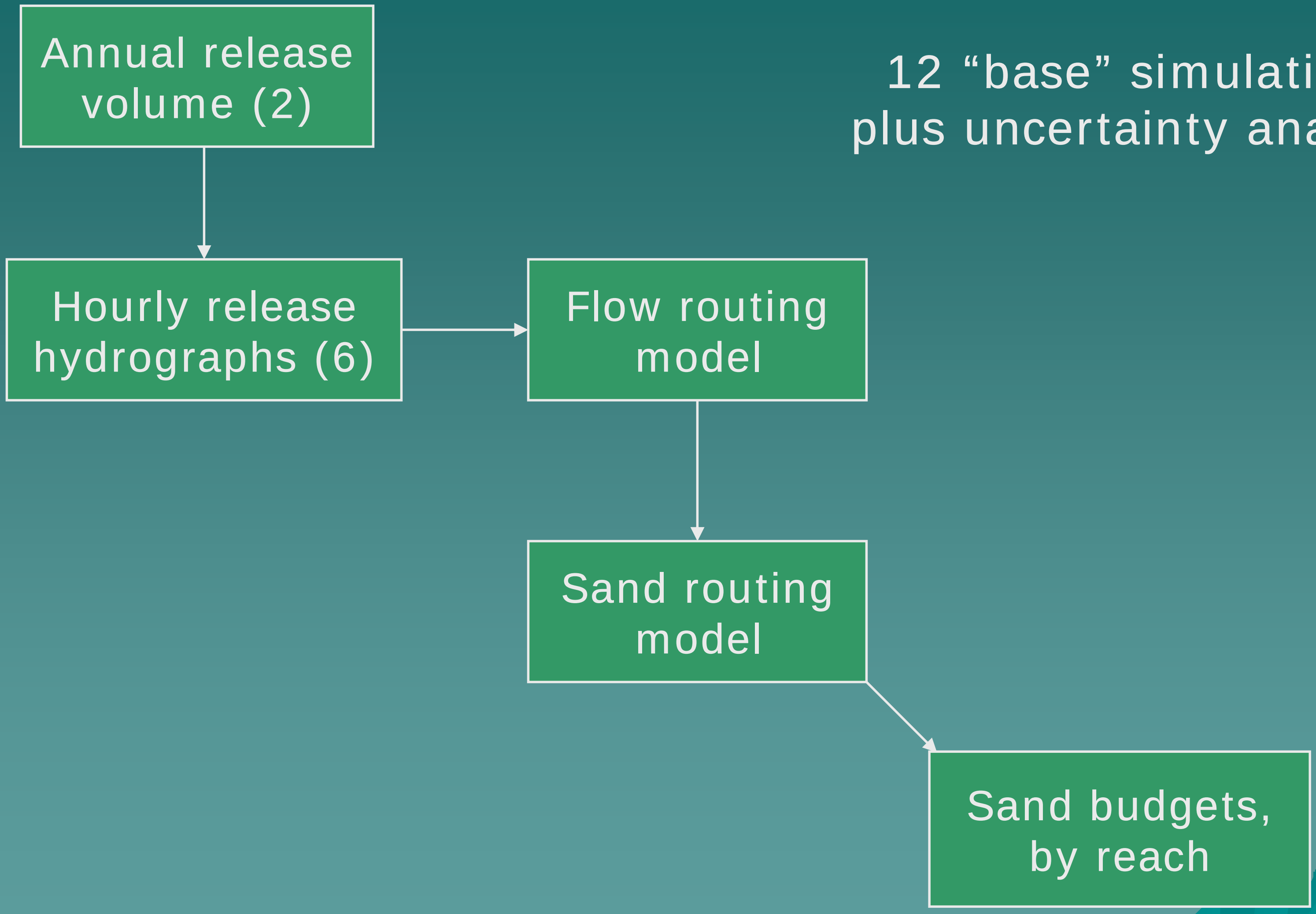
USGS-approved, on-line soon

USGS

Attachment A

Approach

12 “base” simulations,
plus uncertainty analyses



Attachment A

Sand Routing Model

Wright, S.A., Topping, D.J., Rubin, D.M., and Melis, T.S., in press. An approach for modeling sediment budgets in supply-limited rivers, *Water Resources Research*.

USGS-approved, accepted by WRR, on-line soon

USGS

Attachment A

Scenarios Modeled

2 annual volumes: 8.23 MAF and 11.0 (MAF, most probable from April 24-month study)

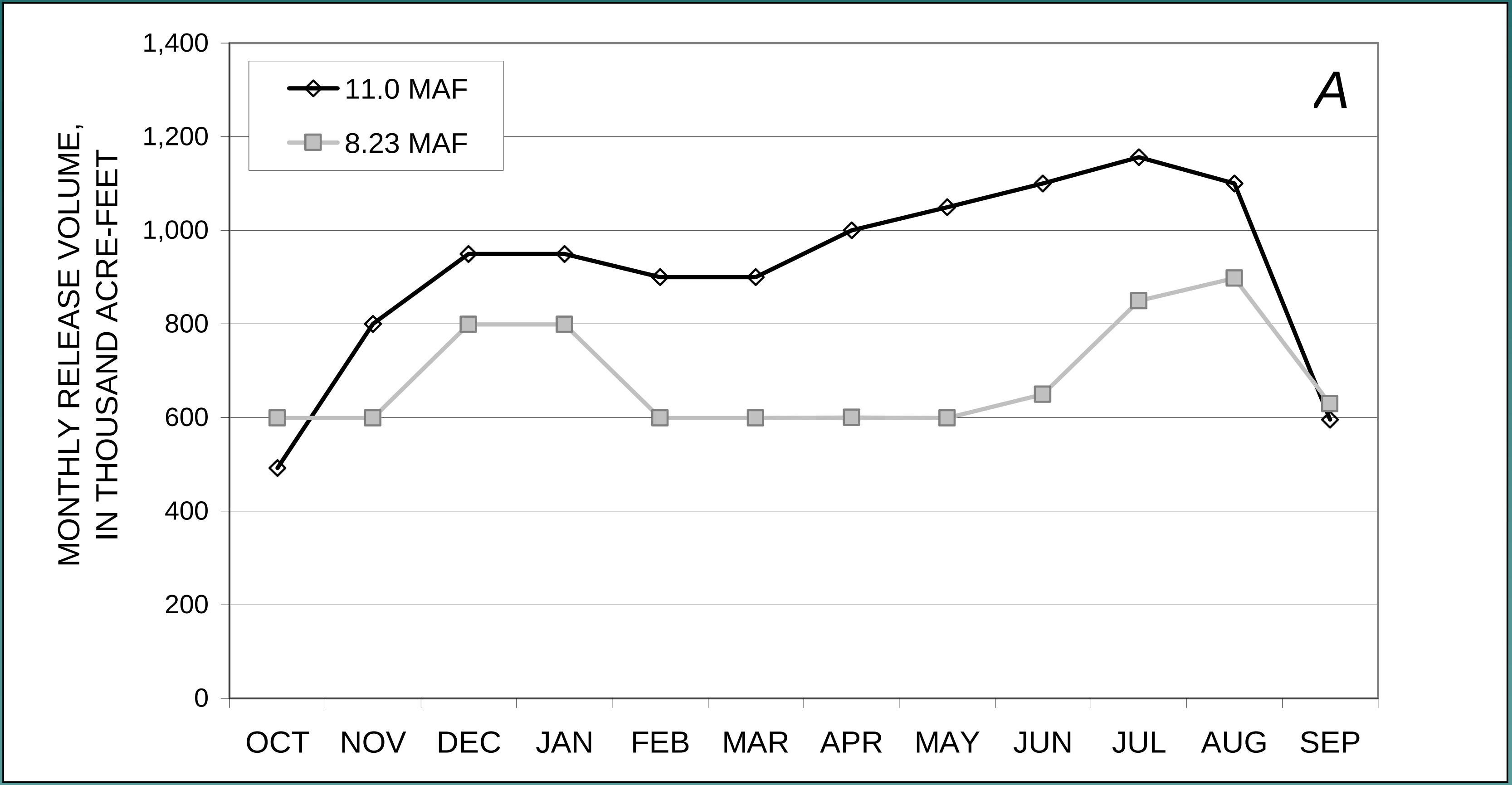
6 daily/monthly release patters:

1) Modified Low Fluctuating Flows (MLFF)
2) Steady Daily Flows (SDF) – No daily fluctuations, MLFF monthly volumes
3) Equal Monthly Volumes (EMV) – MLFF daily fluctuations, equal volume each month
4) Steady Year Round (SYR) – No daily or monthly fluctuations
5) Seasonally Adjusted Steady (SAS) – From the 1995 EIS
6) Increased Daily Range and Down Ramp (IDR) – Option “A Variation” from 2006 assessment

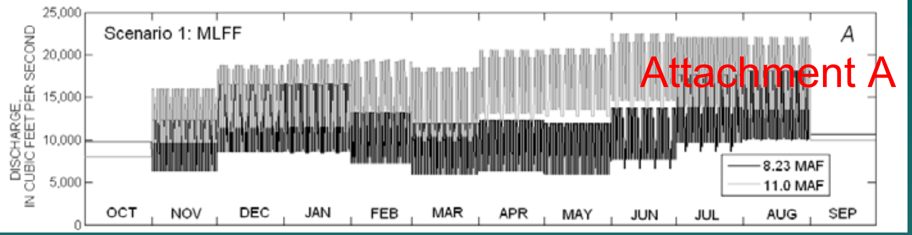
USGS

Attachment A

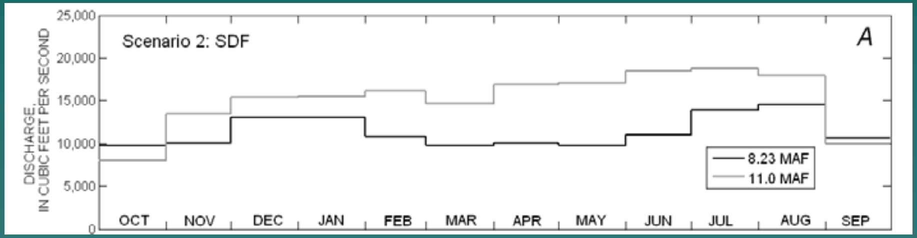
Annual and monthly volumes



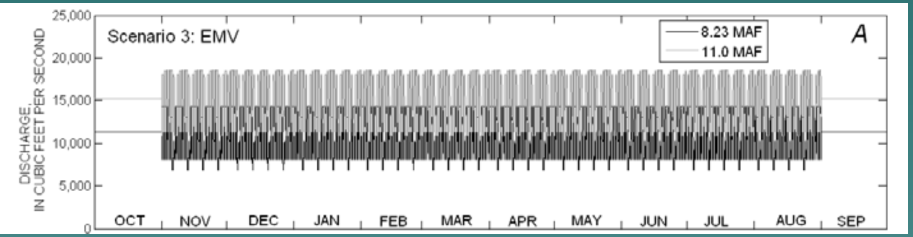
USGS



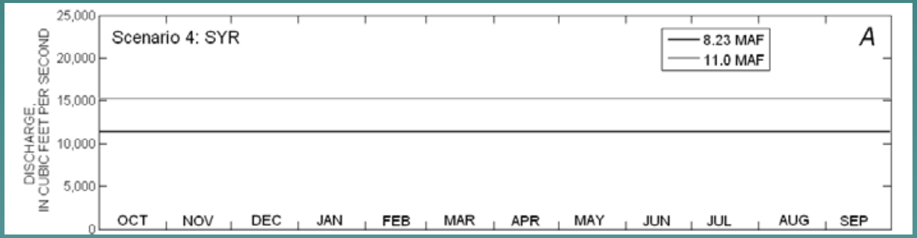
MLFF



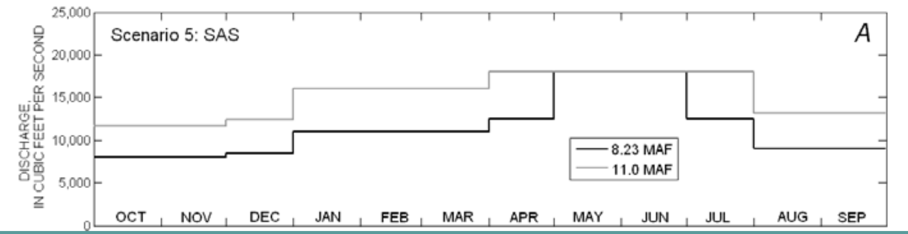
SDF



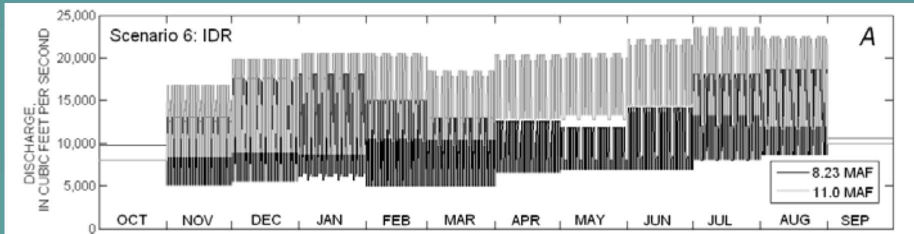
EMV



SYR



SAS

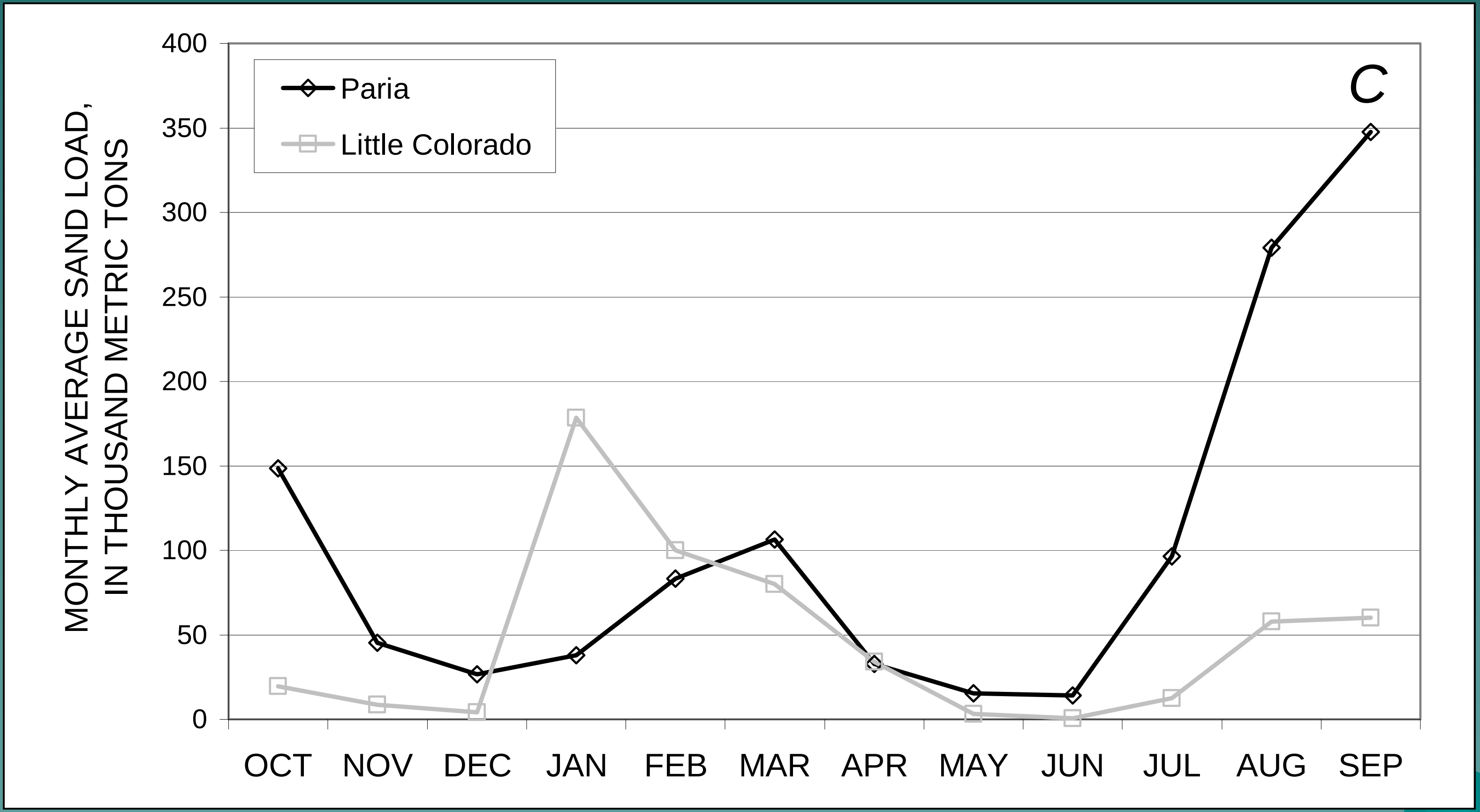


IDR

Attachment A

Tributary sand inputs

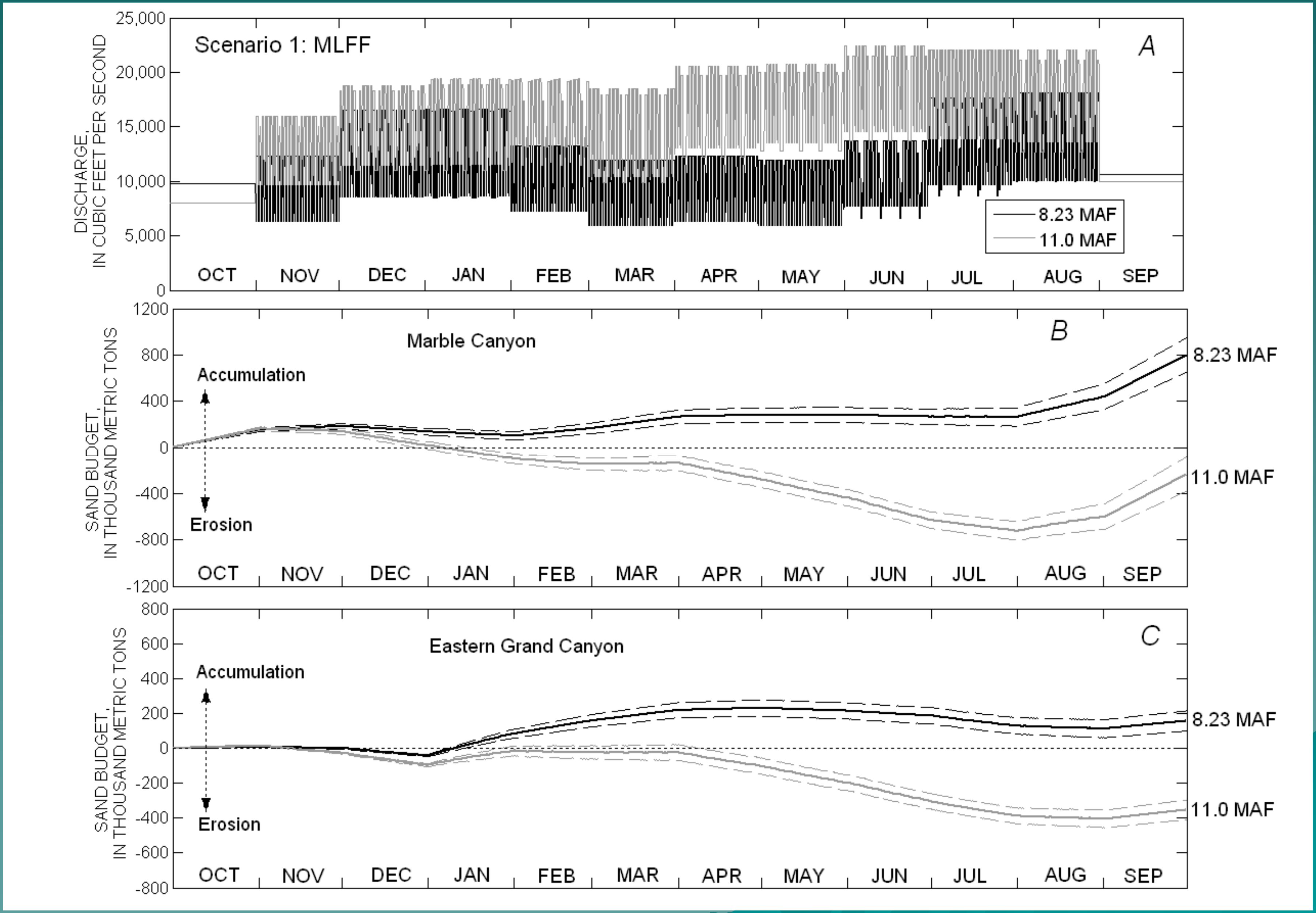
Averages for each month based on historical record



USGS

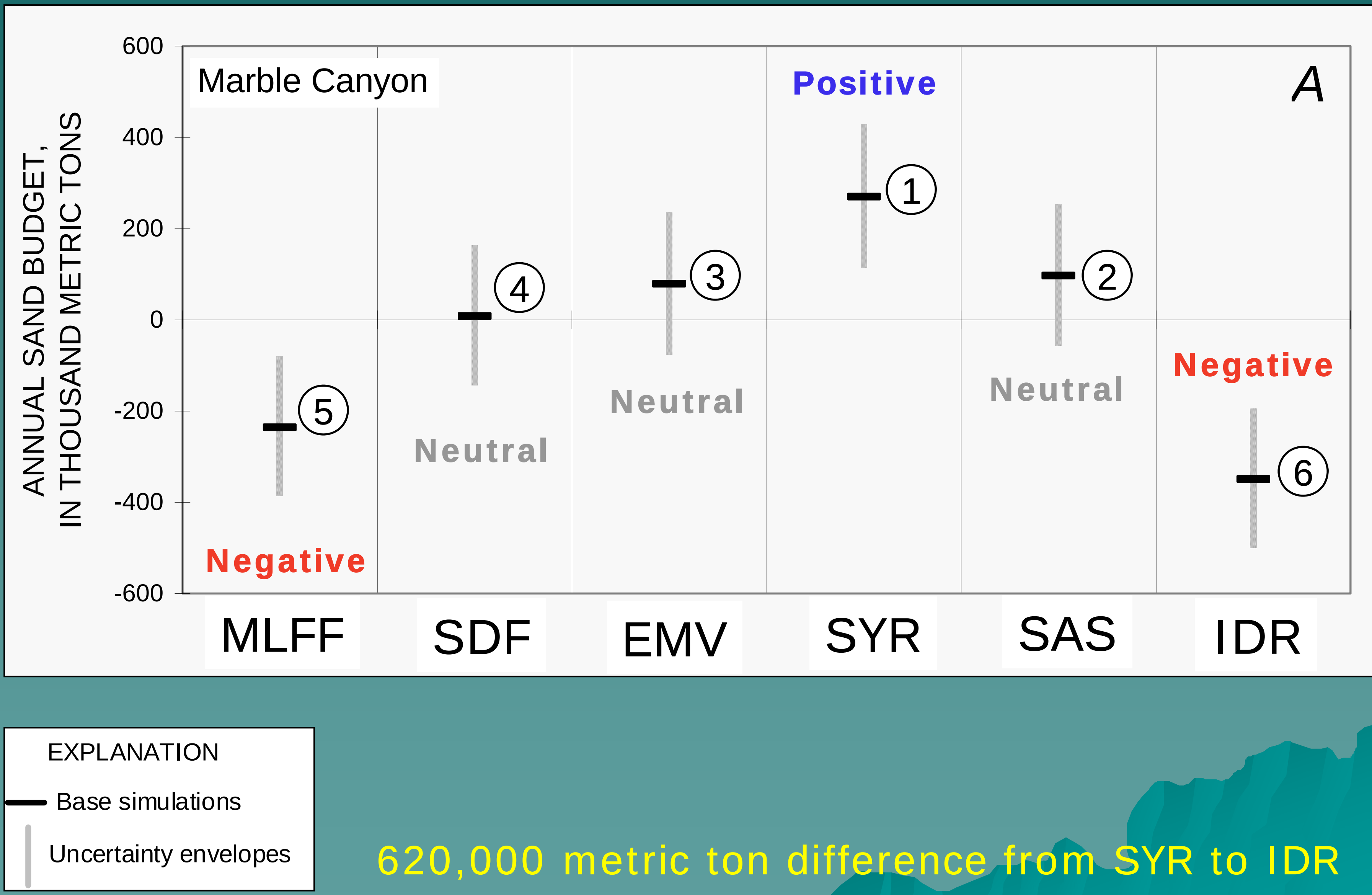
Example results plot

Attachment A



Attachment A

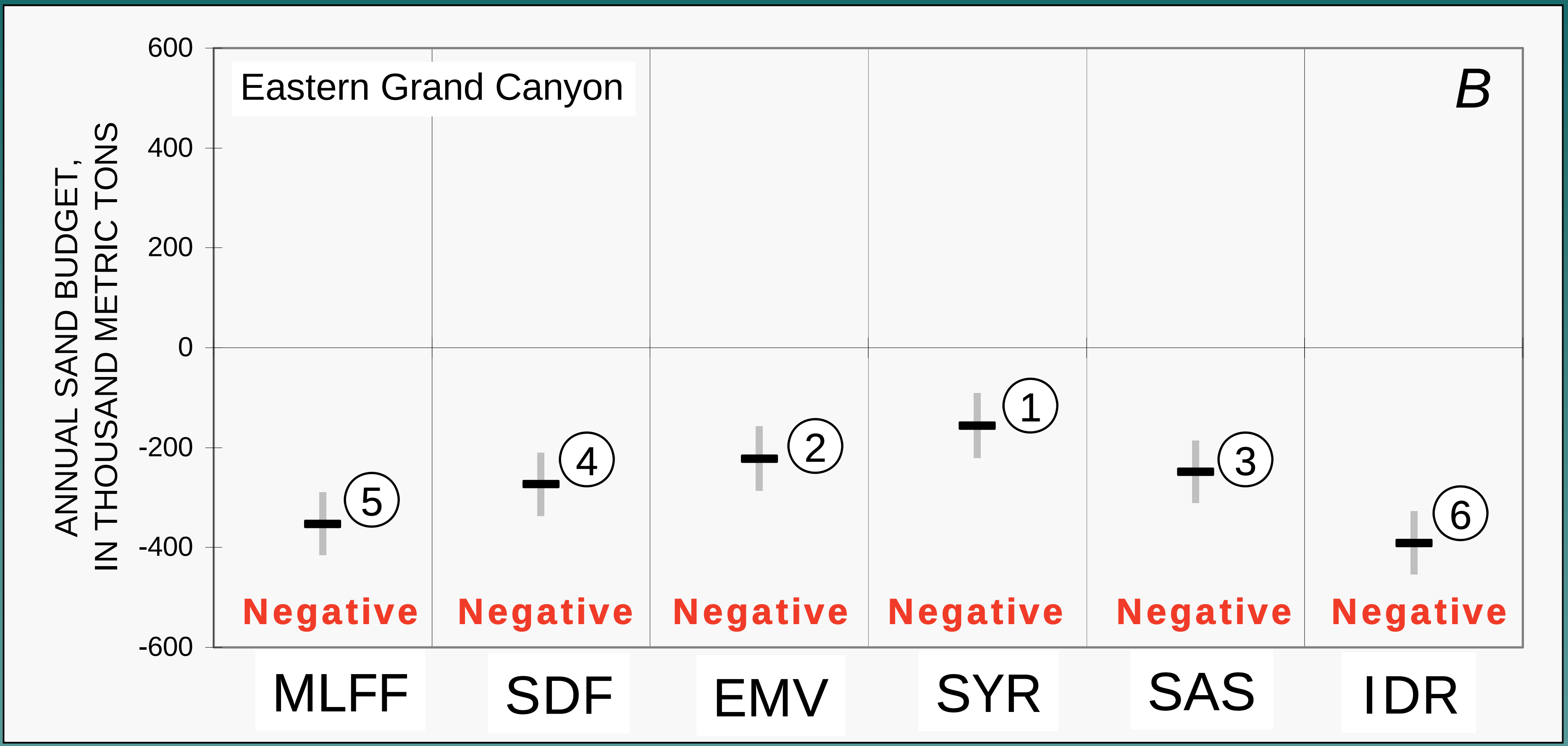
Marble Canyon, 11.0 MAF



620,000 metric ton difference from SYR to IDR

Attachment A

Eastern Grand Canyon, 11.0 MAF



EXPLANATION

Base simulations

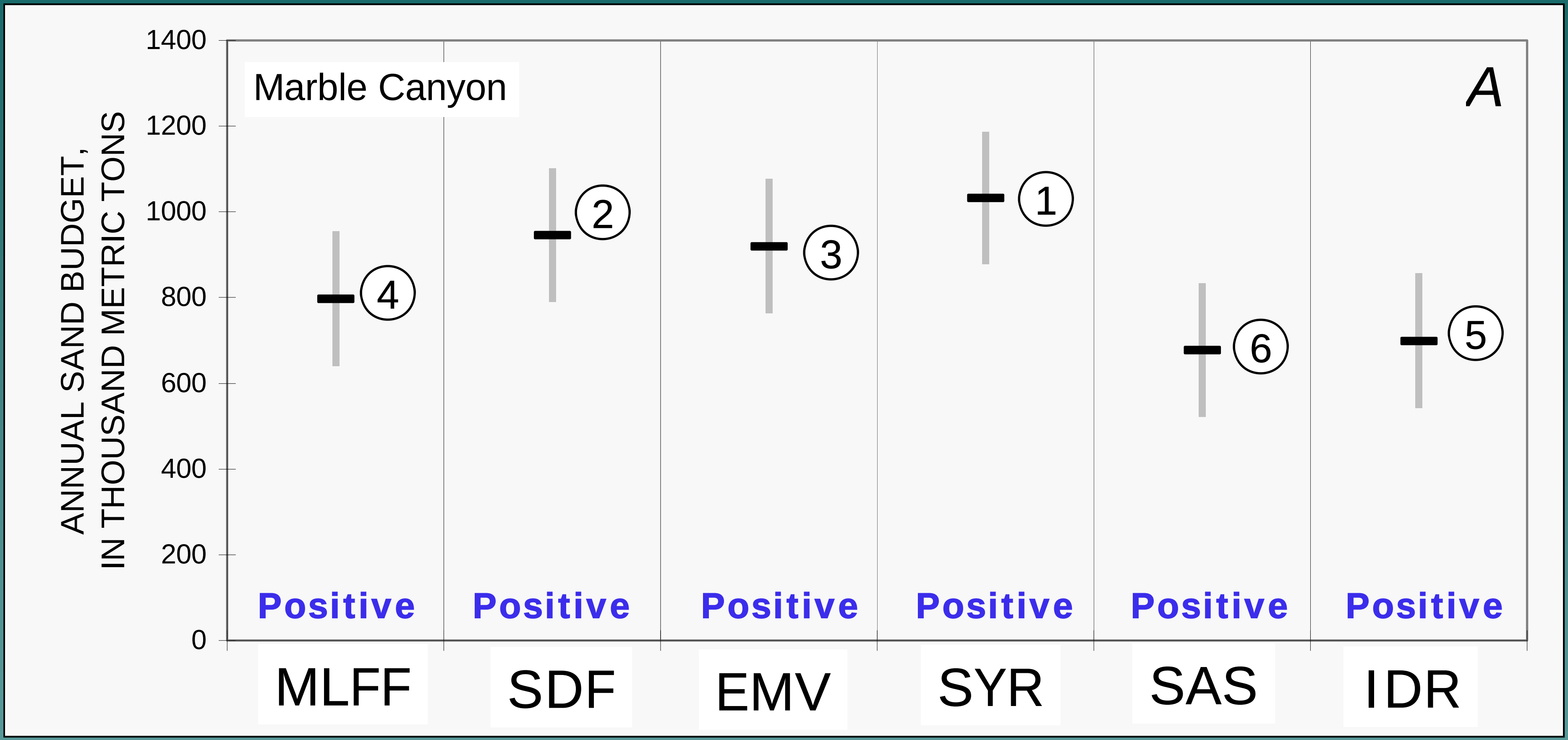
Uncertainty envelopes

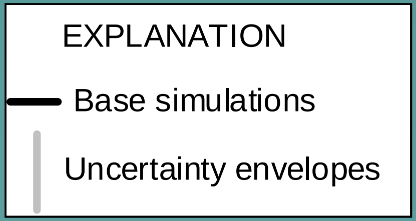
Why all negative? LCR inputs are less than Paria, timing of inputs late in simulations

230,000 metric ton difference from SYR to IDR

Attachment A

Marble Canyon, 8.23 MAF

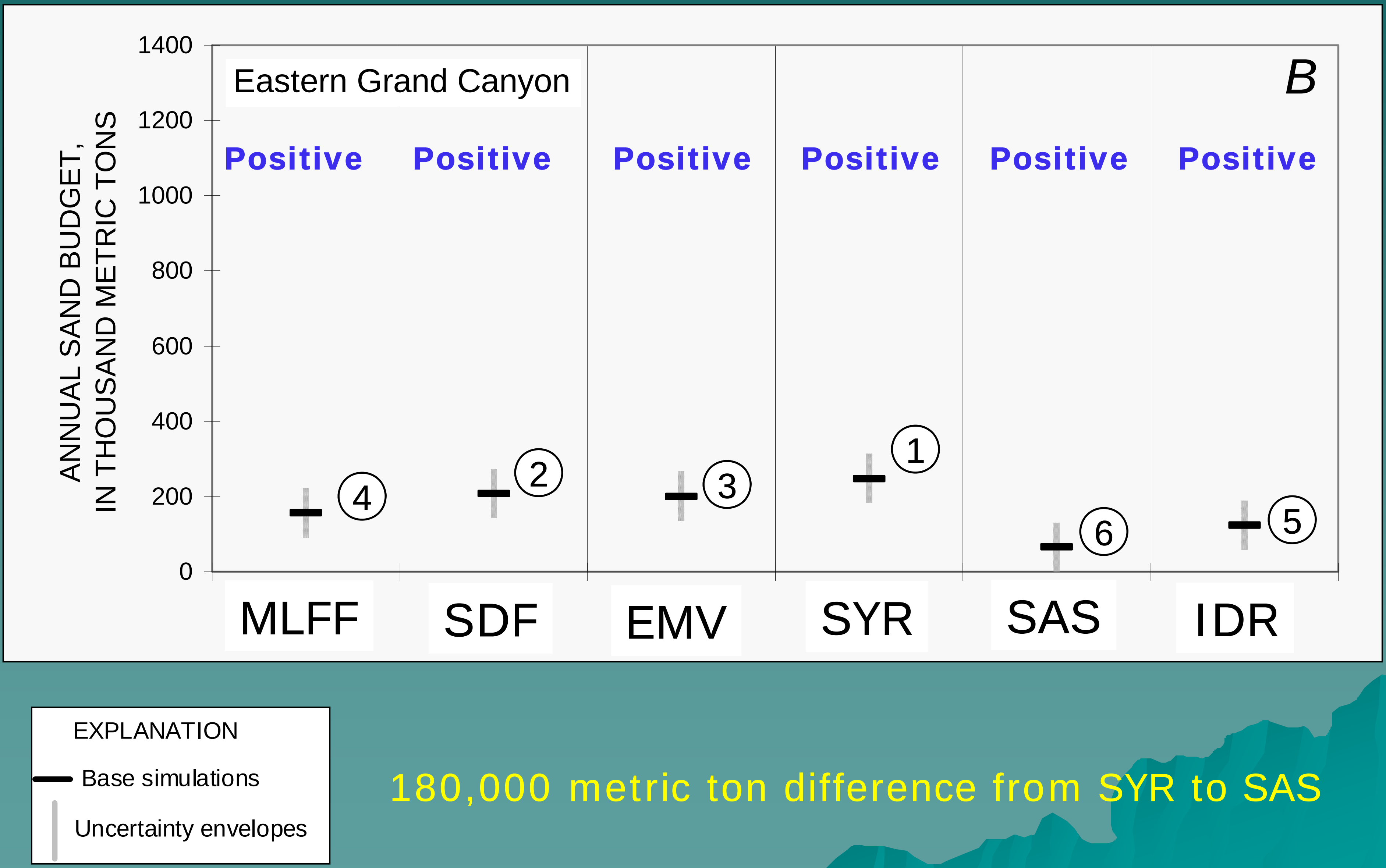




Why all positive? Below average annual volume combined with average tributary inputs

350,000 metric ton difference from SYR to SAS

Eastern Grand Canyon, 8.23 MAF



180,000 metric ton difference from SYR to SAS

Attachment A

Summary

Since we don't really know what the 2011 annual volume and tributary inputs will be, the results should be viewed in a relative sense (i.e. against each other)

SYR consistently ranks 1st in terms of sand retention and provides an upper bound for comparison

SDF and EMV yield similar results indicating more sand retention than MLFF. EMV is slightly better for 11.0 MAF while SDF is slightly better for 8.23 MAF.

SAS ranks high for 11.0 MAF (2nd or 3rd depending on reach), but ranks 6th for 8.23 MAF. This is because the maximum flow (18,000 cfs) is imposed and the same for both volumes.

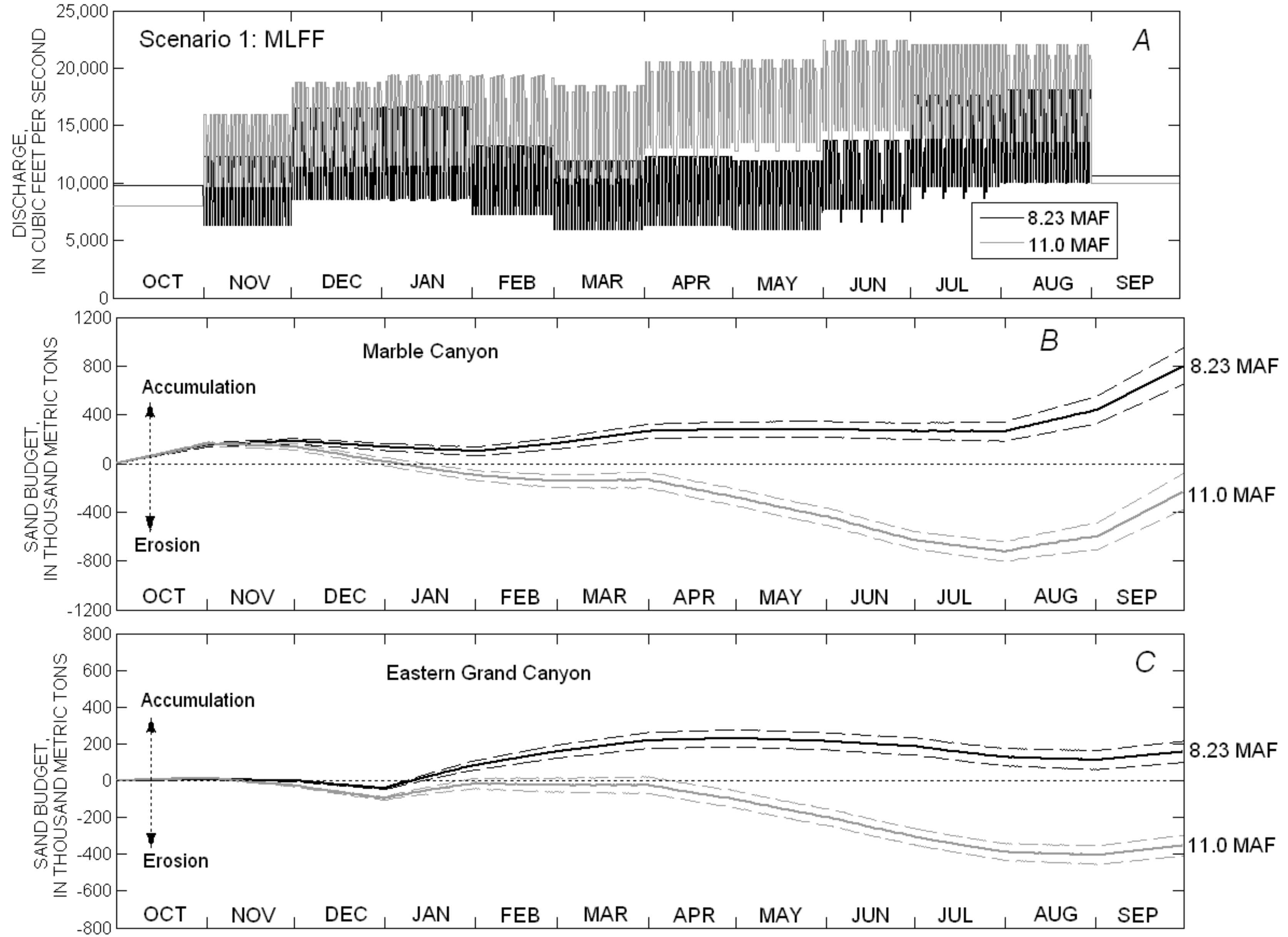
IDR consistently ranks just below MLFF for sand retention

Questions?

USGS

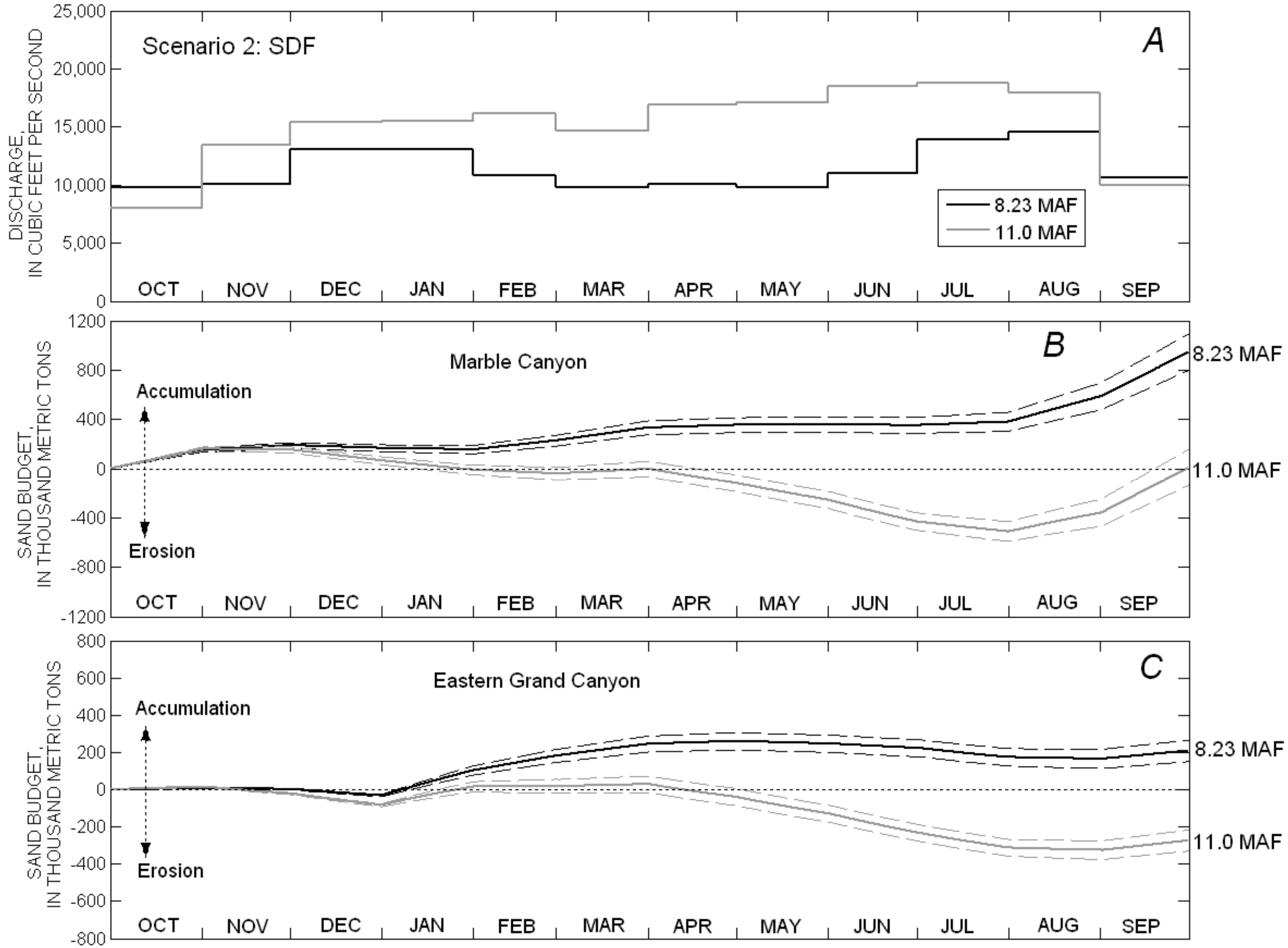
MLFF

Attachment A



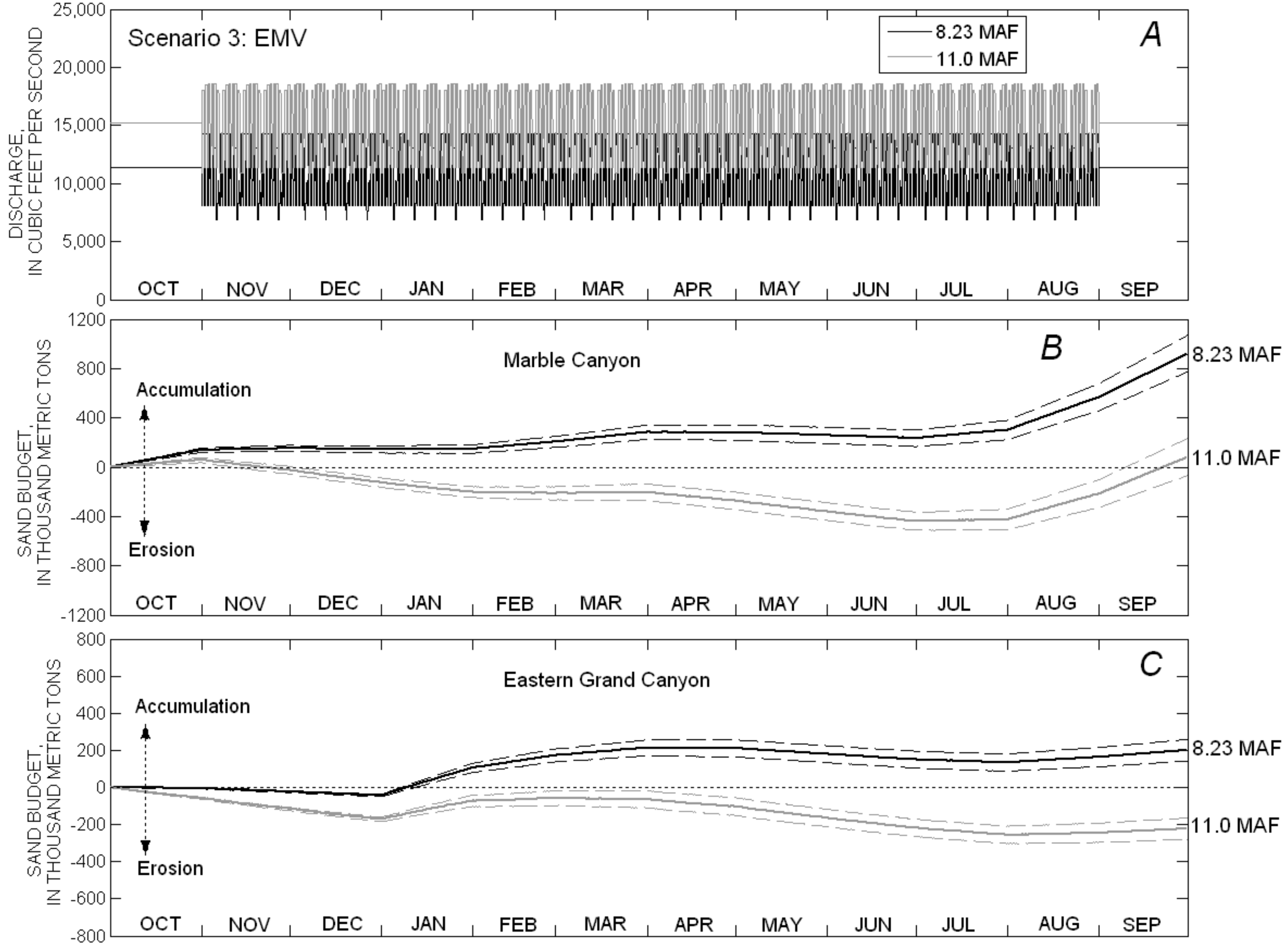
Attachment A

SDF



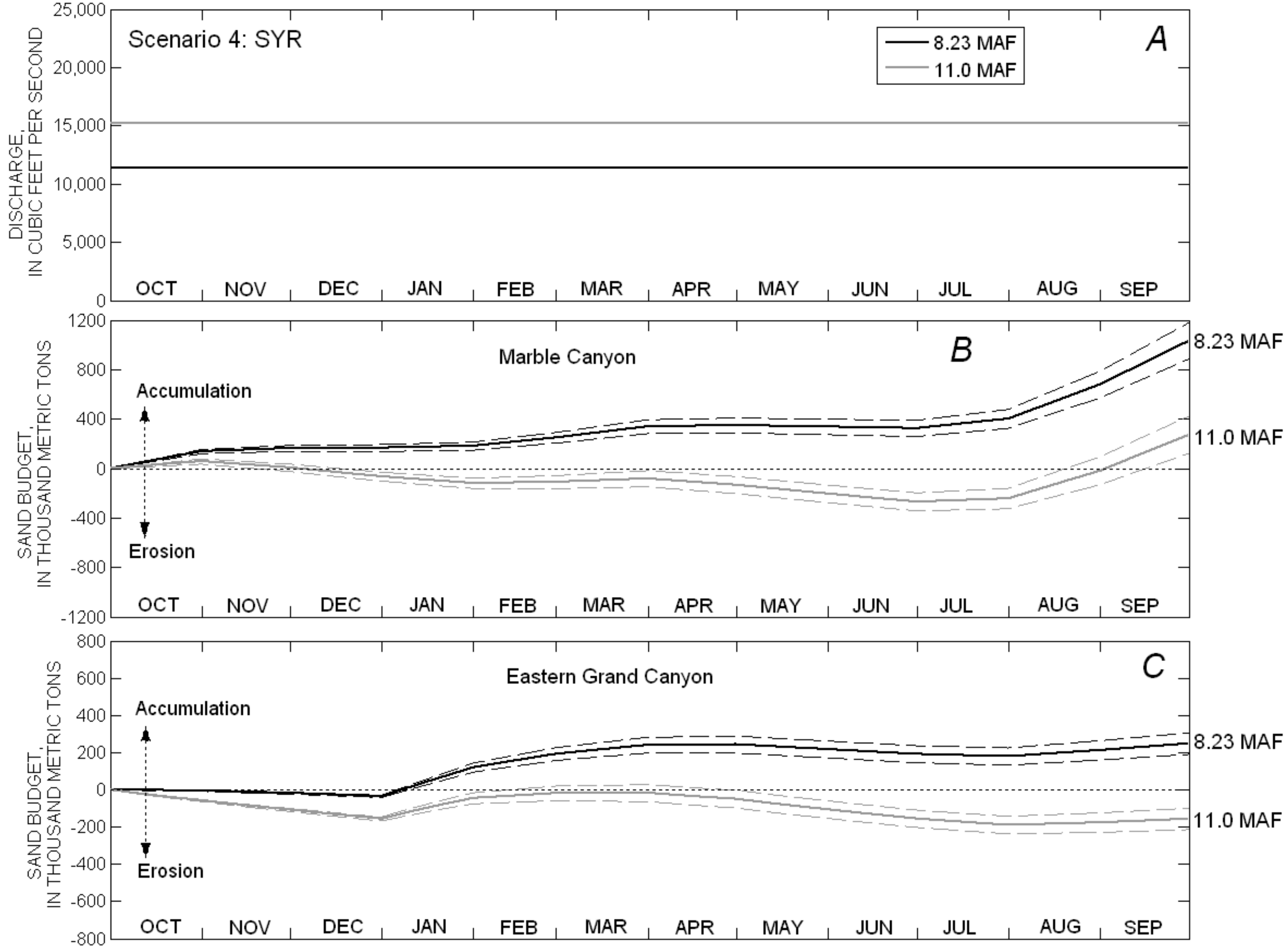
Attachment A

EMV



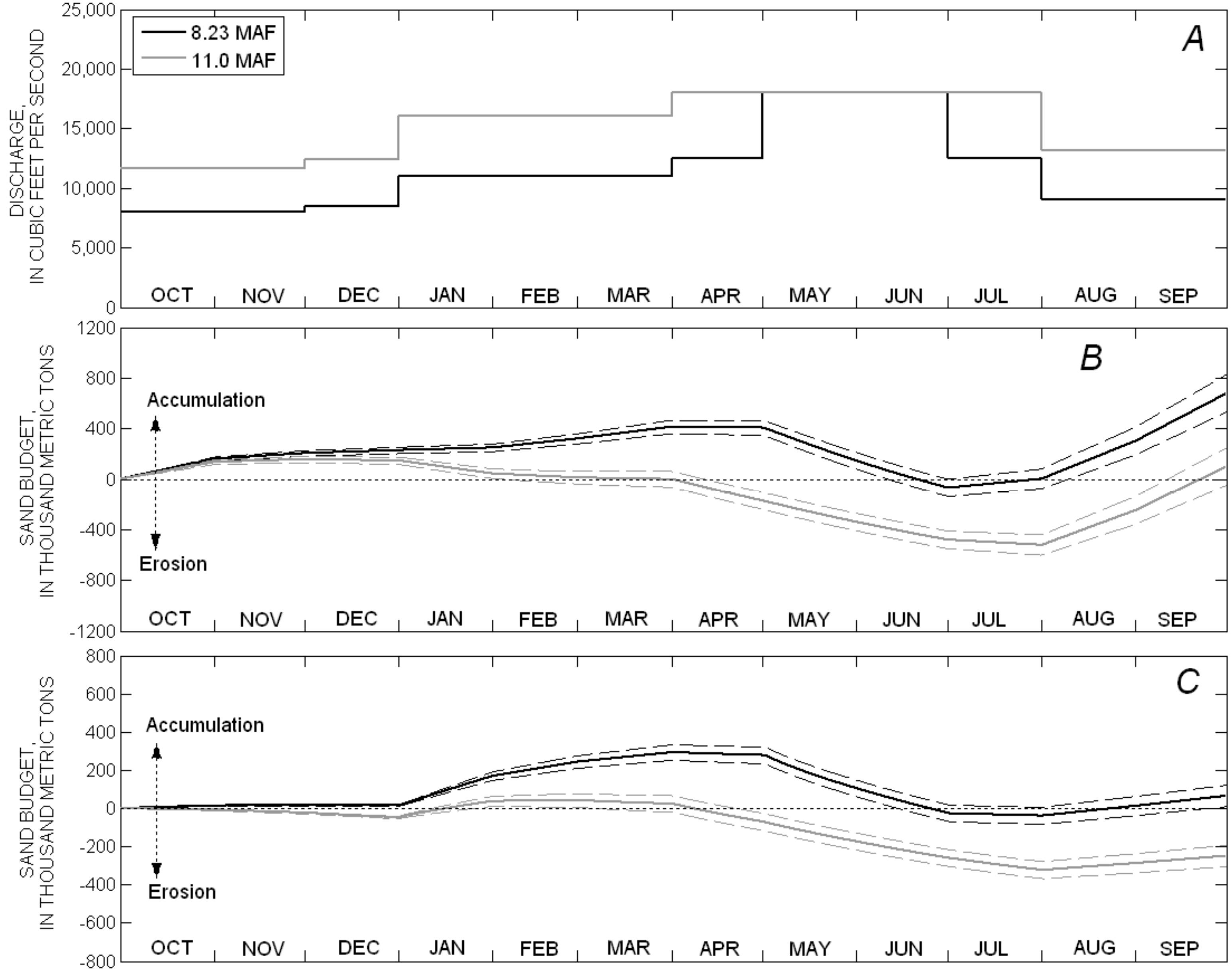
Attachment A

SYR



Attachment A

SAS



United States Department of the Interior
U.S. GEOLOGICAL SURVEY
GRAND CANYON MONITORING AND RESEARCH CENTER
2255 NORTH GEMINI DRIVE, MS-5000
FLAGSTAFF, ARIZONA 86001
520 556-7094 Telephone
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MEMORANDUM

To: Shane Capron, Chair, Technical Work Group, Glen Canyon Dam Adaptive Management Program

From: John Hamill, Chief, Grand Canyon Monitoring and Research Center, U.S. Geological Survey, Flagstaff, AZ John Hamill

Date: May 17, 2010

Subject: Technical Work Group and stakeholder requests for GCMRC to evaluate the effects of various dam operation scenarios on sediment storage and loss in the Grand Canyon

Beginning February, 2009 and more recently at the March, 2010 Technical Work Group (TWG) meeting, members requested that the Grand Canyon Monitoring and Research Center (GCMRC) use a recently developed sediment transport model to assess the effects of various dam operations on sediment storage and loss in the Grand Canyon (see attachment). The information was requested to assist in developing a 2011 hydrograph for Glen Canyon Dam to recommend to the Adaptive Management Work Group (AMWG).

GCMRC will evaluate several dam operation and hydrologic scenarios and provide a preliminary report describing the results to the Technical Work Group by June 14, 2010. The completion and dissemination of this report is contingent on final acceptance of the model for publication in the scientific literature. We expect to receive notification on the status of the publication on or before May 21. Because of the limited time, we will target the model runs to be specifically applicable to anticipated 2011 hydrology. Thus, we intend to model one sediment input scenario, two hydrologic scenarios, and six operation scenarios for a total of 12 modeling runs. The specific conditions are as follows:

Sediment input: Paria and Little Colorado River average annual sand supply
Hydrology: 8.23 maf and 10.8 maf (2011 most probable as of April 8, 2010)
Operations:

A. Modified Low Fluctuating Flows (MLFF) –normal monthly and daily fluctuations
B. MLFF -- normal monthly volumes with steady daily flows,
C. Equalized monthly volumes with normal (MLFF) daily flow fluctuations,
D. Equalized monthly volumes with steady daily flows,
E. Seasonally adjusted steady flows (SASF) as outlined in the 1995 Environmental Impact Statement, and

F. MLFF with increased (4,000 cfs) down ramp rates (Science Planning Group option A').

For model input, we will rely on available hydrographs using either actual hourly hydrographs from selected past years or artificial hourly hydrographs generated in the 2006 Science Planning Group process.

The GCMRC's sediment staff has longstanding commitments to attend a major conference the same week of the TWG meeting. Special arrangements will be needed if a presentation on the results of the above analysis is desired.

Please contact me if you have any questions

Attachment

cc TWG
AMWG
Secretary's Designee

Attachment B

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

Open-File Report 2010–1133

U.S. Department of the Interior
U.S. Geological Survey

Attachment B

U.S. Department of the Interior
KEN SALAZAR, Secretary

U.S. Geological Survey
Marcia K. McNutt, Director

U.S. Geological Survey, Reston, Virginia 2010

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Contents

Figures

Attachment B

Tables

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)

Attachment B

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

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.

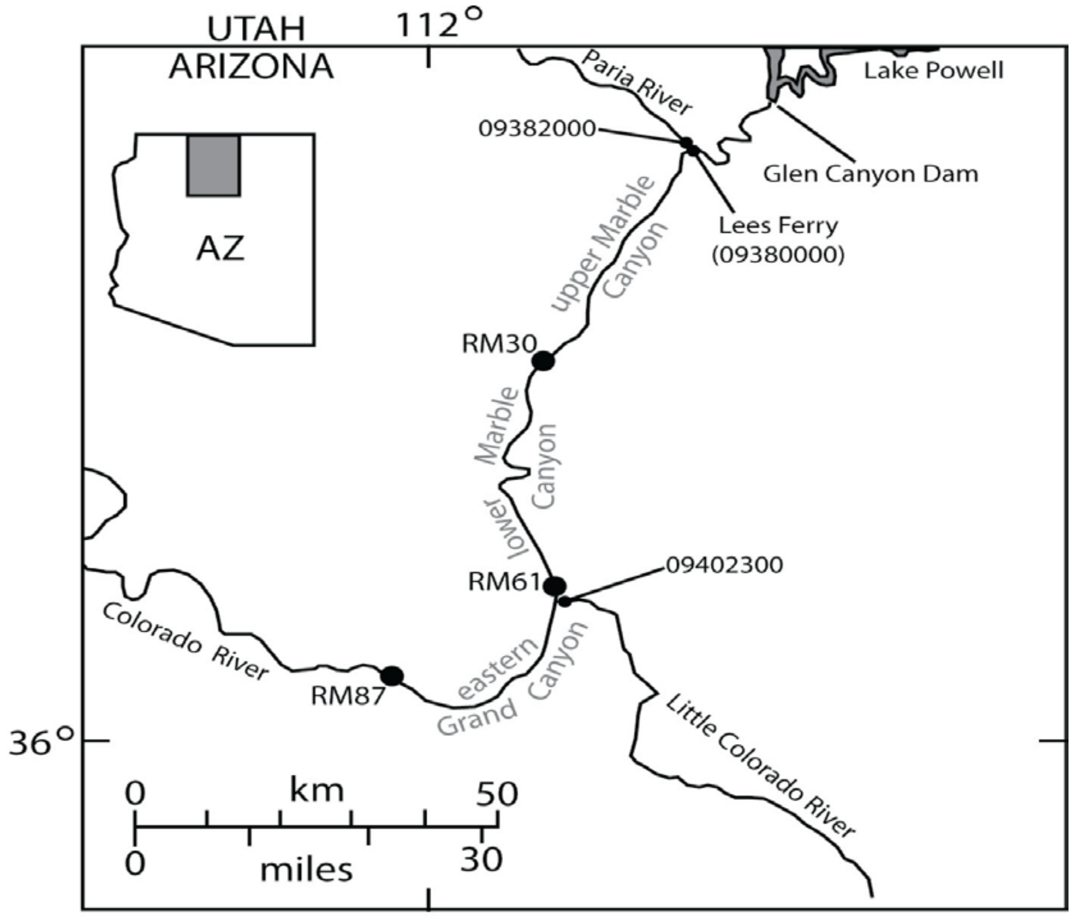

Figure 1. Colorado River below Glen Canyon Dam (GCD). Lees Ferry is designated river-mile (RM) 0 and is about 15.5 miles downstream from the dam. RM 30, RM 61, and RM 87 denote model nodes and are labeled according to river miles downstream from Lees Ferry. 8-digit numbers denote U.S. Geological Survey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

Attachment B

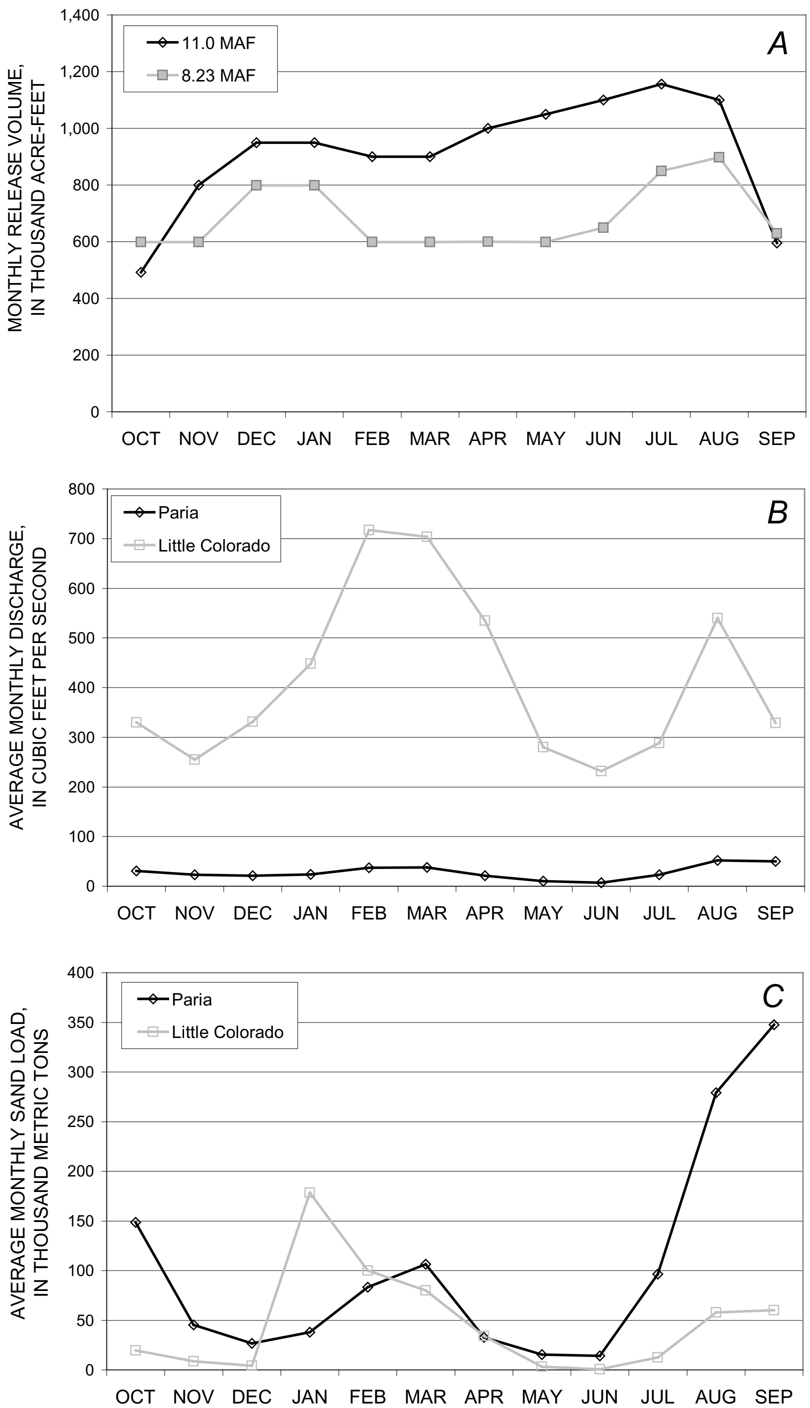

Figure 2. Monthly release volumes for the two modeled annual release volumes for Modified Low Fluctuating Flows (MLFF) operations and major tributary average monthly flow and sand inputs. *A*, Monthly Glen Canyon Dam release volumes, B, Average monthly Paria and Little Colorado River discharges. *C*,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

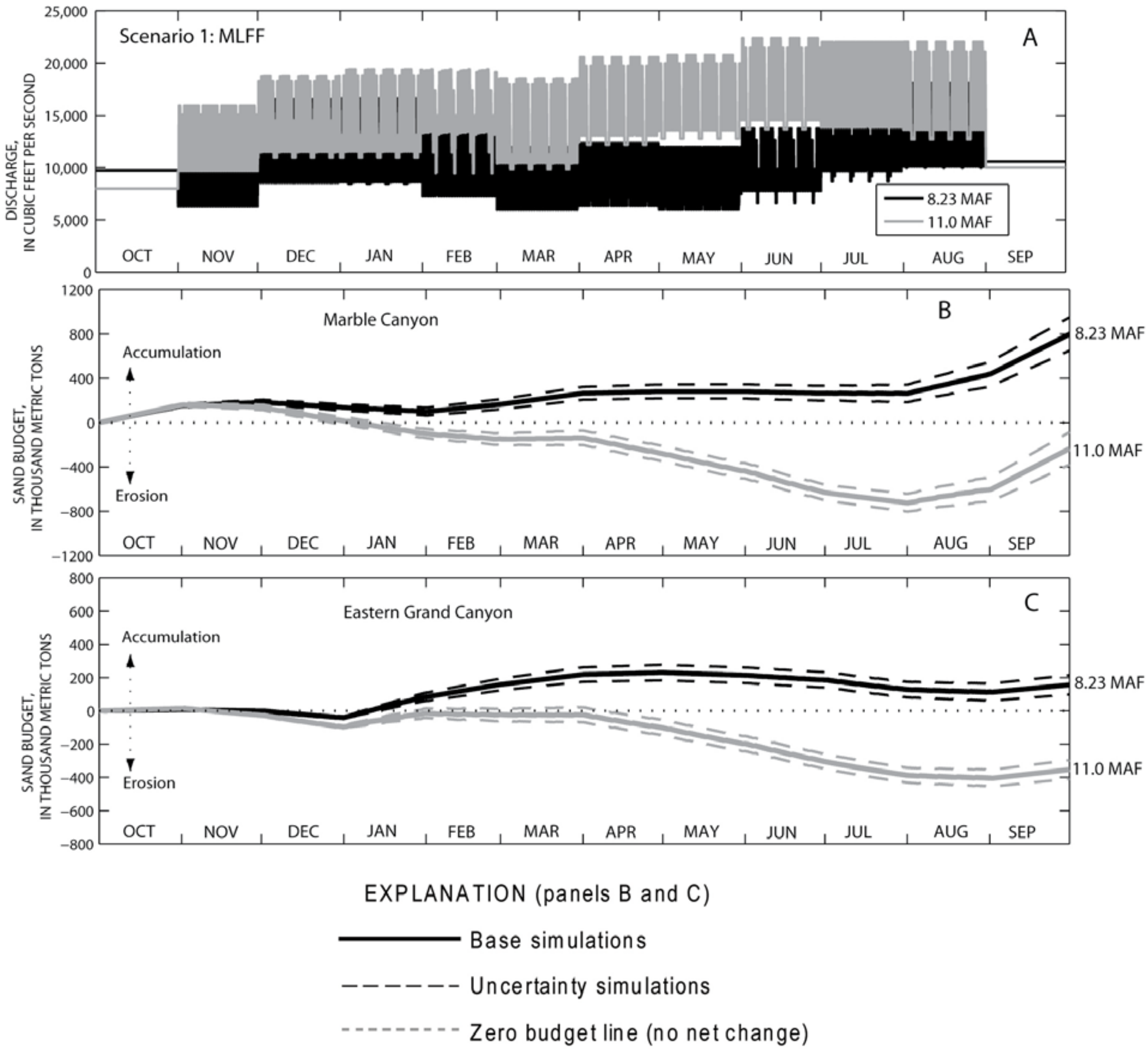

Figure 3. Glen Canyon Dam (GCD) flow releases and model results for Modified Low Fluctuating Flow (MLFF) operations at 8.23 and 11.0 MAF annual release volumes. *A*, GCD hourly hydrograph. *B*, Modeled sand budget for Marble Canyon. *C*, Modeled sand budget for eastern Grand Canyon. MAF, million acre-feet.

Attachment B

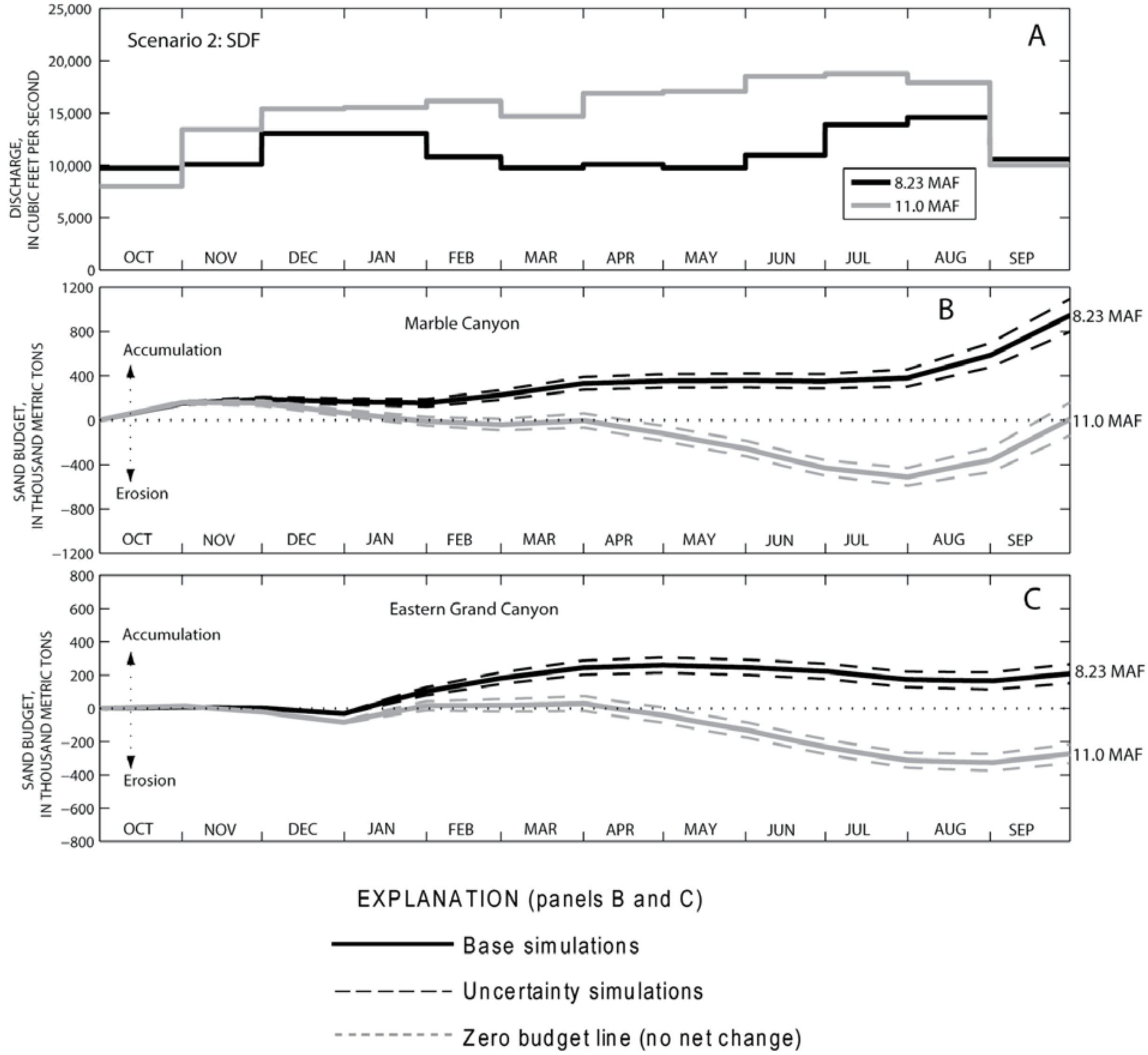

Figure 4. Glen Canyon Dam (GCD) flow releases and model results for Steady Daily Flow (SDF) operations at 8.23 and 11.0 MAF annual release volumes. *A*, GCD hourly hydrograph. *B*, Modeled sand budget for Marble Canyon. *C*, Modeled sand budget for eastern Grand Canyon. MAF, million acre-feet

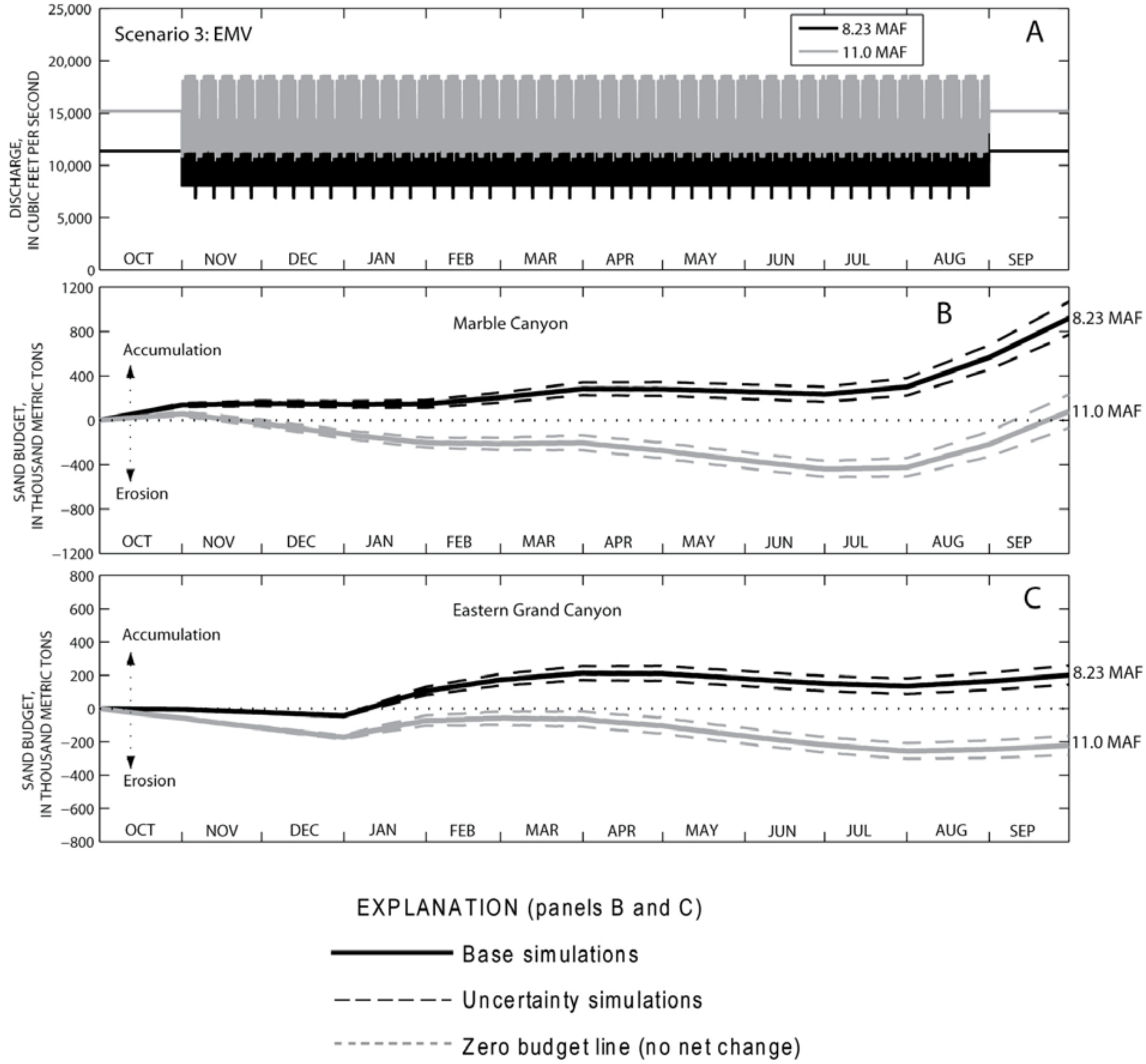

Figure 5. Glen Canyon Dam (GCD) low releases and model results for Equal Monthly Volume (EMV) operations at 8.23 and 11.0 MAF annual release volumes. *A*, GCD hourly hydrograph. *B*, Modeled sand budget for Marble Canyon. *C*, Modeled sand budget for eastern Grand Canyon. MAF, million acre-feet

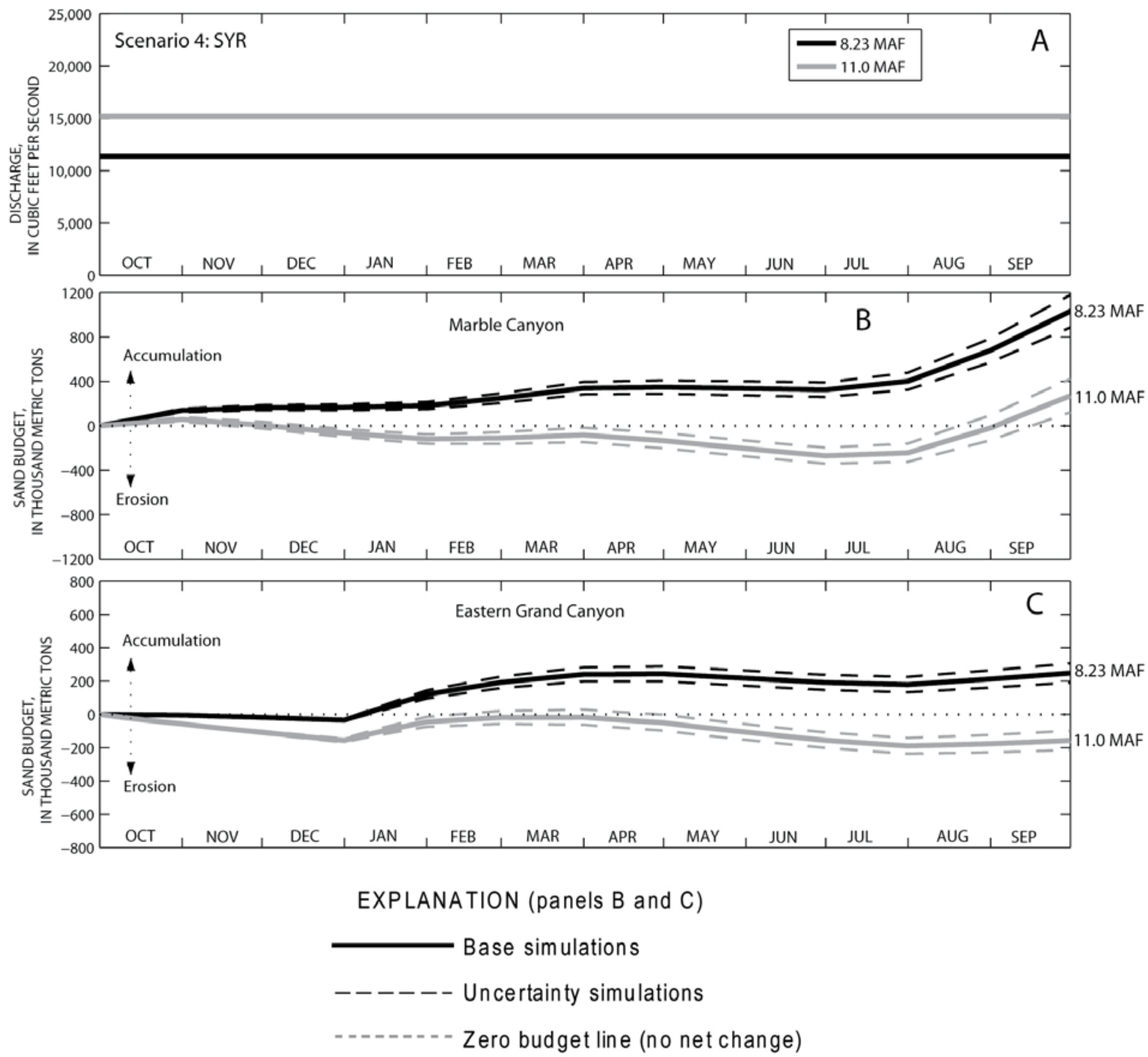

Figure 6. Glen Canyon Dam (GCD) flow releases and model results for Steady Year Round (SYR) operations at 8.23 and 11.0 MAF annual release volumes. *A*, GCD hourly hydrograph. *B*, Modeled sand budget for Marble Canyon. *C*, Modeled sand budget for eastern Grand Canyon. MAF, million acre-feet

Attachment B

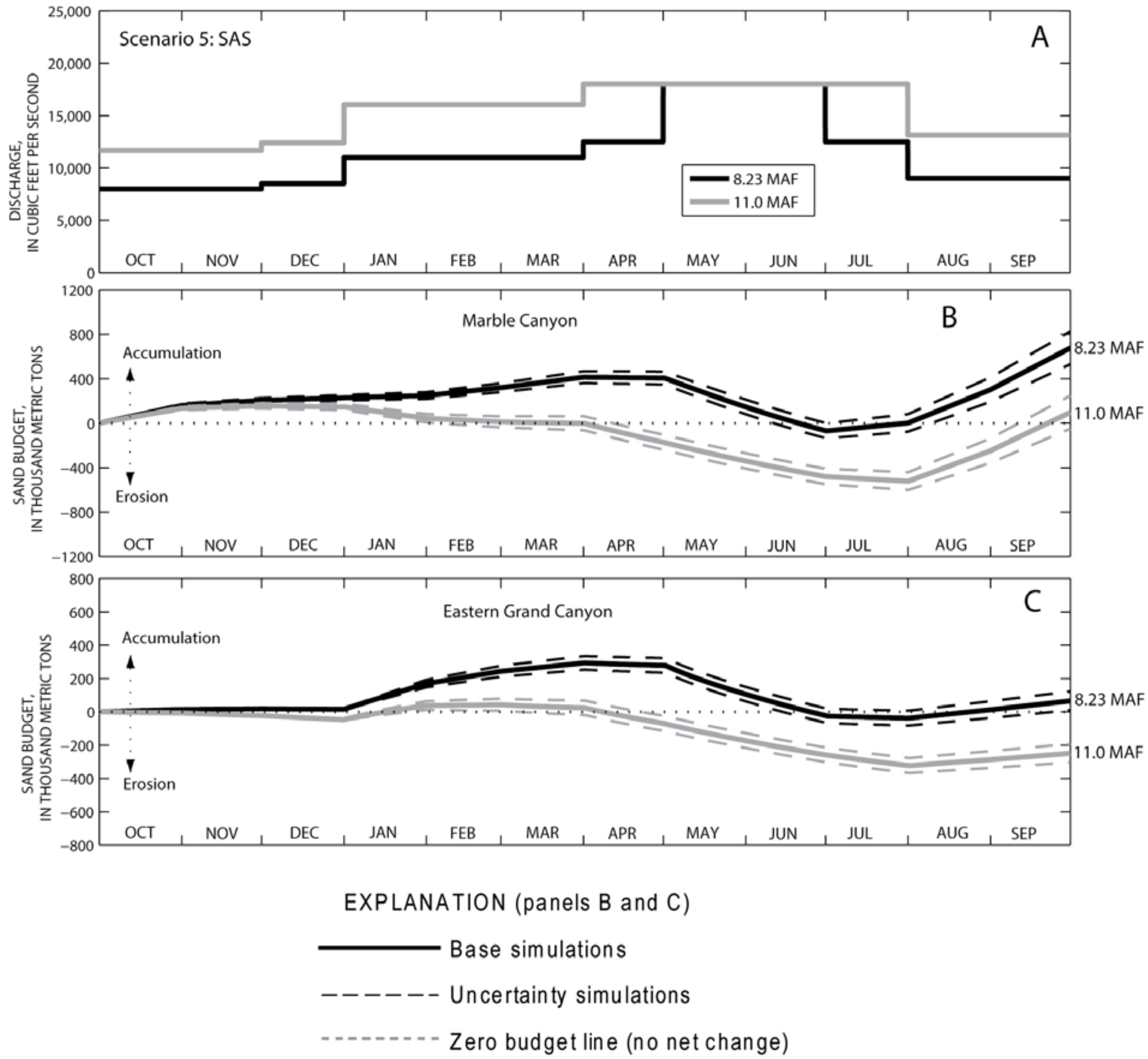

Figure 7. Glen Canyon Dam (GCD) flow releases and model results for Seasonally Adjusted Steady (SAS) operations at 8.23 and 11.0 MAF annual release volumes. *A*, GCD hourly hydrograph. *B*, Modeled sand budget for Marble Canyon. *C*, Modeled sand budget for eastern Grand Canyon. MAF, million acre-feet

Attachment B

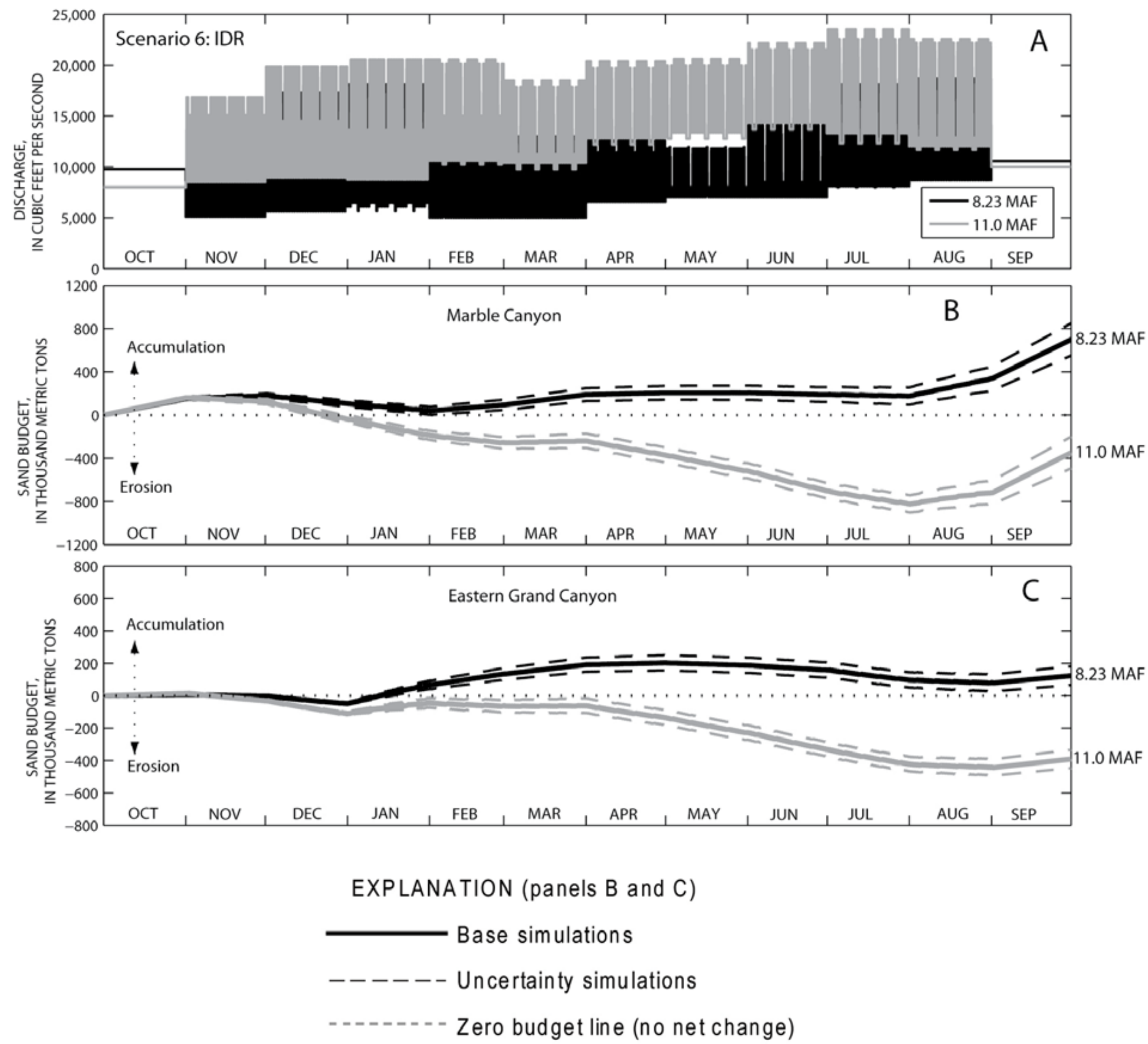

Figure 8. Glen Canyon Dam (GCD) flow releases and model results for Increased Daily Range and Down Ramp (IDR) operations at 8.23 and 11.0 MAF annual release volumes. *A*, GCD hourly hydrograph. *B*, Modeled sand budget for Marble Canyon. *C*, Modeled sand budget for eastern Grand Canyon. MAF, million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

Attachment B

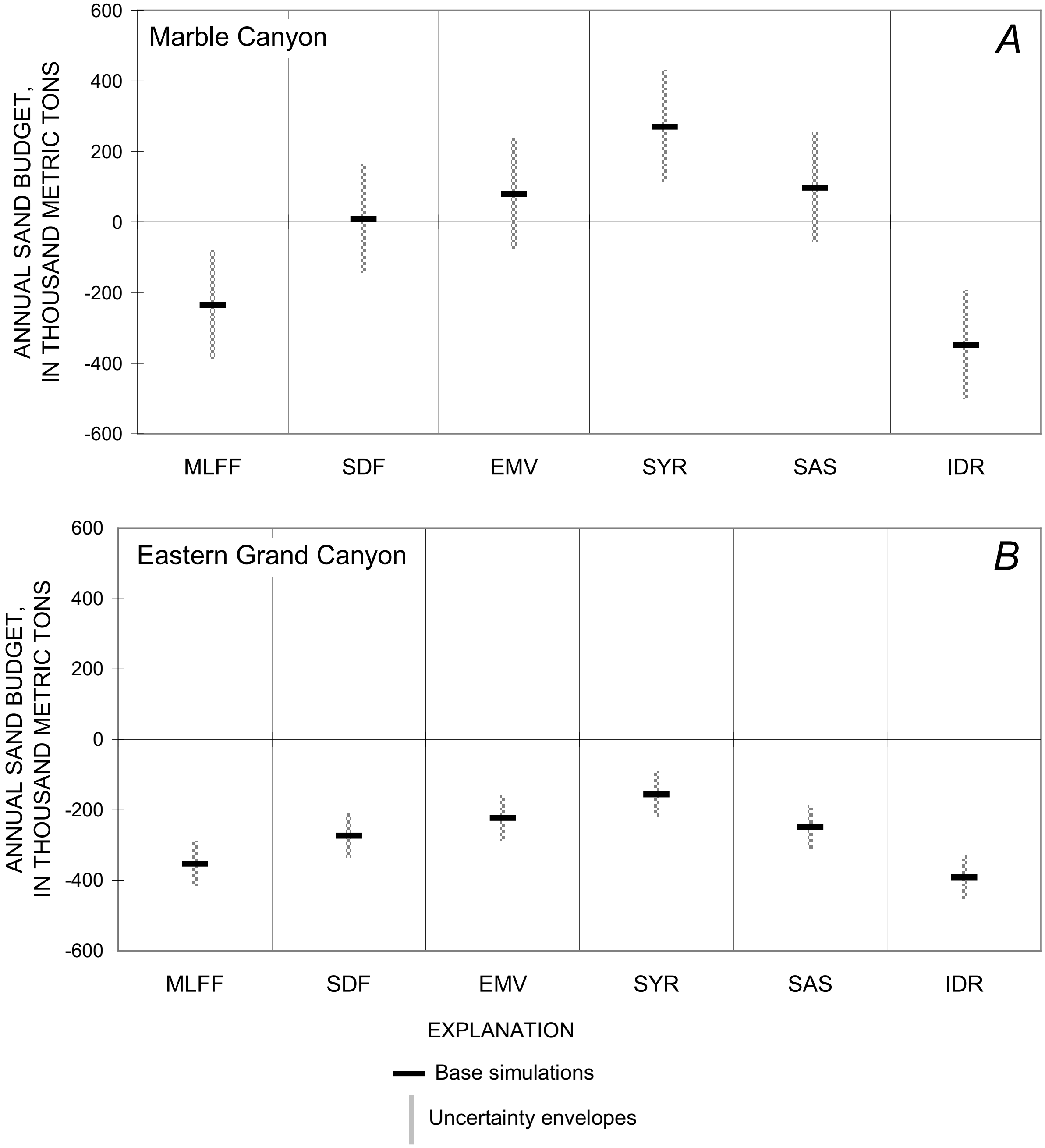

Figure 9. Modeled annual sand budgets for the 11.0 million acre-foot annual hydrologic scenario. *A*, Sand budget for Marble Canyon. *B*, Sand budget for eastern Grand Canyon. Vertical lines denote range based on uncertainty simulations.

Attachment B

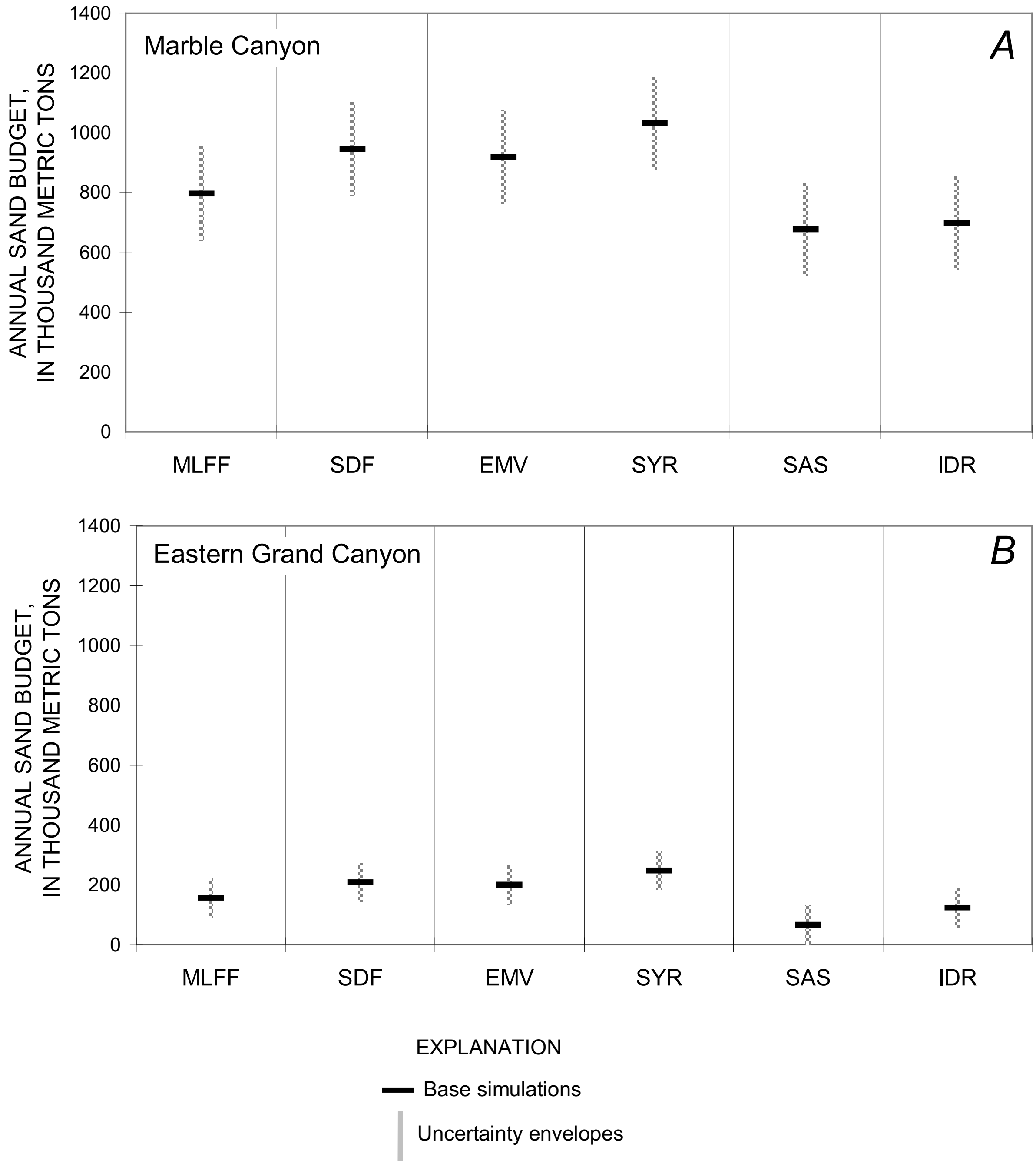

Figure 10. Modeled annual sand budgets for the 8.23 million acre-foot annual hydrologic scenario. *A*, Sand budget for Marble Canyon. *B*, Sand budget for eastern Grand Canyon. Vertical lines denote range based on uncertainty simulations.

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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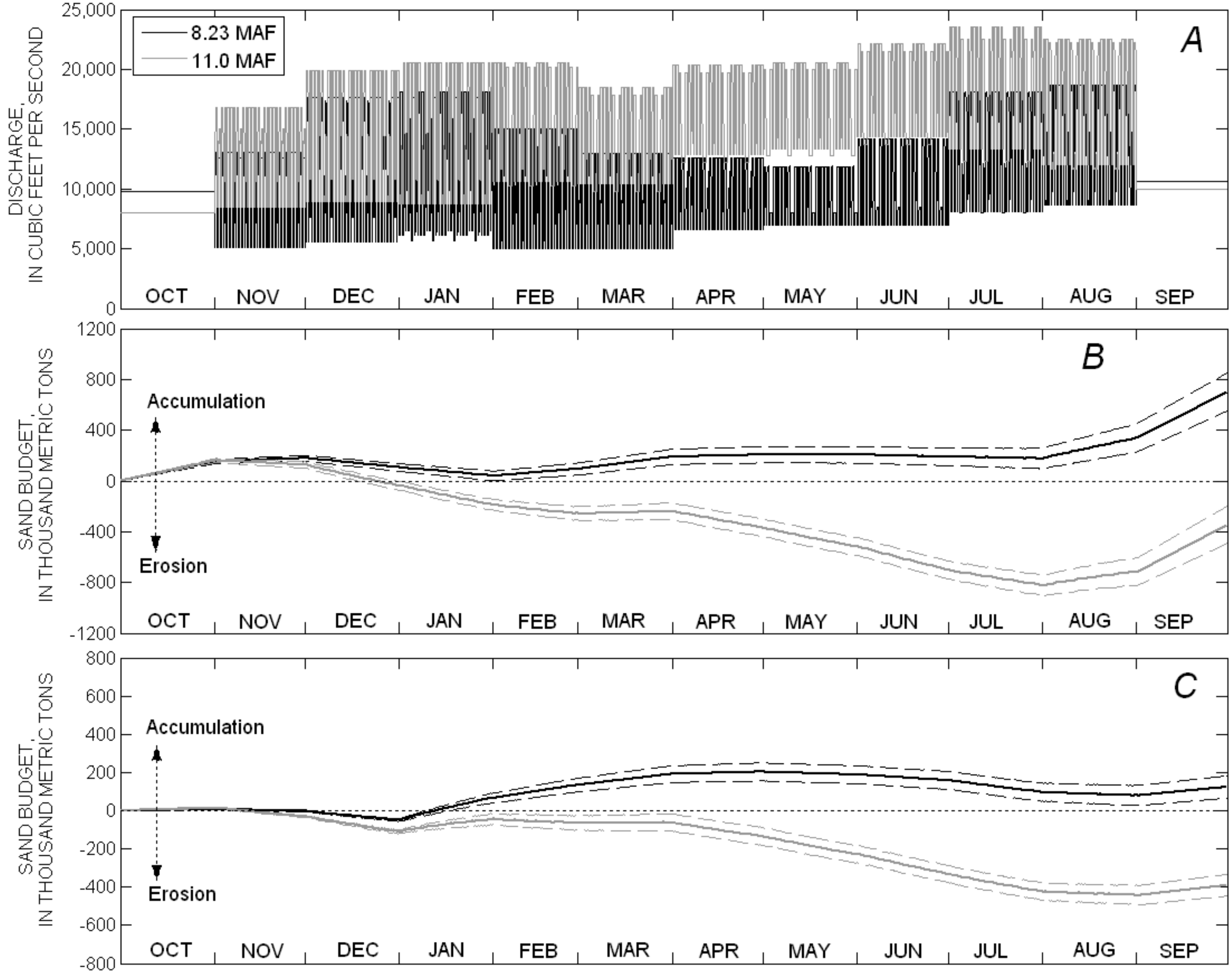
Attachment A

IDR



An approach for modeling sediment budgets in supply-limited rivers

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ABSTRACT

Reliable predictions of sediment transport and river morphology in response to variations in natural and human-induced drivers are necessary for river engineering and management. Because engineering and management applications may span a wide range of space and time scales, a broad spectrum of modeling approaches has been developed, ranging from suspended-sediment “rating curves” to complex three-dimensional morphodynamic models. Suspended-sediment rating curves are an attractive approach for evaluating changes in multi-year sediment budgets resulting from changes in flow regimes because they are simple to implement, computationally efficient, and the empirical parameters can be estimated from quantities that are commonly measured in the field (i.e. suspended-sediment concentration and water discharge). However, the standard rating-curve approach assumes a unique suspended-sediment concentration for a given water discharge. This assumption is not valid in rivers where sediment supply varies enough to cause changes in particle size or changes in areal coverage of sediment on the bed; both of these changes cause variations in suspended-sediment concentration for a given water discharge. More complex numerical models of hydraulics and morphodynamics have been developed to address such physical changes of the bed. This additional complexity comes at a cost in terms of computations as well as the type and amount

of data required for model set-up, calibration, and testing. Moreover, application of the resulting sediment-transport models may require observations of bed-sediment boundary conditions that require extensive (and expensive) observations or, alternatively, require the use of an additional model (subject to its own errors) merely to predict the bed-sediment boundary conditions for use by the transport model. In this paper, we present a hybrid approach that combines aspects of the rating-curve method and the more complex morphodynamic models. Our primary objective was to develop an approach complex enough to capture the processes related to sediment-supply limitation, but simple enough to allow for rapid calculations of multi-year sediment budgets. The approach relies on empirical relations between suspended-sediment concentration and discharge, but on a particle-size specific basis, and also tracks and incorporates the particle-size distribution of the bed sediment. We have applied this approach to the Colorado River below Glen Canyon Dam, a reach that is particularly suited to such an approach because it is substantially sediment supply-limited such that transport rates are strongly dependent on both water discharge and sediment supply. The results confirm the ability of the approach to simulate the effects of supply limitation, including periods of accumulation and bed fining as well as erosion and bed coarsening, using a very simple formulation. Though more empirical in nature than standard one-dimensional morphodynamic models, this alternative approach is attractive because its simplicity allows for rapid evaluation of multi-year sediment budgets under a range of flow regimes and sediment-supply conditions, and also because it requires substantially less data for model set-up and use.

INTRODUCTION

It is often important to engineers, geomorphologists, and resource managers to simulate changes in fluvial sediment budgets resulting from changes in driving forces, such as climate, dam operations, land-use changes, etc. Humans have had a dramatic impact on the world’s river systems in terms of water storage and flow regulation (Nilsson et al., 2005) as well as sediment transport and budgets (Syvitski et al., 2005). Because sediment provides the physical framework for aquatic ecosystems, management of aquatic resources requires the ability to simulate changes in sediment budgets resulting from natural and anthropogenic influences.

In response to this need, substantial research and development has been conducted in the area of fluvial sediment-transport modeling. The wide range of space and time scales of interest has led to a range of modeling approaches, from simple empirical concentration-discharge relations (i.e. sediment rating curves, see e.g., ASCE, 1975) to complex multi-dimensional morphodynamic models. Suspended-sediment rating curves assume a unique relation between suspended-sediment concentration (or flux) and water discharge and have thus often been used to evaluate changes in flow regimes. Multi-dimensional morphodynamic models solve some form of the Navier-Stokes equations for the fluid and mass conservation for the sediment, sometimes for a range of particle sizes. Because of their simplicity, rating curves can be applied over large space and time scales, whereas multi-dimensional models are typically limited in the scale of application by computation times and data requirements. Between these two bookends lies an array of one-dimensional, pseudo-one-dimensional, and two-dimensional morphodynamic models, including several "general-use" codes such as HEC-RAS (Corps of Engineers), SRH-1D and 2D (Bureau of Reclamation), MIKE-11 and 21 (Danish Hydraulics Institute), and SOBEK (Delft Hydraulics), as well as codes developed for specific research applications (e.g. Rahuel et al., 1989, van Niekerk et al., 1992, Hoey and Ferguson, 1994, Wright and Parker, 2005, among many others). Even within this family of models there is a wide range of complexity, such as equilibrium versus non-equilibrium transport, uniform sediment versus multiple particle sizes, steady versus unsteady flow, etc. The general use codes typically attempt to include all of these various options in order to be applicable to a range of study areas and conditions. Recently, Ronco et al. (2009) presented criterion for simplification of the standard one-dimensional models, based on the assumption of uniform flow, in order to facilitate long-term simulations for rivers where minimal topographic information is available.

Sediment rating curves are an attractive approach for evaluating long-term sediment budgets resulting from changes in flow regimes because they are very simple, easy to implement computationally, and the empirical parameters can be estimated from quantities that are frequently measured in the field (suspended-sediment concentration and water discharge). However, an implicit assumption in this approach is that sediment transport is always in equilibrium with sediment supply, i.e., that the particle-size distribution of sediment on the bed of the river is not changing (or that it is uniquely correlated with discharge). Rubin and Topping (2001, 2008) presented an approach for evaluating this assumption for sand-bedded rivers and suspended-sand transport, and showed that the bed particle size is often measurably important and sometimes as important as water discharge in regulating suspended-sand transport. Changes in bed particle-size distribution can be accounted for with multiple-size numerical formulations (e.g. Parker et al., 2000); however, this comes at the cost of significant additional complexity, not only in terms of the model formulation but also in terms of the boundary and initial conditions that must be specified. For example, multiple-size morphodynamic models require information on bed particle-size distributions (i.e. the surface “active” layer and the underlying substrate) and sediment flux by particle size for calibration and testing. The methods of Ronco et al. (2009) can potentially overcome the limitations of the rating curve approach by incorporating multiple size classes. However, the primary assumption in their approach, i.e. uniform flow, is not suitable to our study site because the releases from Glen Canyon Dam are highly unsteady, on a daily basis, due to hydroelectric power demand. Where a model requires additional knowledge of sediment boundary conditions, either additional data must be collected, or another model must be used to predict the sediment-boundary conditions; this extra modeling step can introduce error, even before the sediment-transport model is implemented.

Because of the limitations of the available methods, we have developed and tested an alternative approach that combines aspects of several modeling methods. The approach uses empirically based rating curves, but in contrast to the standard approach, they are formulated on a particle-size specific basis. This allows for calculations of the particle-size distribution on the bed within a given reach by applying mass conservation by grain size (i.e., the Exner equation), albeit in a substantially simplified manner. Thus, the rating curves can respond to changes in sediment supply with a formulation that is quite simple, computationally efficient, and easy to implement. The model is spatially discretized over long reaches (~ 50 km) as opposed to attempting to characterize the details of channel complexity. Herein, we present the details of this modeling approach and its application to the Colorado River below Glen Canyon Dam. We do not argue that the empirical parameters developed for the Colorado River have general applicability; rather, they are site-specific. However, the general modeling approach for accounting for changes in sediment supply in order to evaluate long-term changes in sediment budgets should have general applicability, particularly below dams where the flow regime and sediment supply are often dramatically altered (e.g. Schmidt and Wilcock, 2008).

We chose to develop this alternative approach as opposed to applying standard one-dimensional morphodynamic modeling for several reasons. First, our approach is much simpler and thus more computationally efficient than typical one-dimensional models. Increases in computer power have made this less of an issue, and we acknowledge that standard 1D models can be applied to long reaches over multi-year time periods, but computational efficiency is still an advantage when considering a large number of alternative modeling scenarios with highly variable boundary conditions. Second, and probably more important, standard 1D models require information that is not readily available for our study site, namely detailed cross-sections and information on the spatial distribution of sand thickness and bed particle-size distributions (longitudinally). Our study site is a pool-rapid system with very complex channel geometry; attempting to model erosion and deposition within this complicated channel geometry is a difficult task, and likely not necessary for modeling multi-year sediment budgets over long reaches. Finally, our modeling approach builds on a previously developed unsteady discharge-routing model (Wiele and Smith, 1996) that also uses reach-averaging to deal with this complexity. This previously developed model can provide the required flows at the computational nodes and thus circumvent the need to model anew the detailed hydraulics, including critical-flow transitions that occur in rapids along the Colorado River in our study site.

STUDY SITE

The modeling approach described in the next section was developed as part of our ongoing work on the Colorado River below Glen Canyon Dam (fig. 1). The construction of Glen Canyon Dam in the early 1960s substantially reduced 1) the supply of sand to Grand Canyon by trapping most of it in the upstream reservoir (Topping et al., 2000a), and 2) the capacity of the river to transport sand by reducing large flood peaks (Topping et al., 2003). In addition, although operation of the dam reduced the magnitude and frequency of floods during which most of the natural sand transport occurred in the Colorado River in Grand Canyon, dam operations have actually increased the duration of moderate discharges that can transport substantial amounts of sand (Topping et al., 2003). The post-dam flow regime is illustrated in fig. 2 which shows the study period to which the model was applied (top, Sep-2002 through Mar-2009), several weeks of daily fluctuating flows including a transition between months when the release volume typically changes (middle), and an example of a “controlled flood” where flows above powerplant capacity are released with the primary goal of rebuilding eroded sandbars (bottom, see e.g. Schmidt, 1999). For a complete review of pre- and post-dam flow regimes refer to Topping et al. (2003). Note that we use the English unit for water discharge, cubic feet per second or cfs, herein because of its common use and acceptance within the Colorado River scientific, management, and recreational community.

Several attempts have been made at generalizing the post-dam sand budget in Grand Canyon, i.e., whether there is long-term erosion or accumulation in the various reaches below the major tributaries. The answer to this question has important implications for the sustainability of sand deposits in Marble and Grand Canyons (fig. 1), typically referred to as “eddy-sandbars” because they tend to form in recirculating eddies downstream from tributary debris fans (Schmidt, 1990). Eddy-sandbars are considered a valued resource within the Glen Canyon Dam Adaptive Management Program (GCDAMP), a federal advisory committee established to advise the Secretary of the Interior on operations of Glen Canyon Dam (U.S. Department of the Interior, 1996), for a variety of reasons: they are a fundamental element of the pre-dam riverscape; they provide areas for recreational use by river runners and hikers; they provide low-velocity, warm water habitat for potential use by juvenile native fish; they are the substrate for riparian vegetation; and they are a source of sand for upslope wind-driven transport that may help protect archeological resources (Draut and Rubin, 2007). The numerous studies of the post-dam sand budget have come to conflicting results about long-term erosion versus accumulation. However, recent work indicates that eddy-sandbars have been substantially eroded since construction of the dam and that this erosion has not been abated by enactment of the Record-of-Decision (ROD) operation of Glen Canyon Dam in the mid-1990s (U.S. Department of Interior, 1995, U.S. Department of Interior, 1996) which constrained the allowable daily hydropower fluctuations.

The approach presented herein was designed specifically to bridge the gap between approaches that have previously been used to evaluate the post-dam sand budget. Randle and Pemberton (1987) used suspended-sand rating curves developed by Pemberton (1987) as the basis for the sand budgets used in development of the ROD, but it has subsequently been shown by Topping et al. (1999, 2000a) that sand transport rates are strongly dependent on tributary sand supply as well as water discharge. This dependence is illustrated in fig. 3 which shows changes in the relation between suspended-sand concentration and water discharge resulting from a flood on the Paria River (the first major tributary downstream from the dam) in October 2006 that delivered substantial quantities of sand directly to upper Marble Canyon (data are described in detail in a subsequent section). It is seen that sand concentrations (for a given discharge) are much greater during the tributary flooding and remain significantly higher than pre-flood levels after the tributary flooding recedes, indicating sand accumulation and fining of the bed sediment. Over time, this fine sediment is subsequently winnowed from the bed and concentrations decrease.

In addition to the rating curve model of Randle and Pemberton (1987), a variety of more complex numerical models have been developed and applied as well, including multi-dimensional models of specific eddy-sandbar sites (Wiele et al., 1996, 1999, Wiele, 1998, Wiele and Torizzo, 2005) and a pseudo-one-dimensional, reach-averaged, multiple-particle size, sand-routing model (Wiele et al., 2007). While the Wiele et al. (2007) model has the potential for application to multi-year time scales, its complexity in terms of initial and boundary conditions dictate that it is more suitable to event-scale (e.g. weeks to months) applications. In contrast, the approach described herein was developed specifically to reduce the required input data and number of tunable parameters to facilitate multi-year simulations of sand flux, and thus help address the primary sediment-related question identified by program scientists at a knowledge assessment workshop held in July 2005 (Melis et al., 2006): "Is there a 'flow-only' (non-sediment augmentation) operation that will restore and maintain eddy-sandbar habitats over decadal time scales?"

MODELING APPROACH

Because our approach was developed with a specific application in mind, there were several overarching goals guiding its development, as follows:

1) The model should reproduce the basic processes of sand accumulation and fining of the bed during and immediately after tributary flooding, followed by erosion and bed coarsening during tributary quiescence (see fig. 3).
2) The model should be simple enough to allow for multi-year simulations, potentially in a Monte Carlo framework to account for variability in hydrology and tributary sediment supply.
3) The number of adjustable empirical model parameters should be as few as possible and, along with the initial/boundary conditions, be readily specifiable from available data sources and ongoing monitoring programs.

Our approach is similar to more standard formulations in that it relies on a relation between hydraulic variables (e.g. depth, velocity, shear stress, discharge) and sediment transport rate, and sediment mass conservation for computing erosion, deposition, and bed particle-size distributions. A large number of "transport relations" have been proposed over the past half century, for bed load, suspended load, and combined total load (e.g. ASCE, 1975, Yang, 1996), and most "general-use" morphodynamic models allow the user a choice between various relations. Most of the relations are formulated in terms of power-laws between transport rate, bed shear stress, and particle size, some with additional complexity to account for phenomena such as hiding and exposure. Our approach differs from the general-use models in that, instead of choosing an available transport relation, we have developed empirical rating-curve-type relations specific to the Colorado River below Glen Canyon Dam, as described below.

Rubin and Topping (2001, 2008) applied the transport relation formulation of McLean (1992) to a wide range of hydraulic conditions and particle size distributions and found that the results could be adequately generalized into the following form:

$$C \propto u_*^J D_b^K \tag{1}$$

where C is suspended-sediment concentration, u_* is shear velocity, D_b is the median bed particle diameter, and J and K are empirical coefficients. For conditions with and without dunes and for wide and narrow bed particle size distributions, Rubin and Topping (2001) found that J ranges from 3.5 to 5.0, and K ranges from -1.5 to -3.0. Application of eq. 1 on a site-specific basis requires estimation of the constant of proportionality and a model for shear velocity. The longitudinal shear velocity field in a pool-rapid system such as our study site can be quite complex, and we argue that the spatial variability is less important than changes with discharge for modeling broad-scale sediment budgets. Thus, we have assumed that shear velocity can be approximated as a power-law function of discharge. While this assumption is clearly not strictly correct, it is a reasonable approximation that facilitates achieving our stated goals. We also note that for steady, uniform flow, shear velocity goes as the square root of the depth-slope product, and at-a-station hydraulic geometry (e.g. Leopold and Maddock, 1953) suggests that this quantity can often be characterized by a power-law with discharge. Applying this assumption to eq. 1 and writing in terms of individual particle sizes (necessary for bed composition calculations as described below) yields:

$$C_i = F_{bi} A Q^L D_i^K \tag{2}$$

where Q is water discharge, i denotes individual particle sizes, F_{bi} is the fraction of particle size i in the bed sediment ($\sum F_{bi} = 1$), and A is an empirical, site-specific constant (discussed further in the next section). Note that eq. 2 is a more general form of the classical sediment rating curve, the difference being that bed particle-size distributions are used to compute concentrations for individual sizes (as opposed to for all particle sizes lumped together). To apply eq. 2, *A*, *L*, and *K* must be estimated empirically on a site-specific basis; the advantage is that *A* and *L* can be estimated from measurements of concentration and discharge, two quantities that are routinely measured on many rivers. The parameter *K* is more difficult to specify, as discussed in the next section, but it should fall between -1.5 and -3.0 as per Rubin and Topping (2001).

Application of eq. 2 requires a method for computing changes in the bed-sediment particle-size distribution (i.e. F_{bi}), and this is indeed the mechanism for simulating bed fining and coarsening in response to changing sediment supply, as outlined in modeling goal #2. For this we apply the active layer form of the Exner equation for bed sediment mass conservation (e.g. Parker et al., 2000), in a slightly simplified form. For our study site, which is a bedrock controlled canyon river, it is reasonable to approximate the mobile bed sediment, i.e. the active layer, as a relatively thin layer of sand overlying bedrock; this assumption is supported by data presented in the following section. Also, underwater video and time-lapse side-scan sonar movies (Rubin and Carter, 2006) of the bed of the river within our study sites indicates the presence of sand-starved dunes (i.e. with gravel in the troughs) which further supports the assumption of complete mixing of the sand layer (though we note that complete sand "equilibrium" dunes and thick sand deposits in eddies without dunes also exist, such that complete mixing is an approximation). By assuming that the substrate (i.e. bedrock, gravel, cobble) is non-erodible and that the sand layer thickness (H_s) is equivalent to the active layer thickness (i.e. it is completely mixed and available to the flow), the Exner equation reduces to:

$$(1-\lambda_p)B\frac{\partial H_s}{\partial t} = -\frac{\partial Q_s}{\partial x} \quad (3)$$

$$(1-\lambda_p)B\frac{\partial}{\partial t}(H_s F_{bi}) = -\frac{\partial Q_{si}}{\partial x} \quad (4)$$

where $Q_s = CQ$, $C = \sum C_i$, $Q_{si} = C_i Q$, *B* is channel width, and λ_p is bed porosity. Note that eq. 3 is the result of integrating eq. 4 over the entire bed-sediment particle-size distribution since

$\sum F_{bi} = 1$ and $\sum Q_{si} = Q_s$. This formulation provides significant simplification over the standard Exner equation because it circumvents the need to keep track of substrate layering and associated size distributions.

The non-erodible substrate (bedrock, gravel, cobble) substrate limits transport from a reach, in a given time step, to the amount of sediment in the reach plus what comes into the reach during that time step (by grain size). Thus, if the potential transport rate of a size *i* is greater than what's available for transport, the reach becomes exhausted of that size such that $F_{bi} = 0$ and $C_i = 0$. It is well known that patches of river contain little or no sand (e.g. rapids, gravel bars). One way to account for this is with a "bed-sand area" correction factor in transport relations (i.e. eq. 2, see for example Topping et al., 2007b), however, this requires information on the area of the bed that is covered in sand and how these areas are distributed with respect to bed shear stress, as well as a mechanism for simulating changes presumably based on local hydraulics and sediment supply. Because our modeling approach does not incorporate the necessary local hydraulics, we have not attempted to include this effect. The bed sand area is effectively lumped into the "catch all" coefficient *A* in eq. 2, and thus remains constant for our simulations. Instead, we focus on accounting for changes in bed particle-size distribution, which has been shown to exert greater control on transport rates than bed sand area (Topping et al., 2007b).

The set of eq. 2-4 constitutes a model for C_i, H_s, and F_{bi}, so long as water discharge can be estimated or modeled independently. The boundary conditions are Q_{si} at the upstream boundary and major tributaries; required initial conditions are H_s and F_{bi} for each reach. The final approximation of our modeling approach is that we apply the formulation to relatively long reaches, as opposed to attempting to discretize the river into short segments. This assumption sacrifices the ability to accurately model short-duration, localized, changes in concentration and bed particle-size distributions, such as that shown during the Paria River flood peak (squares) in fig. 3. That is, the spatial averaging will tend to “smooth out” these short duration effects while capturing the reach scale effects that have greater influence on the long term flux. However, it circumvents the need for detailed information on sand thickness and bed particle size within the reaches; instead, these parameters are lumped into reach-averages. Also, the empirical nature of eq. 1 dictates that it should only be applied at locations where data are available to estimate the empirical parameters (A, L, K). To this end, we applied the formulation to three reaches bracketed by sites where suspended-sand concentration, grain size, and water discharge are monitored. The three modeling reaches are shown geographically in fig. 1 and schematically in fig. 4 and are defined as follows: 1) upper Marble Canyon (UMC), from Lees Ferry/Paria River confluence to RM30; 2) lower Marble Canyon (LMC), from RM30 to RM61/Little Colorado River confluence; and 3) eastern Grand Canyon (EGC), from RM61/Little Colorado River confluence to RM87. For the model applications described herein upwind finite differences were used to solve eq. 3-4, with the following specifications: 15-minute time step, 20 particle sizes spaced logarithmically between 0.0625 – 2 mm, $B = 80$ m, and $\lambda_p = 0.4$. While it is well known that channel width varies, for example, between pool and rapid, and by reach, and with discharge, these variations in channel width are relatively small in the study area and the use of a constant width is consistent with our reach-averaged approach. The implication is that variability in sand storage resulting from variability in channel width is not modeled. The following section describes specification of the remaining model parameters and initial/boundary conditions.

ESTIMATION OF MODEL PARAMETERS

Application of the modeling approach requires specification of the coefficients in eq. 2, the initial sand thickness and bed material composition, and the incoming sediment flux (by particle size) from the Paria and Little Colorado Rivers (the primary tributaries), as well as estimates of water discharge at RM30, RM61, and RM87 (where fluxes are calculated). For the Colorado River below Glen Canyon Dam, a program of extensive suspended-sediment transport, bed material, and bathymetric surveying has been ongoing in various forms since approximately 1999, with previous periods of intensive monitoring as well including pre-dam years and during the high flows of the mid-1980s. One of the goals of this monitoring program is to construct reach-based sand budgets that are used to determine the timing of controlled flood releases from GCD for the purposes of rebuilding sandbars (Wright et al., 2005, Topping et al., 2006a). This monitoring program has provided the data necessary to implement the modeling approach, namely measurements of 1) suspended-sand concentration and water discharge at multiple sites, 2) tributary sand inputs, 3) sand thickness on the bed, and 4) bed particle size.

The time period of available high-resolution sand transport data extends from Sep-2002 through Mar-2009. For purposes of model calibration and validation, this period was split roughly equally into two parts. The calibration period was from Sep-2002 through Mar-2006, and the validation period was from Apr-2006 through Mar-2009. Each period contains episodes of substantial tributary inputs from the Paria and Little Colorado Rivers, a range of fluctuating releases from Glen Canyon Dam, and a controlled flood release. The primary calibration parameter is the coefficient A in eq. 2; the calibration and validation procedure is described in detail below following definition of the boundary and initial conditions.

Boundary conditions

The main boundary condition requirements are size-specific sand fluxes from the major tributaries, the Paria and Little Colorado Rivers. Mainstem sand transport at Lees Ferry was assumed to be zero because the reach between the dam and Lees Ferry is substantially sand-depleted (Grams et al., 2007) such that measured concentrations at Lees Ferry are typically very low. For the Paria River, a U.S. Geological Survey (USGS) gage is located near the confluence with the Colorado River (09382000 Paria River at Lees Ferry, AZ) where water discharge and suspended-sediment concentration and particle-size measurements are made, primarily during floods, using standard USGS techniques (http://pubs.usgs.gov/twri/). The water discharge record is then used to estimate suspended-sand transport using both the suspended-sediment data and the model developed by Topping (1997). Because sand transport in the largely alluvial Paria River is essentially "flow regulated" with no systematic hysteresis in suspended-sand concentration during floods, a reach-averaged coupled flow and sediment transport approach is used. For the Little Colorado River, data from two USGS gages (09402000 Little Colorado River near Cameron, AZ, and 09402300 Little Colorado River above mouth near Desert View, AZ) were used to estimate sand transport rates using time-weighted suspended-sand rating curves. Daily mean water discharge and total cumulative sand flux for these two tributaries for the study period are shown in fig. 5. The tributary sand particle-size distributions were estimated by averaging the distributions from the available samples, and it was found that log-normal distributions (φ-scale) with $D_{50} = 0.1$ mm and $\sigma_g = 1.8$ for the Paria and 2.0 the Little Colorado fit the data very well (D_{50} and σ_g are median diameter and geometric standard deviation, respectively). There are numerous ungaged tributaries entering the Colorado River along the study reach in addition to the Paria and Little Colorado Rivers. Recent monitoring data (not shown) indicate that ungaged inputs to upper Marble Canyon are about 10% of Paria inputs and are significantly larger than ungaged inputs to lower Marble Canyon and eastern Grand Canyon. Thus, for modeling purposes we increased inputs to UMC by 10% and neglected the ungaged inputs to the LMC and EGC reaches. We note that these estimates are different from (somewhat less than but within the error bars) those published by Webb et al. (2000); we chose to use the more recent estimates because they are based on direct measurements of suspended-sediment transport whereas the Webb et al. (2000) estimates were made using indirect methods.

Water-discharge time series must also be specified at the downstream end of each reach (i.e. at RM30, RM61, RM87) for application of eq. 2. For the modeling period, discharge was estimated at each site from 15-minute stage measurements and stage-discharge relations based on episodic discharge measurements. For modeling potential future scenarios, the water discharges could be routed downstream from the dam to the computational sites using the model of Wiele and Smith (1996).

Initial conditions

Solution of eq. 3-4 requires specification of the initial sand thickness and initial bed particle-size distribution, for each of the three reaches. To estimate these quantities, we used data from reach-based monitoring program implemented from 2000 – 2005. This program consisted of remote sensing, ground surveys, and bathymetric surveys (Kaplinski et al., 2009, Hazel et al., 2008) and bed particle-size measurements (using digital photographic techniques, Rubin, 2004, Rubin et al., 2007) for several 3-5 km reaches between Lees Ferry and RM87. The reach surveys closest in time to the beginning of the modeling period were conducted in May 2002. Thus, we averaged the available May 2002 sand thickness and particle-size data (M. Breedlove, Grand Canyon Monitoring and Research Center, written communication) within each modeling reach resulting in thicknesses of 0.4, 0.5, and 0.5 m and mean particle sizes of 0.4, 0.3, and 0.3 mm for UMC, LMC, and EGC, respectively. The sand thicknesses were estimated by differencing the maximum and minimum surfaces in sandy areas and thus represent the amount of erosion and accumulation that took place during the monitoring period. The digital photographic technique provides a mean particle size of the bed surface only; the initial size distributions were estimated by assuming log-normal distributions with $\sigma_g = 2.0$ (estimated from available grab samples from the gage locations). The initial conditions are summarized in table 1.

Transport relation parameters

Three parameters (*A*, *L*, and *K*) must be specified to apply eq. 2, on a site-specific basis. We estimated these parameters using the high-resolution (every 15 minutes) suspended-sediment monitoring data from the three monitoring sites. This monitoring program uses a combination of standard USGS techniques and "surrogate" technologies, including laser diffraction and hydroacoustic scattering. These techniques are described in detail elsewhere (Melis et al., 2003, Topping et al., 2004, 2006b, 2007a), and the data are available on-line at http://www.gcmrc.gov/products/other_data/. Figure 6 shows suspended-sand concentration versus water discharge for the study period (Sep-2002 to Mar-2009) for the three monitoring sites. These data further illustrate the range in sand concentration for a given discharge due to changes in the upstream supply. Also shown in fig. 6 are power-law curves based on our empirical estimates of the discharge exponents (*L* in eq. 2); the data indicate a break in the curve for each site at about 25,000 cfs (Randle and Pemberton, 1987, also noted this break), and we have incorporated this break by using two sets of exponents. The exponents were estimated by power-law curve fitting to the rising and falling limbs of the high flow releases conducted in 2004 and 2008. This approach was used because these periods encompass nearly the full range of discharge over the study period, and are also of short duration (< 1 day) such that the effects of changes in supply should be relatively small. The exponents, for above and below 25,000 cfs, are given in table 1. We chose to estimate *L* based on total sand concentration, as opposed to using particle-size specific concentrations, because this latter approach would require a priori knowledge of the exponent *K* (discussed further below). The exponents for below 25,000 cfs are likely greater than what would be expected for uniform flow over a spatially-constant bed particle-size distribution. Under this assumption, the exponents should be approximately 2 assuming shear velocity goes as the square root of discharge which is a reasonable assumption for our gage locations. This is the result of the complex organization of bed shear stress and bed particle-sizes in the pool-rapid system of the Colorado River (for example, as flow goes up it accesses finer particle sizes along the channel margins and in eddies).

The particle size exponent in eq. 2 (K) is more difficult to estimate empirically because it requires data on reach-averaged particle size distributions and particle-size-specific transport rates. However, Rubin and Topping (2001) reported a range of computed exponents of -1.5 to -3.0, thus providing a range of reasonable values. We conducted exploratory simulations and evaluated the results, particularly in terms of the degree of bed fining and coarsening that occurred for a given K-value. It was found that a value on the high end of the reasonable range was necessary to achieve the degree of fining and coarsening that has been observed (particularly during the high flow releases), and thus we chose a value of $K = -3.0$. It is perhaps not surprising that an exponent that tends to accentuate particle size dependence is necessary, given the reach-averaged nature of the model and assumption of complete mixing of the bed sediment.

There are several options for estimating the remaining coefficient in eq. 2, the proportionality constant A. Because the ultimate goal of our modeling is to predict multi-year sand budgets for the individual reaches, we chose to calibrate A at each gage location in order to match the measured total sand flux from the reach over the calibration time period, Sep-2002 through Mar-2006. These computations proceeded in a downstream direction, whereby trial-and-error was used for A until the total sand flux from the reach matched the measured sand flux to within <1%. The resulting A coefficients are given in table 1. The form of eq. 1 and its empirical nature dictate that the coefficients are not dimensionless and are a combination of various units to different powers. The values of A given in table 1 are such that, when applied to eq. 2 with Q in m^3/s and D_i in m, the resulting C_i is a volumetric concentration. Finally, the fact that A is such a small number is simply the result of the units used in its determination; concentration is linearly related to A (eq. 2) and it thus has a direct influence on modeled sand fluxes.

ANALYSIS AND DISCUSSION OF RESULTS

Several measures can be used to evaluate the model's performance, during both the calibration and validation time periods. Because the model was calibrated to match the total sand flux from each reach over the calibration period (through specification of A), it is appropriate to evaluate how well the model predictions agree with the measurements over shorter time scales within the calibration period. The validation time period provides an independent test of the model calibration. In particular, as stated in our overall modeling goals, the model should be able to simulate sand accumulation and bed fining in response to tributary flooding, followed by erosion and coarsening. Both the calibration and validation periods contain episodes of sand accumulation and bed fining, followed by high flow releases wherein substantial coarsening occurred. Substantial tributary flooding and sand inputs occurred during fall 2004, winter 2005, fall 2006, and fall 2007 (fig. 3). High flow releases occurred in Nov-2004 and Mar-2008 (fig. 2).

An initial test of model performance is a comparison of the total sand flux at each monitoring site during the validation period, since the model was calibrated to match the total fluxes during the calibration period. Table 2 shows percent differences between modeled and measured fluxes over the validation period. The differences are 11%, 0.70%, and -4.6% for RM30, RM61, and RM87, respectively. Though the model over-estimates the flux at RM30 by 11%, it is a substantial improvement over a stable sand rating curve which under-estimates this flux by 37% because it cannot incorporate bed fining due to large Paria River flooding in Oct-2006. A variety of reasons could explain the model over-estimates for this reach, including the various model simplifications as well as uncertainty in the tributary inputs (which control the degree of bed fining). The measured and modeled cumulative sand fluxes for the entire study period for each of the three monitoring sites are shown in fig. 7 (note that the calibration procedure forces these to match at the end of the calibration period). The measurement uncertainty has been estimated to be ±5% as per Topping et al. (2000a) and this envelope is included in fig. 7.

<u>Monthly sand flux and annual sand budgets</u>

Water discharge varies substantially on a monthly basis below Glen Canyon Dam in order to meet hydroelectricity demand; that is, release volumes are highest in the summer and winter when demand is highest and lowest in spring and fall. Thus, a potential application of the model would be to compare monthly sand flux for a range of release volumes. To this end, measured and modeled monthly sand fluxes for the three sites are compared in fig. 8 for both calibration and validation periods. While the model captures the general behavior well, there is substantial variability and some indication of model over-estimation at the lowest fluxes particularly at RM87. The modeled and measured monthly fluxes are compared numerically in table 2, where R is the ratio of modeled to measured monthly flux. In table 2, values for the validation period are shown in parentheses alongside those for the calibration period, for comparison. A very high percentage (~90%) of the modeled monthly fluxes are within a factor of 2 of the measurements, for both calibration and validation time periods. The percentage of modeled fluxes within a factor of 1.5 of the measured values ranges from 56% (RM61) to 79% (RM30) for the calibration period (the agreement at RM30 and RM87 is generally better than at RM61). The agreement during the calibration period is generally slightly better than during the validation period, as expected, though there in a couple instances the agreement is better during the validation period. It is again seen that the model is superior to the stable sand rating curve approach, as expected.

One of the main goals outlined for the model is the ability to simulate the sand budget over annual to decadal time scales. To this end, fig. 9 compares the measured and modeled annual sand budgets for each of the three reaches. The sand budget is defined as the sand inputs to the reach minus the sand export (fig. 4), i.e. the annual change in storage on a mass basis. The model proves capable of reproducing periods of substantial accumulation as well as erosion (during both calibration and validation time periods), an important test for the model. The modeled sand budgets are primarily a test of the modeled annual sand fluxes, since inputs are a specified boundary condition. Table 2 summarizes the ratios of measured to modeled annual sand flux (R) for the three sites; the median ratios are near one and all years have ratios within a factor of 1.5.

Accumulation/fining and erosion/coarsening

The monthly and annual comparisons, in particular the comparison with a stable sand rating curve approach, indicate that the model is capable of simulating sequences of sand accumulation and bed fining followed by erosion and bed coarsening. This is further illustrated in fig. 10 which shows the modeled sand thickness (top), median bed particle size (D_{50}, middle) and cumulative sand budget (bottom) for the upper Marble Canyon reach. The figure also contains available measurements of sand thickness and bed D_{50}, as well as the measured cumulative sand budget (data sources are described in the previous section). Several examples of accumulation and fining followed by erosion and coarsening are apparent. The most significant accumulation and fining occurred during Paria River flooding in October 2006 (see fig. 2), which resulted in more than 1×10^6 metric tons of sand accumulation in the reach (fig. 10 bottom). The model simulation indicates a 25 cm increase in sand thickness and corresponding decrease in bed D_{50} from about 0.40 to 0.25 mm (no measurements of sand thickness or bed D_{50} are available for this time period). For time periods with available sand thickness and bed D_{50} measurements (2002 – 2004), the model is in agreement in terms of the overall trends but not in terms of the magnitudes (fig. 10 top, middle). The measurements exhibit greater variability, particularly in the period leading up to and following the Nov-2004 high flow release. The measurements indicate greater accumulation and fining followed by greater erosion and coarsening than the model. This could be due to the fact that the measurement reaches constitute only a small percentage of the entire reach (and thus may represent the overall trend but not the magnitude), or could be a result of the reach-averaging and assumption of complete mixing of the bed sand layer (which tends to smooth out rapid changes). Likely, it is a combination of these and other factors. It is also noteworthy that sand thickness (fig. 10 top) and bed D_{50} (fig. 10 middle) are near mirror images of each other. This is a direct result of the assumption of complete bed mixing, which dictates that processes such as erosion through a coarse surface layer into finer material are precluded. However, the model does not impose a unique relation between sand thickness and bed-sand D_{50}. For example, two tributary inputs of the same magnitude and particle-size distribution, without any coarsening in between, will result in different degrees of bed fining because the new tributary sand is mixing with a progressively finer bed (i.e. the 2nd tributary flood would result in the same increase in sand thickness as the 1st flood, but proportionately less fining since it's mixing with an initially finer bed).

The controlled flood releases in Nov-2004 (during the calibration period) and Mar-2008 (during the validation period) provide excellent tests of the model's ability to simulate sand erosion and coarsening of the bed. Though these releases are designed to facilitate deposition in recirculating eddies and associated sandbars, they necessarily export significant amounts of sand from the system and substantially coarsen the bed of the river (Topping et al., 1999, 2006a) over a short period of time (days). Coarsening of the bed during the flood peak is reflected in decreasing suspended-sand concentrations while water discharge is constant, indicating winnowing of the finest sizes leaving behind the coarser sizes that are less transportable. This effect is illustrated in fig. 11 which shows measured and modeled suspended-sand concentrations for the three sites for the two high flow releases that occurred during the study period. Note that all panels have the same y-axis scale which illustrates the differences in sand supply preceding the events and the models' ability to simulate these differences. In general, the model does a very good job of simulating the coarsening of the bed and resulting decrease in suspended-sand concentration during the flow peak (the Mar-2008 hydrograph is shown in fig. 2; the Nov-2004 hydrograph was nearly identical). There is a general tendency, however, for the model to under-estimate the concentrations on the rising limb of the hydrograph, as well as the peak concentration. One possible explanation for this is the inability of the model to account for variations in bed particle size with elevation within the channel; i.e. bed-sand particle size tends to be coarsest in deeper parts of the channel and finest in higher elevation deposits such as eddy sandbars (Topping et al., 2005). This structure is to some degree embedded in the rating curve exponents; however it is not treated explicitly in the modeled particle size distribtions and would require a significantly more complex formulation. Several other explanations are possible as well, such as unsteady transport process, local hydraulics (particularly in eddies), breaking of “armor layers” that release finer sand, among others.

SENSITIVITY ANALYSIS

Because of the simplified and empirical nature of the modeling approach, it is instructive to evaluate the sensitivity of the model results to the various model parameters that must be specified, include boundary and initial conditions. To this end, we conducted a suite of simulations with the following parameters varied by ±10%: 1) tributary sand loads (Paria and Little Colorado); 2) tributary sand D_{50}; 3) initial sand thickness on the bed (H_s); 4) initial bed D_{50}; 5) rating curve coefficient (A in eq. 2); 6) discharge exponent (L in eq. 2); 7) bed-sand particle-size exponent (K in eq. 2), and 8) channel width (B). The choice of ±10% is arbitrary to some degree and does not necessarily represent uncertainty in the various parameter (the uncertainty is unknown). Rather, the ±10% is simply a reasonable perturbation to impose on the model in order to study its sensitivity. Imposing the same relative perturbation for all parameters allows for evaluation of the relative sensitivity to each parameter and can thus provide guidance on, for example, which parameters warrant further study and measurements.

Model sensitivity was evaluated by comparing the sand flux at each gage for the ±10% runs with that of the calibrated model (total flux over the simulation period (Sep-2002 though Mar-2009). While each parameter influences the model in different and complex ways, comparison of total fluxes is the simplest, most direct, and most relevant method because simulation of multi-year sand flux is the primary objective of the model. The results are displayed in figure 12, in terms of percent differences between the sensitivity runs and the calibrated model, for the three gage locations. From the figure it is immediately apparent that the rating-curve exponents (L and K in eq. 2) exert, by far, the greatest control on the model results. The ±10% perturbation introduced in these exponents results in differences in total flux at the gages ranging from ~50-100%, depending on the site. In contrast, all other parameters yield differences that are less than the ±10% perturbation. Tributary loads, tributary D_{50}, initial bed D_{50}, and the rating coefficient (A) all yield differences in the 3-7% range, while initial sand thickness and channel width had almost no effect on the results (differences <0.5%).

It is perhaps not surprising that the exponents exert such strong influence, given that they are substantially greater than one resulting in a highly non-linear response in sand concentration with changes in discharge and particle size. This sensitivity supports our approach of directly calibrating the rating coefficient A to match measured loads; without this type of calibration large differences in loads could easily occur. It is also instructive for sediment-transport modeling in general, because any model must incorporate a similar sediment-transport formula whereby concentration or flux is dependent on hydraulic variables (and particle size) in a highly non-linear way (for example, the Rouse equation with a near-bed concentration predictor). Thus, some calibration of concentration or flux (directly or through shear-stress partitioning) is likely always necessary for sediment-transport modeling of this type.

LIMITATIONS OF THE APPROACH

The modeling approach that we have developed and applied is empirical in nature and substantially simplified with respect to the physical processes known to govern sediment transport in the study reach. The empiricism and simplifications were necessary to meet the primary goal of the modeling, i.e. the ability to simulate the long-term (decadal scale) sand budget for the reach with only one adjustable calibration parameter. The consequences of the simplifications have been noted throughout this article, but warrant summary here so that potential users of this approach have a clear understanding of the limitations, as follows:

- Though the approach should have general applicability to supply-limited rivers, and particularly those where complete bed mixing is a reasonable approximation, the model coefficients (table 1) are specific to the study reach and thus do not have general applicability.
- The model integrates the pool-rapid-eddy morphology over long reaches, and thus should not be expected to capture the specific effects of this morphology on sediment transport. For example, the model cannot discriminate between sand on the main channel bed and sand within eddy-sandbars.
- The model does not account for changes in the area of sand covering the bed at a given time. This phenomenon is essentially lumped in the calibration of the rating curve coefficient A. Thus, application of the model to conditions where large changes in bed sand area might be expected (e.g. long-term substantial accumulation) must be viewed with some caution.
- Though the model uses a short (15-min) time step in order to capture the sub-daily variability in flow, it should not be expected to capture rapid changes in bed particle size and suspended-sand concentration, for example during tributary flooding (e.g. fig. 3). The use of long reaches

and assumption of complete mixing of the bed sediment tends to “smooth out” these rapid changes. To capture the type of short-term response shown in fig. 3 (squares), an unsteady, advection-dispersion approach for suspended-sediment would likely be required.

- The model cannot capture variability in particle size as a function of elevation within the channel that is known to exist, i.e. the river bed is coarser in the deeper main channel than in shallower eddy environments. The model lumps all sand deposits into a single pool (for each reach) that is completely mixed.
- The model cannot simulate a scenario where a coarse surface layer temporarily precludes access to a finer substrate. This is thought to have happened following the extremely high flows of the mid-1980s, after which transport rates gradually increased for a given discharge despite a likely negative sand budget. This behavior was presumably a result of morphologic adjustments of eddy-sandbars following the high flows (Topping et al., 2005). The assumption of completely mixed bed sediment precludes simulation of this behavior.

Because of these limitations, we consider the modeling approach as one that should be used in concert with an ongoing monitoring program allowing for ongoing evaluation of the calibration parameter *A*. Indeed, the empirical nature of the transport relation requires at least some monitoring data in order to specify the model parameters. The model, as with almost all models, was designed with the intent to forecast future conditions for various hydrological and management scenarios. However, because of the empirical nature and inherent limitations, the approach and results should be routinely evaluated and adjusted as necessary as new data become available. Ideally, this is the approach that should be taken with all simulation models, but it is particularly important for the approach described here.

CONCLUSIONS

The modeling approach described herein represents a compromise between a desire for model simplicity, in order to limit input data requirements as well as facilitate multi-year simulations of a large number of scenarios, and the need to capture a fundamental mechanism controlling transport rates in the study reach, i.e. supply-driven changes in bed particle size and suspended-sediment concentration. In the spectrum of sediment-transport models, it lies between suspended-sediment rating curves and standard one-dimensional, multiple-particle-size, morphodynamic models. The approach was formulated specifically for sand supply-limited conditions, in particular the conditions along the Colorado River below Glen Canyon Dam where the relation between suspended-sand concentration and water discharge strongly depends on sand supply from tributaries downstream from the dam. A primary objective of the modeling approach was the ability to simulate multi-year sediment budgets, perhaps in a Monte Carlo framework to account for variability in hydrology and tributary sediment supply. Achieving this objective required various simplifications and empiricism, as summarized in the previous section. The proposed formulation certainly achieved this objective as the approximately 7-year simulations described herein took only ~30 seconds on a standard desktop computer.

The model was applied to the reach of the Colorado River below Glen Canyon Dam for the period Sep-2002 through Mar-2009. The model was calibrated such that the total sand flux from each of the three modeling reaches matched the measured total flux during the calibration time period (i.e. the first 3.5 years of the simulation). Comparisons between measured and modeled monthly sand fluxes and annual sand budgets showed the model capable of simulating the variability in sand flux resulting from discharge variability as well as changes in sand supply. Model comparisons to data were generally comparable during the calibration and validation time periods. Comparisons of measured and modeled bed sand thickness and bed D_{50} confirmed the models' ability to simulate accumulation of sand accompanied by bed fining during and immediately following tributary flooding, followed by erosion and bed coarsening during tributary quiescence. Comparisons of measured and modeled suspended-sand concentrations during the high flow releases in Nov-2004 and Mar-2008 indicate that the model can adequately simulate bed coarsening during the peak flows, but tends to under-estimate suspended-sand concentration on the rising limb of the high flow hydrograph. The model was also shown to provide significant improvement over a stable suspended-sand rating curve approach for our study site, as expected. Analysis of model sensitivity to input parameters illustrated strong dependencies on the rating curve exponents (discharge and particle size), thus providing support for our procedure of direct calibration of the rating curve coefficient to match measured loads. Finally, these comparisons provide confidence in application of the model to forecast future conditions under various dam operation scenarios, for example to estimate how much accumulation or erosion might occur for a given dam operation and tributary supply. This information could then potentially be used to plan future high flow releases designed to rebuild sandbars.

As formulated, the modeling approach should have general applicability to supply-limited rivers, particularly those where the assumption of complete bed mixing is appropriate such as many rivers flowing through bedrock canyons. However, the empirical model parameters (i.e. table 1) are not expected to have general applicability, but must rather be estimated on a site-specific basis. Thus, this type of approach can only be applied to river reaches where sufficient data are available to estimate the model parameters. Also, given the simplified and empirical nature of the approach, applications will be most successful if conducted within the context of an ongoing monitoring program so that the results can be evaluated on a regular basis and, if necessary, the formulation can be modified to account for new findings related to sand transport processes within the river.

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Table 1 – Initial conditions for the reaches and model parameters at the computation/monitoring sites.

	UMC/RM30	**LMC/RM61**	**EGC/RM87**
Initial H_s (m)	0.4	0.5	0.5
Initial D_{50} (mm), σ_g	0.4, 2.0	0.3, 2.0	0.3, 2.0
L, below 25,000 cfs	3.7	4.0	3.7
L, above 25,000 cfs	1.7	1.7	1.3
K	-3.0	-3.0	-3.0
A[1]	4.3×10^{-26}	6.2×10^{-27}	6.1×10^{-26}

[1] coefficients yield C_i as a volumetric concentration for Q in m^3/s and D_i in m (see eq. 2)

Table 2 – Model-result statistics for the fluxes at the computation/monitoring sites.

	RM30	**RM61**	**RM87**	**RM30 stable**
% difference in total sand flux, validation period	11%	0.70%	-4.6%	-37%
Monthly flux statistics (n = 43 months for calibration, 36 months for validation)				
median R	1.03 (1.23)[1]	1.15 (1.34)	1.17 (1.08)	0.89 (0.64)
% of months with 0.5<R<2	93 (100)	88 (86)	98 (97)	86 (67)
% of months with 0.67<R<1.5	79 (72)	56 (61)	74 (67)	56 (42)
Annual flux statistics (n = 7 years)				
median R	0.90	0.94	1.0	N/A
range in R	0.69 – 1.15	0.71 – 1.24	0.84 – 1.11	N/A

[1] first value is calibration, value in parentheses is validation

Figure 1 – Colorado River below Glen Canyon Dam. Lees Ferry is designated river-mile 0 and is about 15 miles downstream from Glen Canyon Dam. RM30, RM61, and RM87 denote locations of monitoring sites and are labeled according to river miles downstream from Lees Ferry (i.e. RM30 is approximately thirty river miles downstream). The Paria and Little Colorado Rivers are the primary sand-supplying tributaries.

Figure 2 – Examples of the flow regime below Glen Canyon Dam. Top: Sep-2002 through Mar-2009, which is the entire period of model application. Middle: Daily fluctuating flows in the spring and summer of 2006. Bottom: Controlled flood release hydrograph from March 2008.

Figure 3 – Left: Suspended-sand concentration versus water discharge for the RM30 gage (all data - gray dots) and for three days before (circles), during (squares), and after (triangles) Paria River flooding during October 2006. Right: Paria River daily mean discharge showing the dates of the highlighted data.

Figure 4 – Schematic diagram of the three modeling reaches indicating sand inputs and export from each reach. UMC, LMC, and EGC refer to upper Marble Canyon, lower Marble Canyon, and eastern Grand Canyon, respectively (see fig. 1).

Figure 5 – Top panels: Daily mean discharge for the Paria (left) and Little Colorado (right) rivers during the study period. Bottom panels: Cumulative sand fluxes into the mainstem Colorado River. Tmt denotes thousand metric tons. X-axis ticks are at the beginning of each water year (Oct-1).

Figure 6 – Suspended-sand concentration versus water discharge as measured at the 3 monitoring sites between Sep-2002 and Mar-2009, and relations derived from eq. 2 with the exponents given in table 1.

Figure 7 – Comparison of measured and modeled cumulative sand fluxes at the 3 monitoring sites for the entire modeling period (calibration and validation). Measured fluxes are shown as an envelope with ±5% uncertainty (Topping et al., 2000a). For RM30, the model results using a stable rating curve are also shown.

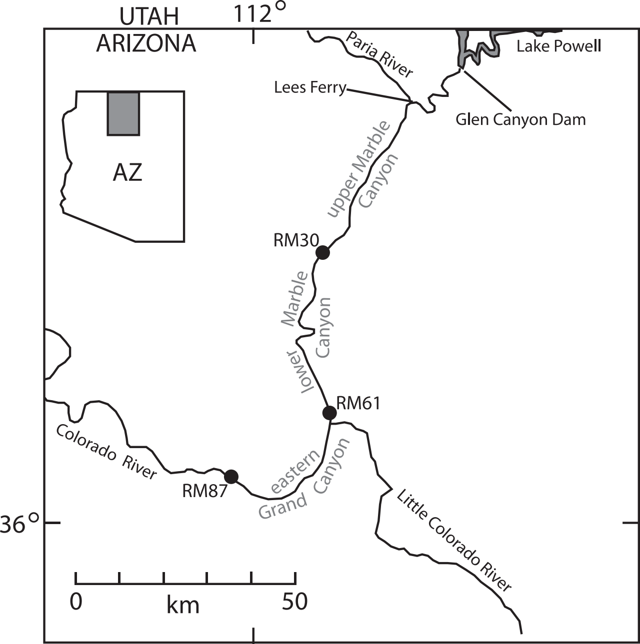
Figure 8 – Comparison of measured and modeled monthly sand fluxes at the 3 monitoring sites (RM30 – top, RM61 – middle, RM87 – bottom) for the calibration and validation periods, line indicates perfect agreement. Statistics are given in table 1.

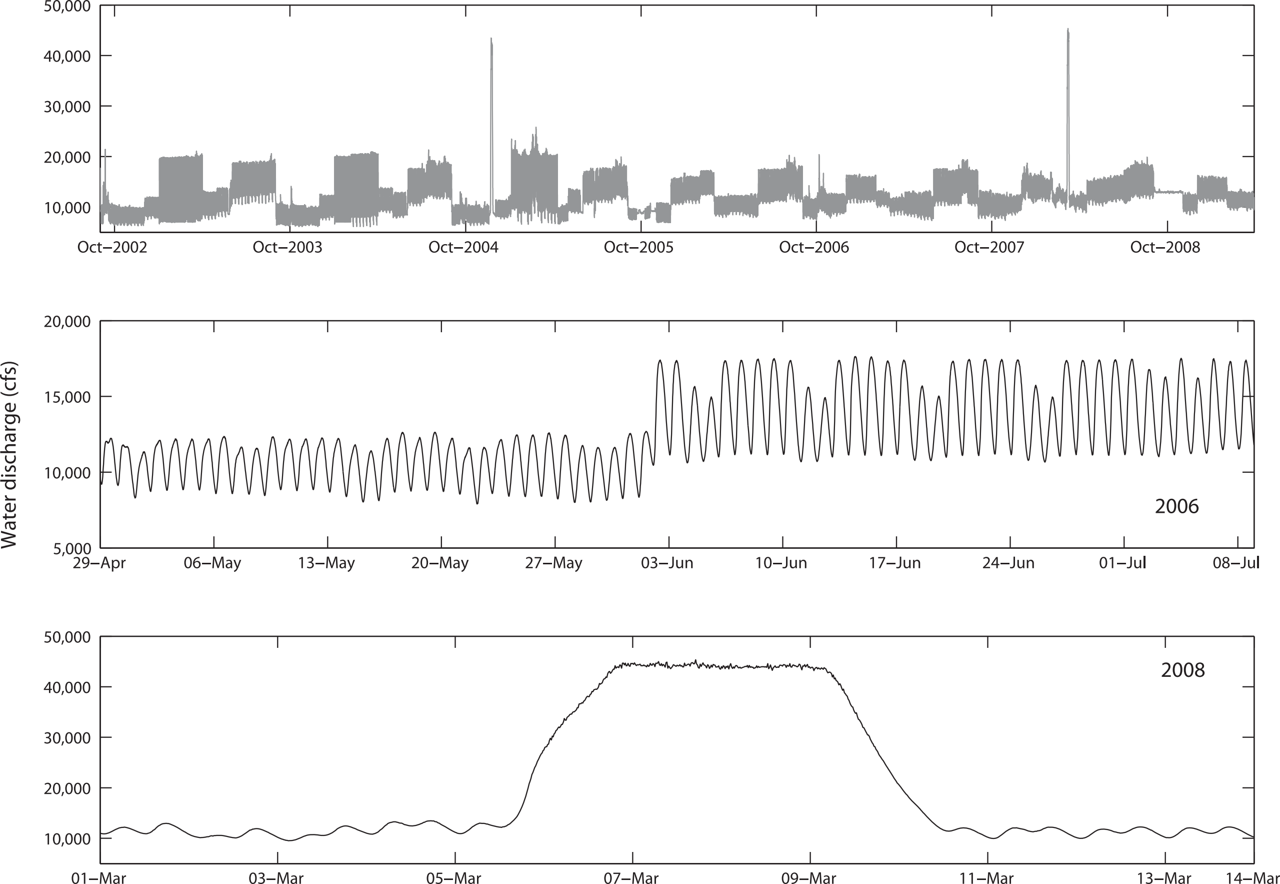
Figure 9 – Comparison of measured and modeled annual sand budgets for the three reaches. The annual sand budget is defined as sand inputs minus export from the reach (based on water year), i.e. the change in storage on a mass basis.

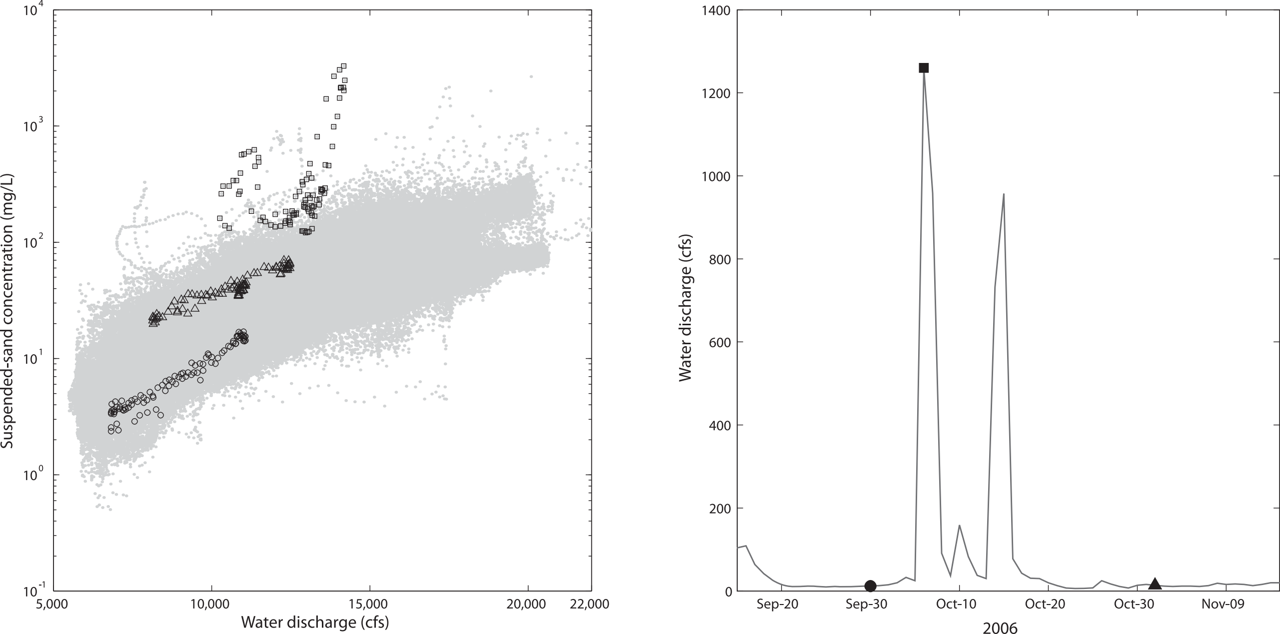
Figure 10 – Time series of measured and modeled sand thickness (top), bed median particle size (middle), and cumulative sand budget (bottom) for the upper Marble Canyon (UMC) reach. Data sources are described in the text

Figure 11 – Comparison of measured (circles) and modeled (solid black lines) suspended-sand concentration at the three monitoring sites during high flow releases in Nov-2004 (during calibration period) and Mar-2008 (during validation period). The high flow hydrographs are shown light solid lines in each panel.

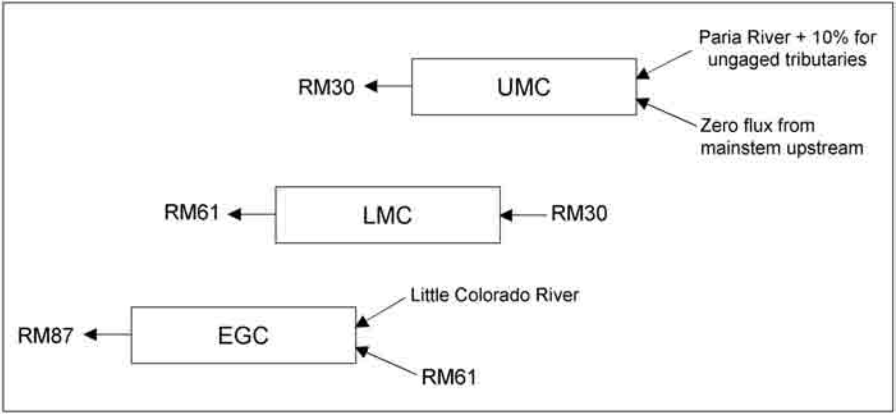
Figure 12 – Results of model sensitivity analyses for the three gage sites. The y-axis portrays the percent difference between the given scenario and the fully calibrated model, for variations in each parameter of ±10%.

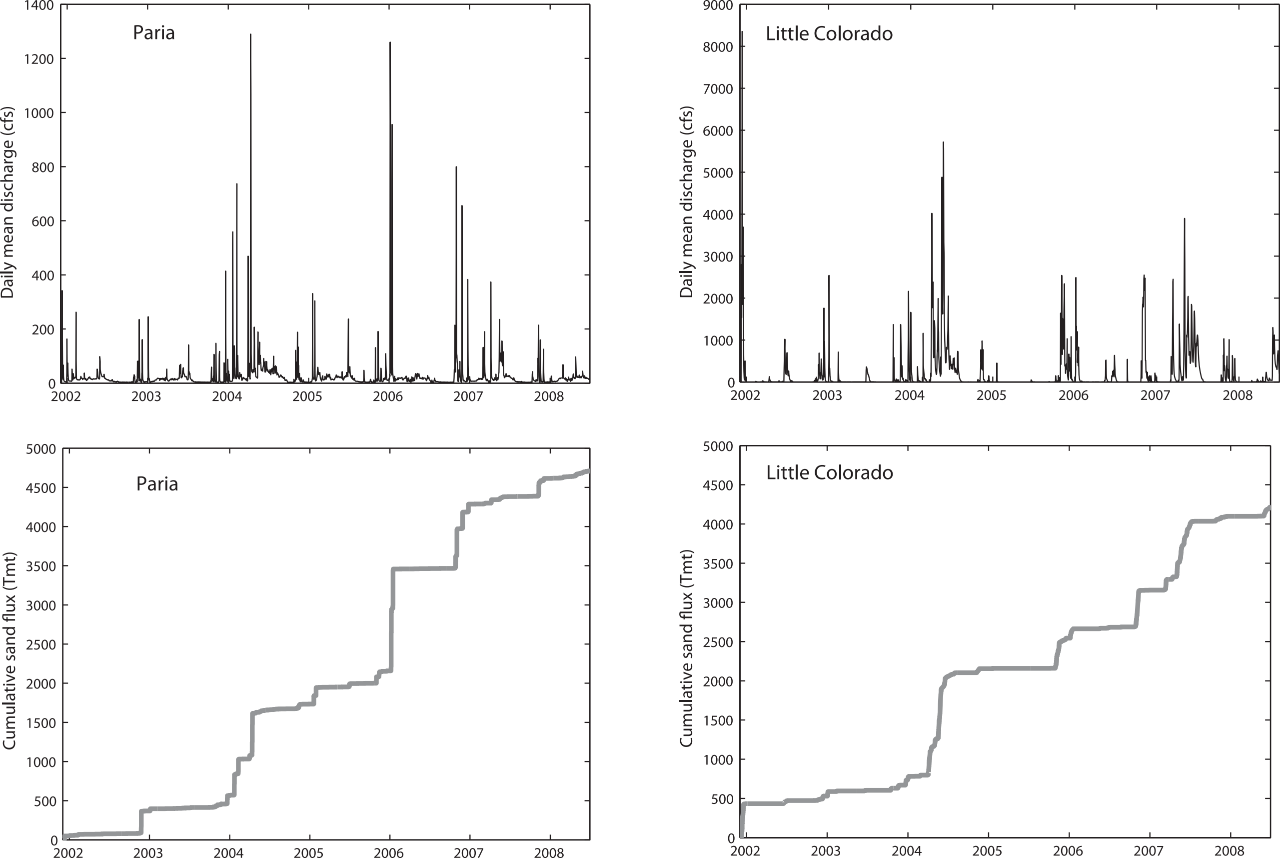

UTAH
ARIZONA
112°
36°
AZ
Paria River
Lake Powell
Lees Ferry
Glen Canyon Dam
upper Marble Canyon
RM30
lower Marble Canyon
RM61
eastern Grand Canyon
Colorado River
RM87
Little Colorado River
0
km
50


Water discharge (cfs)
50,000
40,000
30,000
20,000
10,000
Oct–2002
Oct–2003
Oct–2004
Oct–2005
Oct–2006
Oct–2007
Oct–2008
20,000
15,000
10,000
5,000
2006
29–Apr
06–May
13–May
20–May
27–May
03–Jun
10–Jun
17–Jun
24–Jun
01–Jul
08–Jul
50,000
40,000
30,000
20,000
10,000
2008
01–Mar
03–Mar
05–Mar
07–Mar
09–Mar
11–Mar
13–Mar
14–Mar

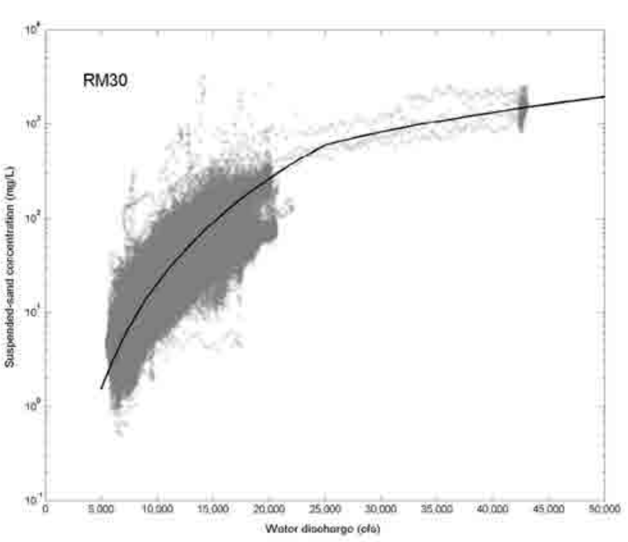


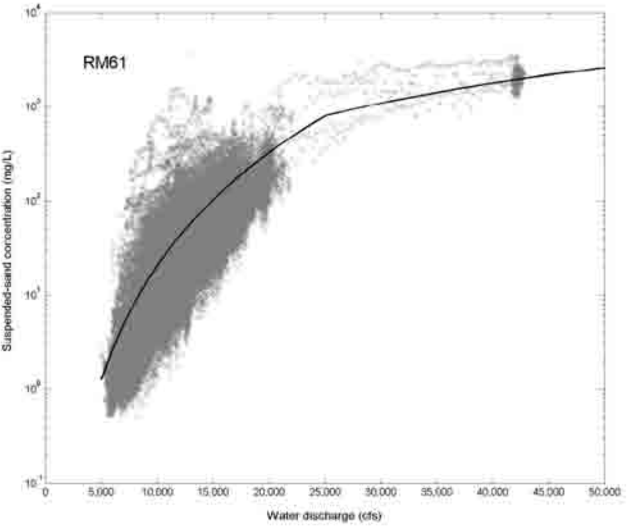
Suspended-sand concentration (mg/L)
Water discharge (cfs)
5,000
10,000
15,000
20,000
22,000
Water discharge (cfs)
1400
1200
1000
800
600
400
200
0
Sep-20
Sep-30
Oct-10
Oct-20
Oct-30
Nov-09
2006

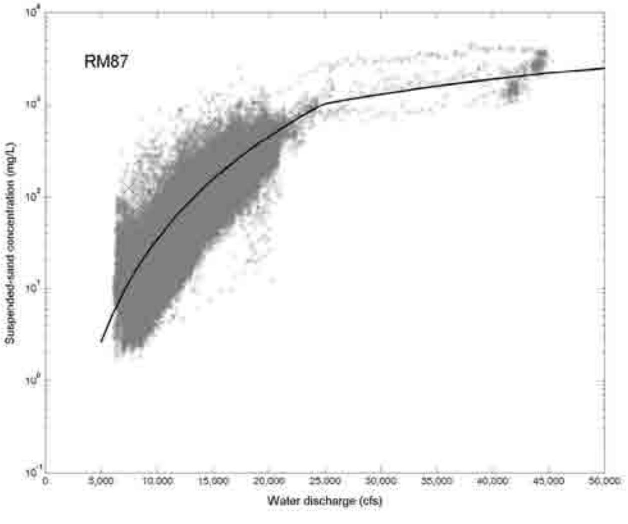

Paria River + 10% for ungaged tributaries
RM30
UMC
Zero flux from mainstem upstream
RM61
LMC
RM30
Little Colorado River
RM87
EGC
RM61

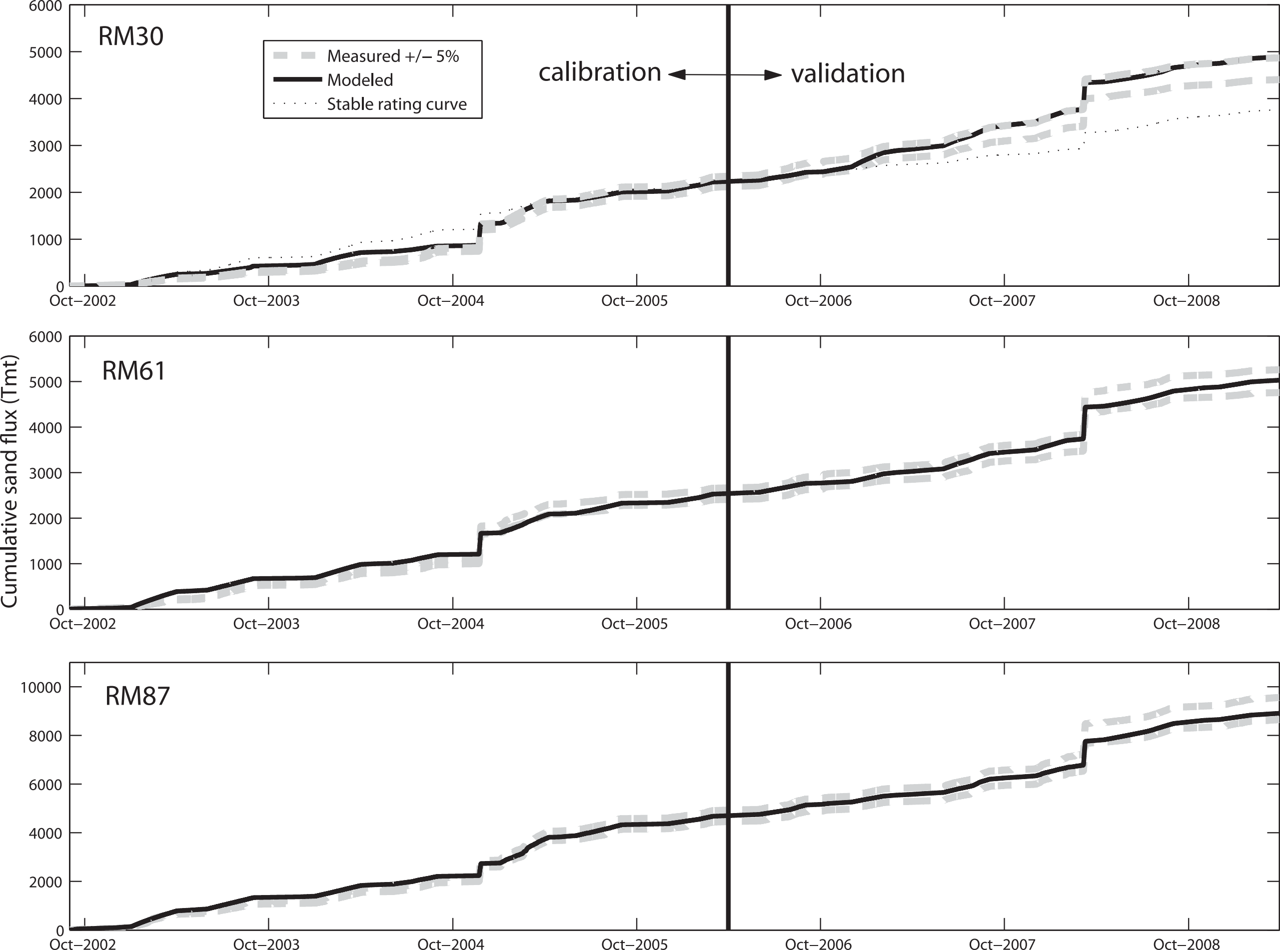


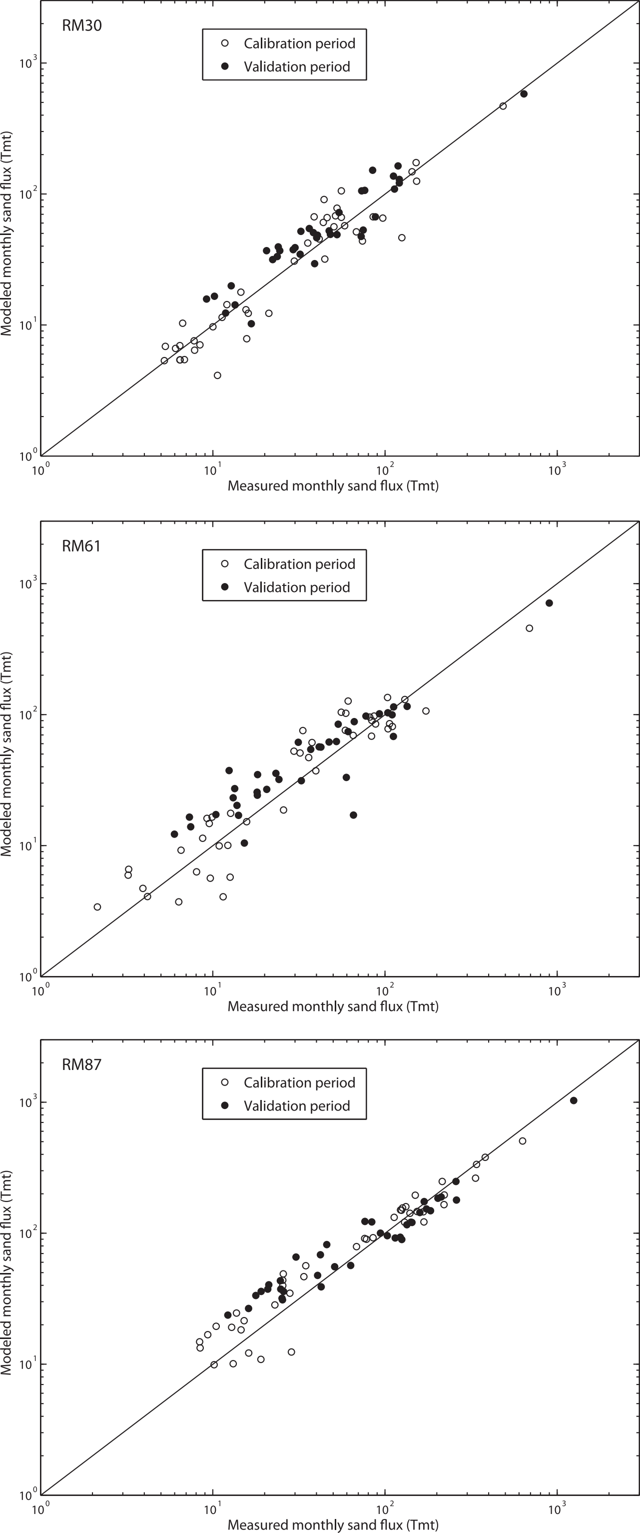
Paria
Daily mean discharge (cfs)
0
200
400
600
800
1000
1200
1400
2002
2003
2004
2005
2006
2007
2008
Little Colorado
Daily mean discharge (cfs)
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
2002
2003
2004
2005
2006
2007
2008
Paria
Cumulative sand flux (Tmt)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
2002
2003
2004
2005
2006
2007
2008
Little Colorado
Cumulative sand flux (Tmt)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
2002
2003
2004
2005
2006
2007
2008

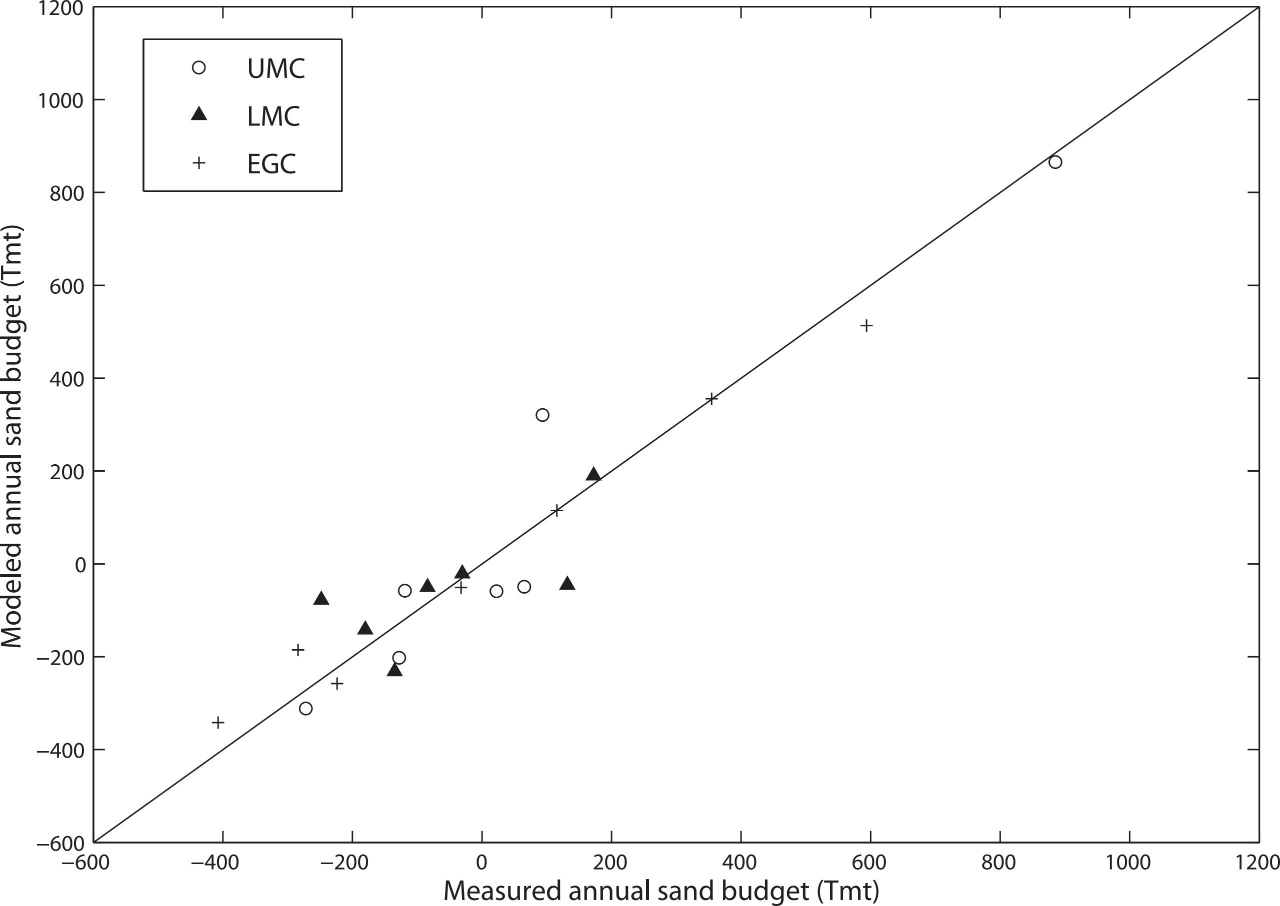

RM30
Suspended-sand concentration (mg/L)
Water discharge (cfs)
0
5,000
10,000
15,000
20,000
25,000
30,000
35,000
40,000
45,000
50,000

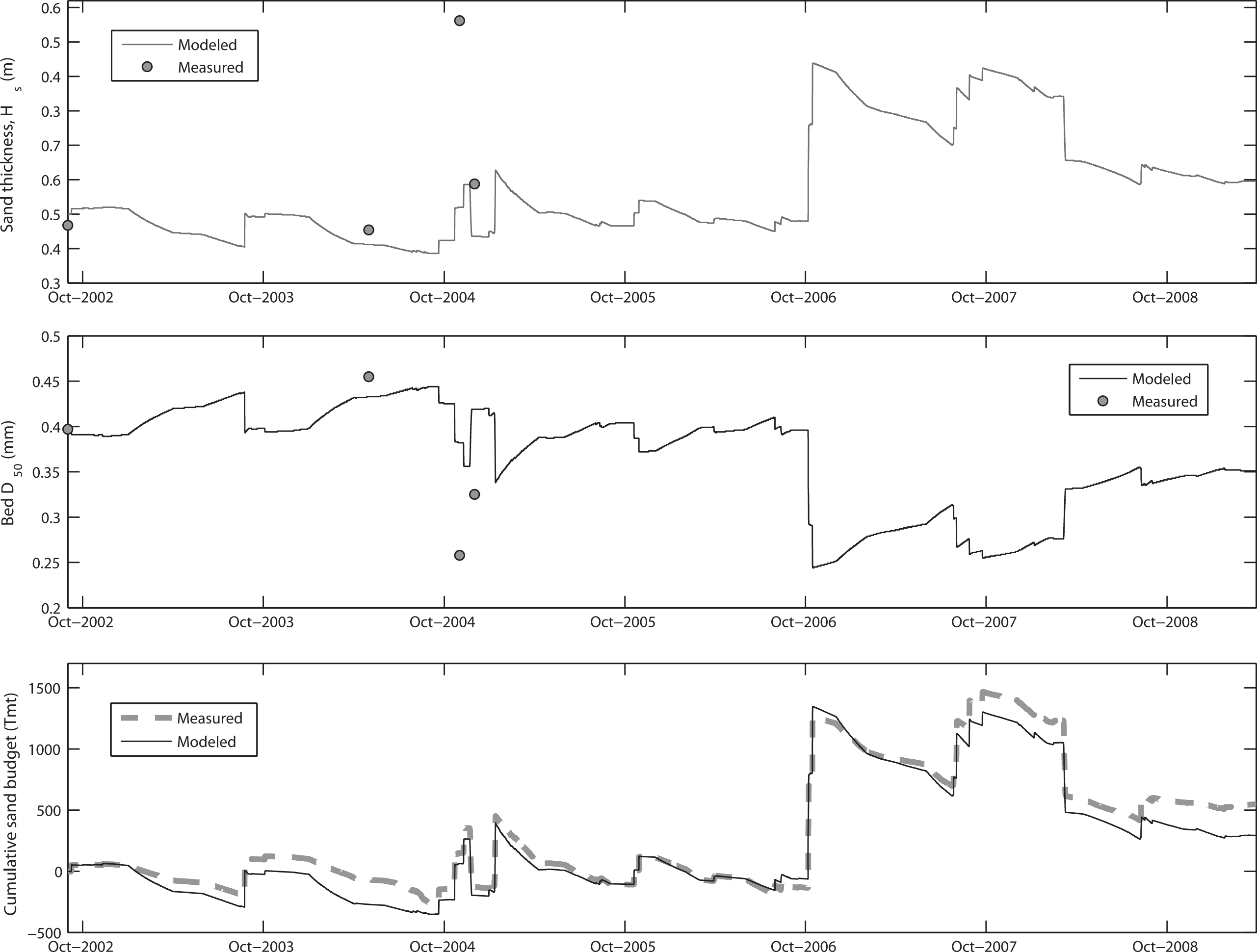

RM61
Suspended-sand concentration (mg/L)
Water discharge (cfs)
0
5,000
10,000
15,000
20,000
25,000
30,000
35,000
40,000
45,000
50,000


RM87
Suspended-sand concentration (mg/L)
Water discharge (cfs)
0
5,000
10,000
15,000
20,000
25,000
30,000
35,000
40,000
45,000
50,000

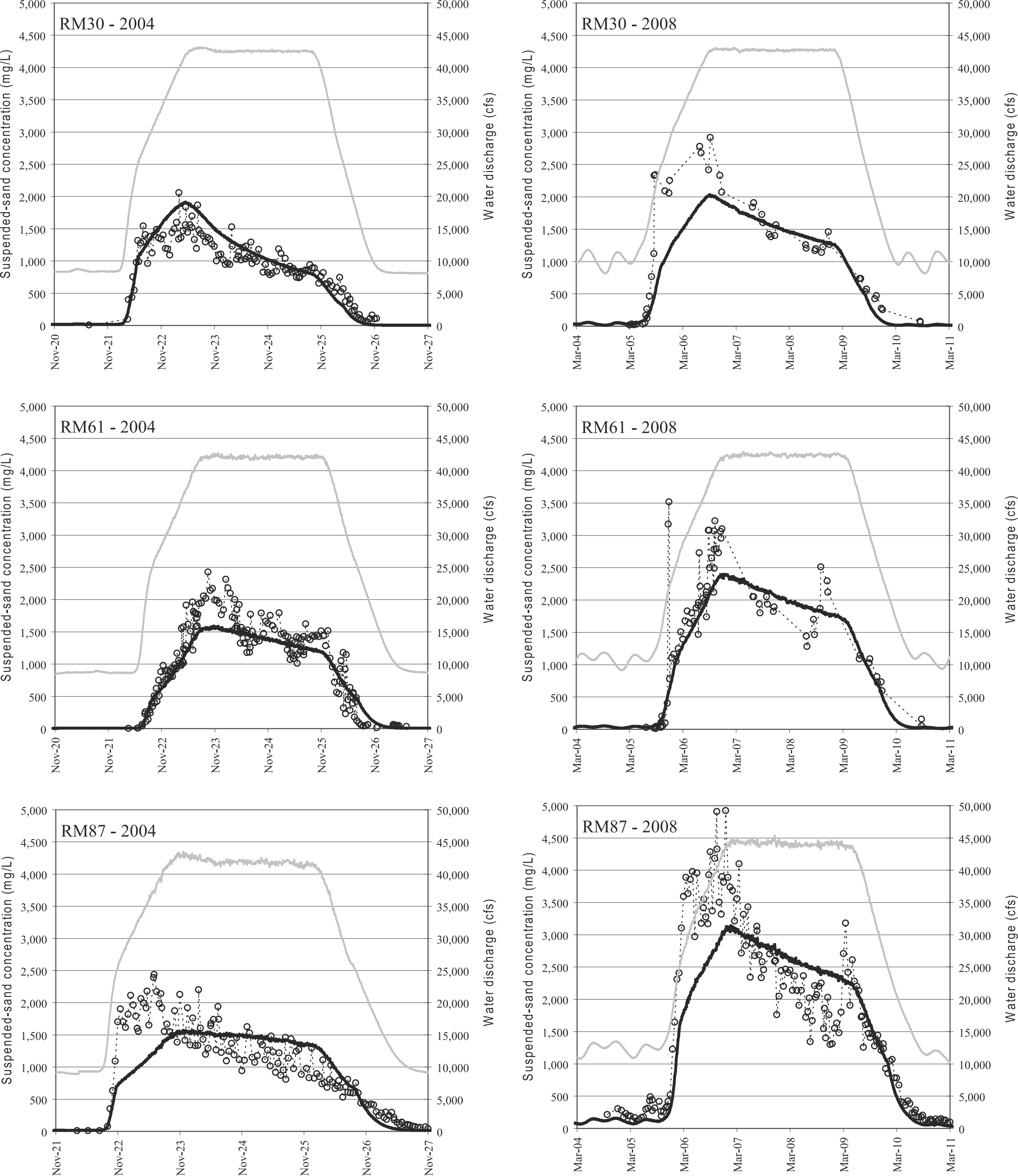

RM30
Measured +/– 5%
Modeled
Stable rating curve
calibration
validation
RM61
RM87
Cumulative sand flux (Tmt)
0
1000
2000
3000
4000
5000
6000
8000
10000
Oct–2002
Oct–2003
Oct–2004
Oct–2005
Oct–2006
Oct–2007
Oct–2008


RM30
Calibration period
Validation period
Modeled monthly sand flux (Tmt)
Measured monthly sand flux (Tmt)
10^0
10^1
10^2
10^3
RM61
Calibration period
Validation period
Modeled monthly sand flux (Tmt)
Measured monthly sand flux (Tmt)
10^0
10^1
10^2
10^3
RM87
Calibration period
Validation period
Modeled monthly sand flux (Tmt)
Measured monthly sand flux (Tmt)
10^0
10^1
10^2
10^3


UMC
LMC
EGC
Modeled annual sand budget (Tmt)
Measured annual sand budget (Tmt)
1200
1000
800
600
400
200
0
−200
−400
−600
−600
−400
−200
0
200
400
600
800
1000
1200



Sand thickness, H s (m)
0.6
0.5
0.4
0.3
0.7
0.6
0.5
0.4
0.3
Modeled
Measured
Oct–2002
Oct–2003
Oct–2004
Oct–2005
Oct–2006
Oct–2007
Oct–2008
Bed D 50 (mm)
0.5
0.45
0.4
0.35
0.3
0.25
0.2
Modeled
Measured
Oct–2002
Oct–2003
Oct–2004
Oct–2005
Oct–2006
Oct–2007
Oct–2008
Cumulative sand budget (Tmt)
1500
1000
500
0
−500
Measured
Modeled
Oct–2002
Oct–2003
Oct–2004
Oct–2005
Oct–2006
Oct–2007
Oct–2008


RM30 - 2004
RM30 - 2008
RM61 - 2004
RM61 - 2008
RM87 - 2004
RM87 - 2008
Suspended-sand concentration (mg/L)
Water discharge (cfs)
0
500
1,000
1,500
2,000
2,500
3,000
3,500
4,000
4,500
5,000
5,000
10,000
15,000
20,000
25,000
30,000
35,000
40,000
45,000
50,000
Nov-20
Nov-21
Nov-22
Nov-23
Nov-24
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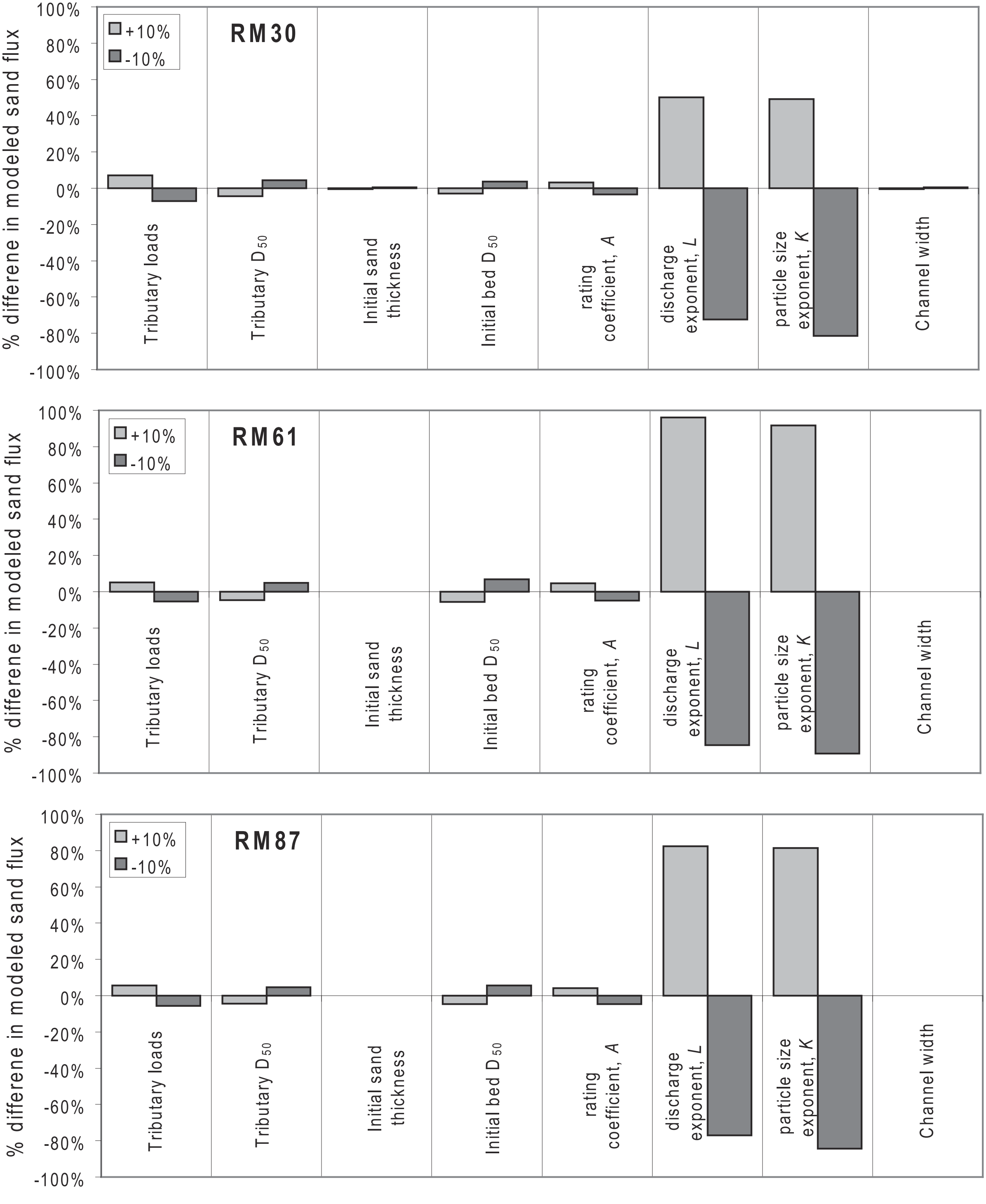
Nov-26
Nov-27
Mar-04
Mar-05
Mar-06
Mar-07
Mar-08
Mar-09
Mar-10
Mar-11



RM30
RM61
RM87
+10%
-10%
% differene in modeled sand flux
100%
80%
60%
40%
20%
0%
-20%
-40%
-60%
-80%
-100%
Tributary loads
Tributary D50
Initial sand thickness
Initial bed D50
rating coefficient, A
discharge exponent, L
particle size exponent, K
Channel width