An approach for modeling sediment budgets in supply-limited rivers

Scott A. Wright,[1] David J. Topping,[2] David M. Rubin,[3] and Theodore S. Melis[2]

Received 1 September 2009; revised 11 June 2010; accepted 18 June 2010; published 28 October 2010.

[1] 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 setup, 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 (GCD), 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. Although 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 setup and use.

Citation: Wright, S. A., D. J. Topping, D. M. Rubin, and T. S. Melis (2010), An approach for modeling sediment budgets in supply-limited rivers, *Water Resour. Res.*, *46*, W10538, doi:10.1029/2009WR008600.

[1]U.S. Geological Survey, California Water Science Center, Sacramento, California, USA.
[2]U.S. Geological Survey, Grand Canyon Monitoring and Research Center, Flagstaff, Arizona, USA.
[3]U.S. Geological Survey, Pacific Science Center, Santa Cruz, California, USA.

1. Introduction

[2] 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.

[3] 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 multidimensional 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. Multidimensional 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 multidimensional 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 nonequilibrium 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 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, to facilitate long-term simulations for rivers where minimal topographic information is available.

[4] 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 (GCD) 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.

[5] 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 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].

[6] 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 1-D 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 1-D 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 devel-

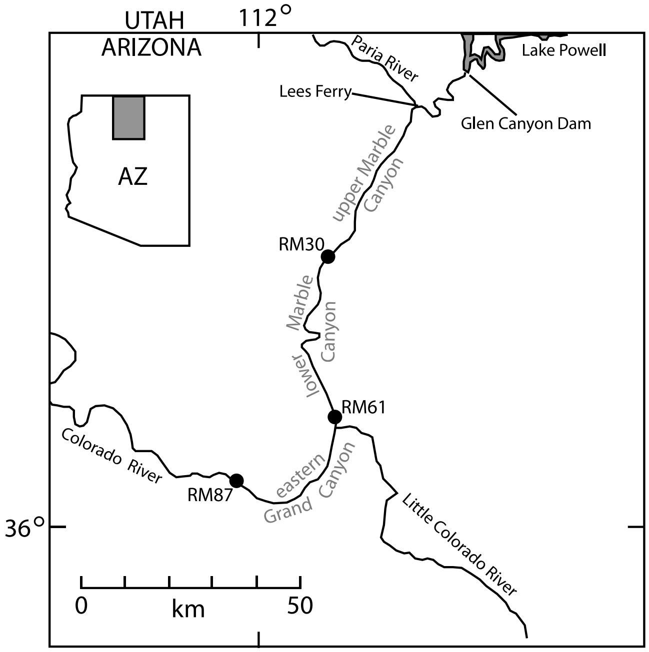

Figure 1. Colorado River below Glen Canyon Dam. Lees Ferry is designated river-mile 0 and is about 15 miles downstream from Glen Canyon Dam. RM30, RM61, and RM87 denote locations of monitoring sites and are labeled according to river miles downstream from Lees Ferry (i.e., RM30 is approximately 30 river miles downstream). The Paria and Little Colorado Rivers are the primary sand-supplying tributaries. RM is river-mile.

oped 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.

2. Study Site

[7] The modeling approach described in the next section was developed as part of our ongoing work on the Colorado River below Glen Canyon Dam (Figure 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.*, 2000] 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 Figure 2 that shows the study period to which the model was applied (top, September 2002 through March 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 the study by *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.

[8] 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 (Figure 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, 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] that constrained the allowable daily hydropower fluctuations.

[9] 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, 2000] that sand transport rates are strongly dependent on tributary sand supply as well as water discharge. This dependence is illustrated in Figure 3 that 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.

[10] 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 multidimensional models of specific eddy sandbar sites

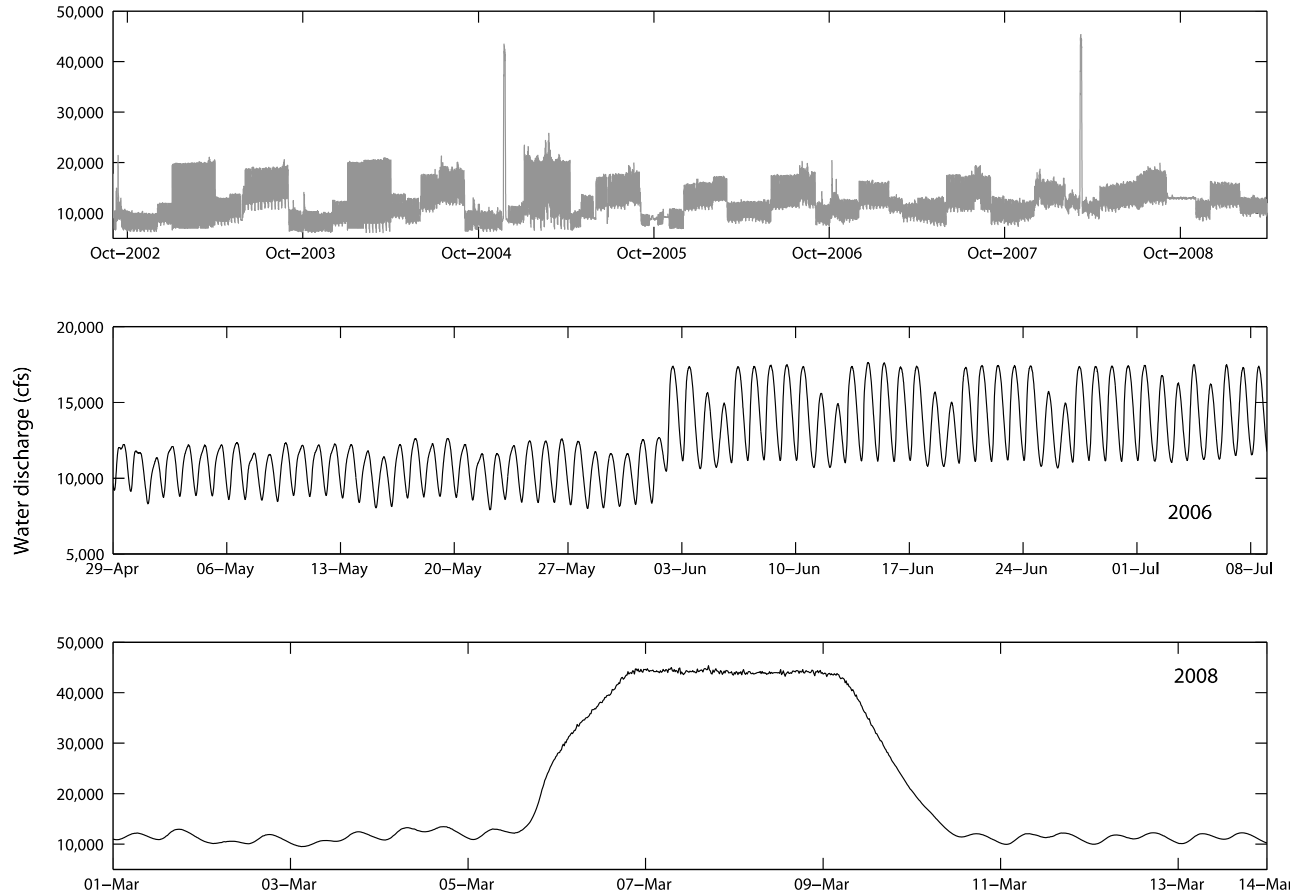

Figure 2. Examples of the flow regime below Glen Canyon Dam. (top) September 2002 through March 2009, which is the entire period of model application. (middle) Daily fluctuating flows in the spring and summer of 2006. (bottom) Controlled flood release hydrograph from March 2008.

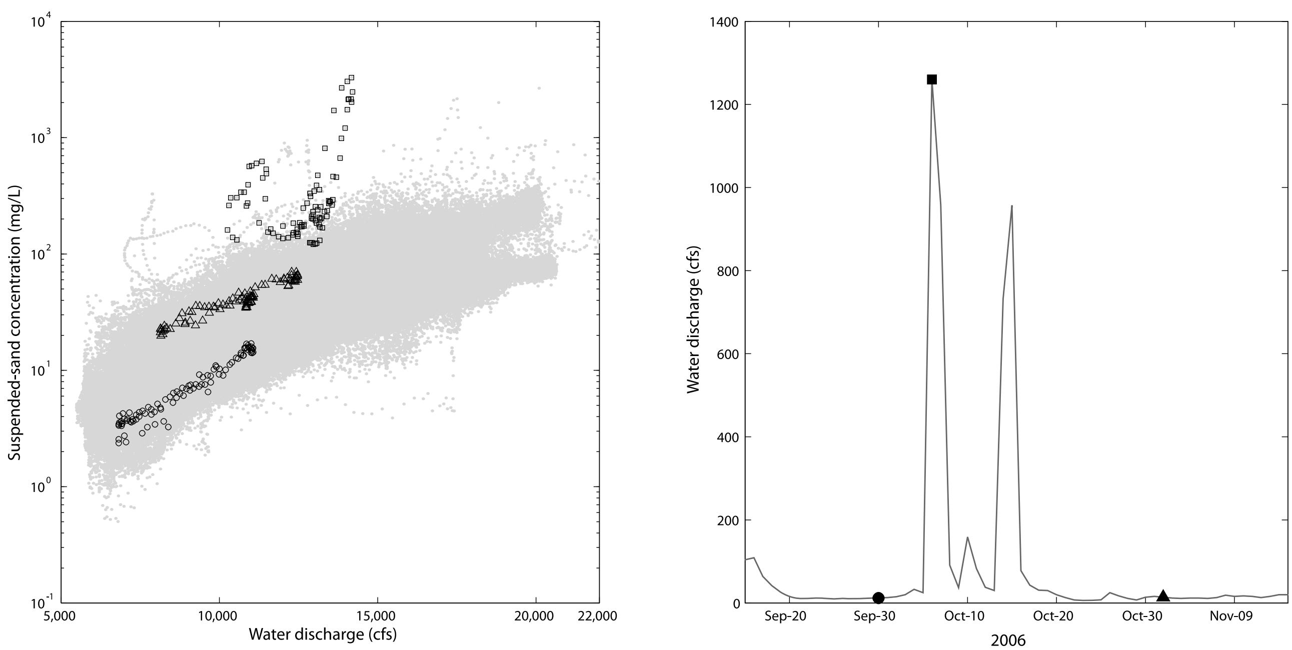

Figure 3. (left) Suspended sand concentration versus water discharge for the RM30 gage (all data—gray dots) and for 3 days before (circles), during (squares), and after (triangles) Paria River flooding during October 2006. (right) Paria River daily mean discharge showing the dates of the highlighted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

[*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' (nonsediment augmentation) operation that will restore and maintain eddy sandbar habitats over decadal time scales?"

3. Modeling Approach

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

[12] 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 Figure 3).

[13] 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.

[14] 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.

[15] 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.

[16] *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 equation (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 equation (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 ($\Sigma F_{bi} = 1$), and A is an empirical, site-specific constant (discussed further in the next section). Note that equation (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 equation (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].

[17] Application of equation (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) that further supports the assumption of complete mixing of the sand layer (although 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 nonerodible and that the sand layer thickness (H_s) is

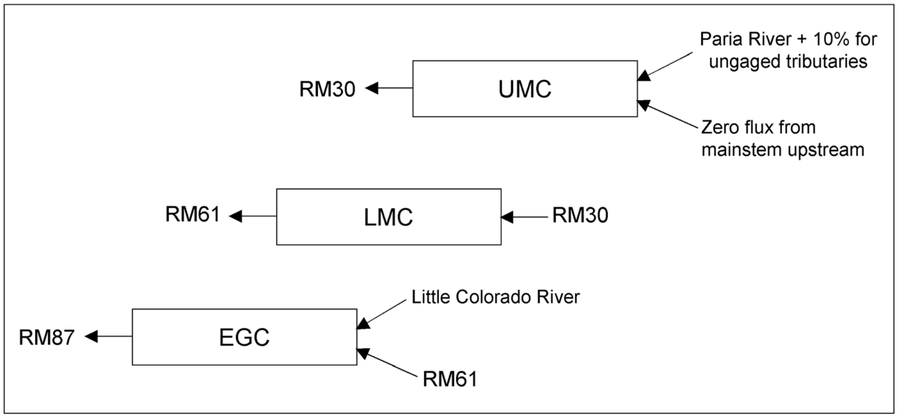

Figure 4. Schematic diagram of the three modeling reaches indicating sand inputs and export from each reach. UMC, LMC, and EGC refer to upper Marble Canyon, lower Marble Canyon, and eastern Grand Canyon, respectively (see Figure 1).

equivalent to the active layer thickness (i.e., it is completely mixed and available to the flow), the Exner equation reduces to

$$\left(1-\lambda_{\mathrm{p}}\right)B\frac{\partial H_{\mathrm{s}}}{\partial t}=-\frac{\partial Q_{\mathrm{s}}}{\partial x} \tag{3}$$

$$\left(1-\lambda_{\mathrm{p}}\right)B\frac{\partial}{\partial t}\left(H_{\mathrm{s}}F_{\mathrm{b}i}\right)=-\frac{\partial Q_{\mathrm{s}i}}{\partial x}, \tag{4}$$

where $Q_{\mathrm{s}} = CQ$, $C = \Sigma C_i$, $Q_{\mathrm{s}i} = C_iQ$, B is channel width, and λ_{p} is bed porosity. Note that equation (3) is the result of integrating equation (4) over the entire bed sediment particle size distribution since $\Sigma F_{\mathrm{b}i} = 1$ and $\Sigma Q_{\mathrm{s}i} = Q_{\mathrm{s}}$. 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.

[18] The nonerodible substrate (bedrock, gravel, cobble) 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 is available for transport, the reach becomes exhausted of that size such that $F_{\mathrm{b}i} = 0$ 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., equation (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 equation (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].

[19] The set of equations (2)–(4) constitutes a model for C_i, H_s, and $F_{\mathrm{b}i}$, so long as water discharge can be estimated or modeled independently. The boundary conditions are $Q_{\mathrm{s}i}$ at the upstream boundary and major tributaries; required initial conditions are H_s and $F_{\mathrm{b}i}$ 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 Figure 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 equation (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 Figure 1 and schematically in Figure 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 equations (3)–(4), with the following specifications: 15 min time step, 20 particle sizes spaced logarithmically between 0.0625 and 2 mm, B = 80 m, and λ_{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.

4. Estimation of Model Parameters

[20] Application of the modeling approach requires specification of the coefficients in equation (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.

[21] The time period of available high-resolution sand transport data extends from September 2002 through March 2009. For purposes of model calibration and validation, this period was split roughly equally into two parts. The calibration period was from September 2002 through March 2006, and the validation period was from April 2006 through March 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 equation (2); the calibration and validation procedure is described in detail below following definition of the boundary and initial conditions.

4.1. Boundary Conditions

[22] 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 Figure 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 σ_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.

[23] Water discharge time series must also be specified at the downstream end of each reach (i.e., at RM30, RM61, RM87) for application of equation (2). For the modeling period, discharge was estimated at each site from 15 min 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].

4.2. Initial Conditions

[24] Solution of equations (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 to 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, 2007) 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

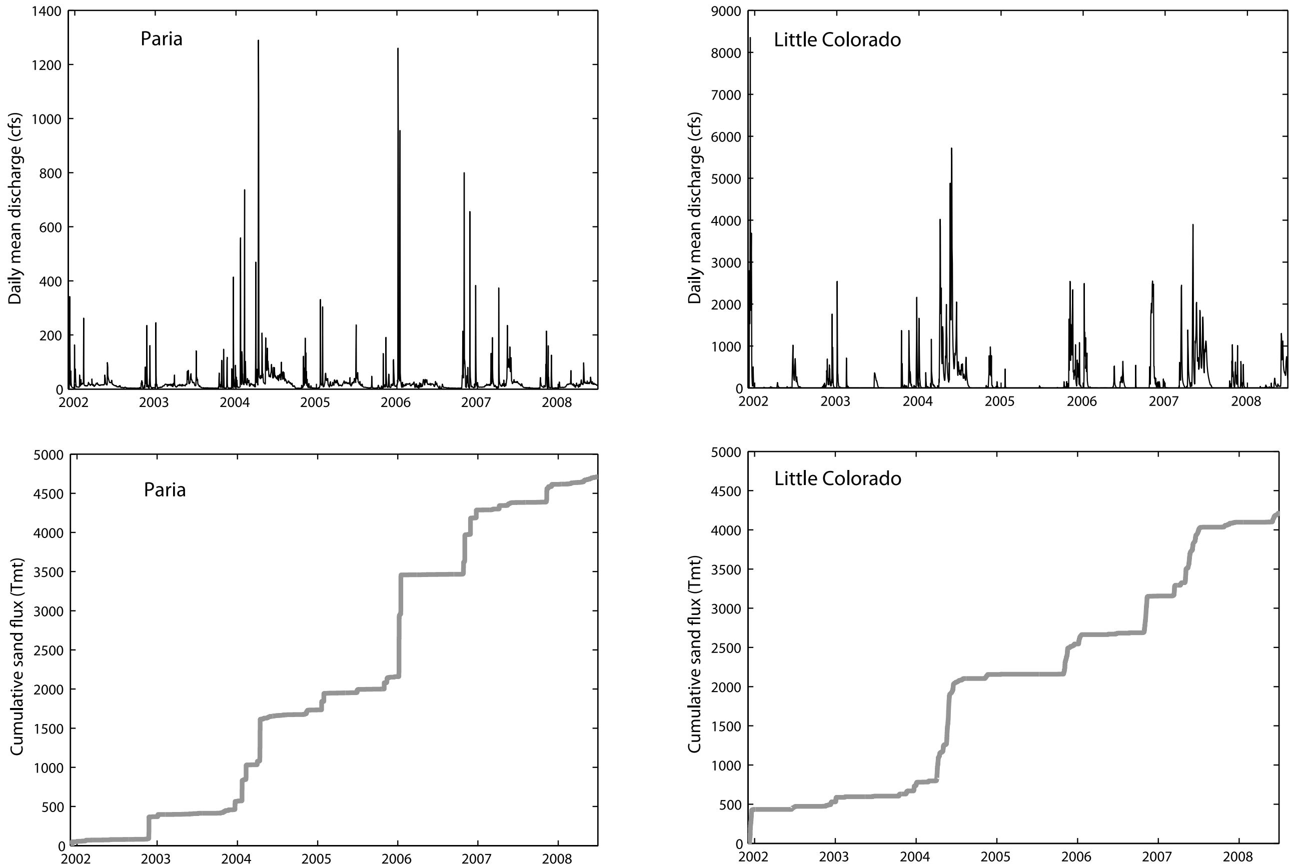

Figure 5. (top) Daily mean discharge for the (left) Paria and (right) Little Colorado rivers during the study period. (bottom) Cumulative sand fluxes into the mainstem Colorado River. Tmt denotes thousand metric tons. *x* axis ticks are at the beginning of each water year (1 October).

σ_g = 2.0 (estimated from available grab samples from the gage locations). The initial conditions are summarized in Table 1.

4.3. Transport Relation Parameters

[25] Three parameters (*A*, *L*, and *K*) must be specified to apply equation (2), on a site-specific basis. We estimated these parameters using the high-resolution (every 15 min) 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 online at http://www.gcmrc.gov/products/other_data/. Figure 6 shows suspended sand concentration versus water discharge for the study period (September 2002 to March 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 Figure 6 are power law curves based on our empirical estimates of the discharge exponents (*L* in equation (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 that is a reasonable assumption for our

Table 1. Initial Conditions for the Reaches and Model Parameters at the Computation/Monitoring Sites[a]

	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	4.3×10^{-26}	6.2×10^{-27}	6.1×10^{-26}

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

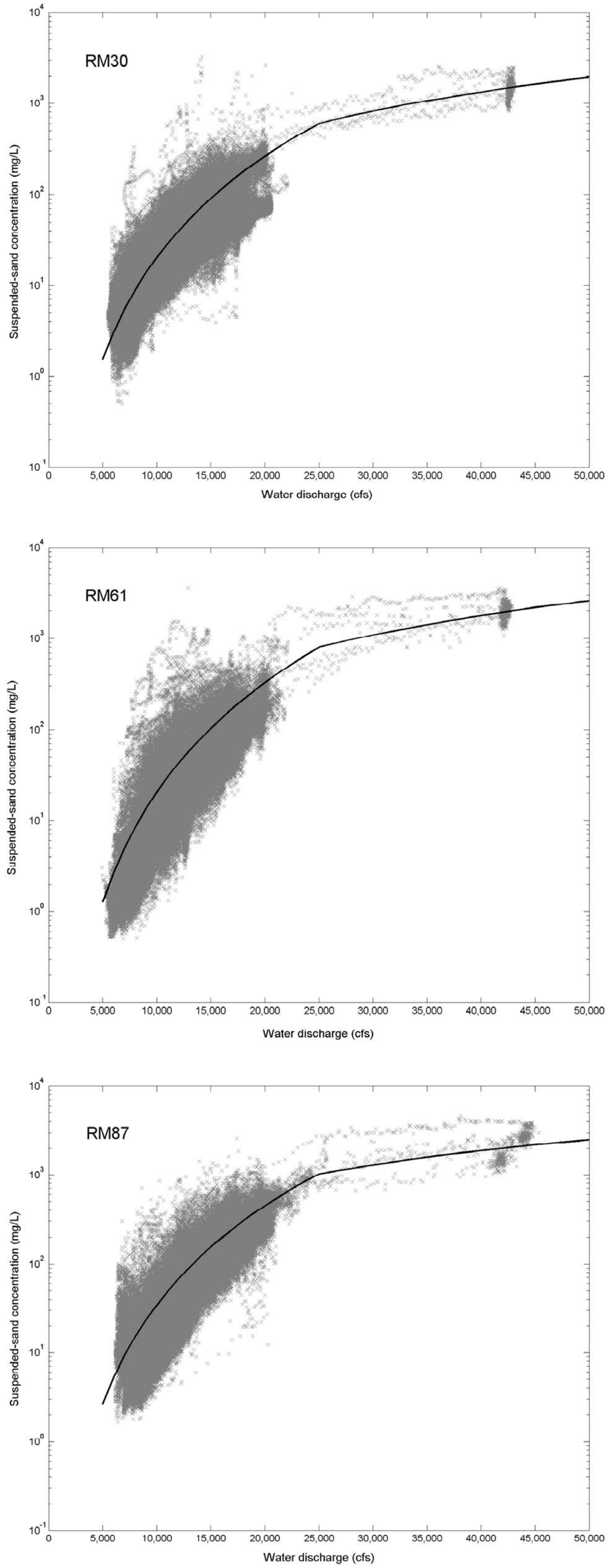

Figure 6. Suspended sand concentration versus water discharge as measured at the three monitoring sites between September 2002 and March 2009 and relations derived from equation (2) with the exponents given in Table 1.

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).

[26] The particle size exponent in equation (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.

[27] There are several options for estimating the remaining coefficient in equation (2), the proportionality constant A. Because the ultimate goal of our modeling was to predict multi-year sand budgets for the individual reaches, we chose to calibrate A at each gage location to match the measured total sand flux from the reach over the calibration time period, September 2002 through March 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 equation (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 equation (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 (equation (2)) and it thus has a direct influence on modeled sand fluxes.

5. Analysis and Discussion of Results

[28] 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 (Figure 3). High-flow

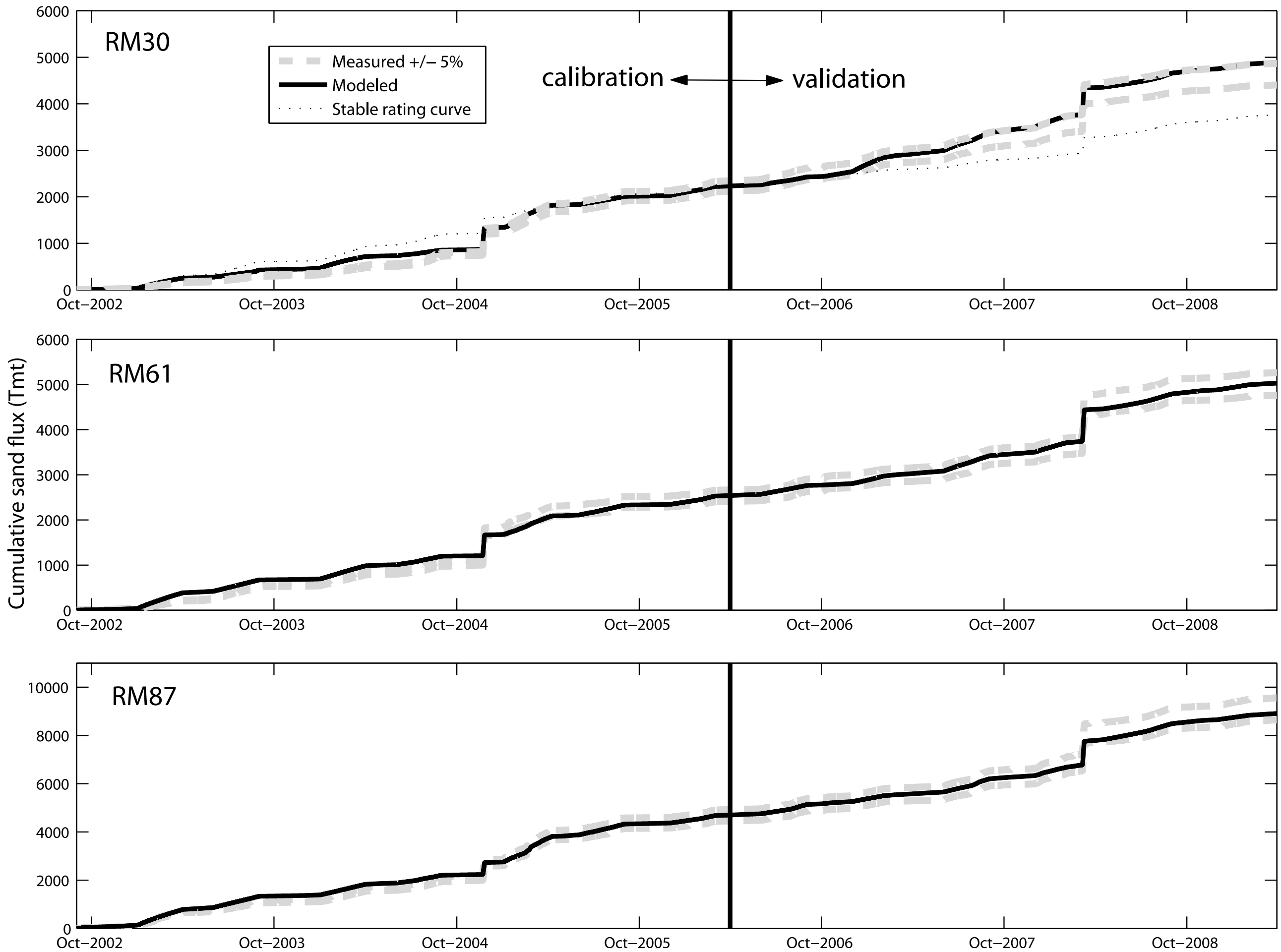

Figure 7. Comparison of measured and modeled cumulative sand fluxes at the three monitoring sites for the entire modeling period (calibration and validation). Measured fluxes are shown as an envelope with ±5% uncertainty [*Topping et al.*, 2000]. For RM30, the model results using a stable rating curve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

releases occurred in November 2004 and March 2008 (Figure 2).

[29] 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. Although the model overestimates the flux at RM30 by 11%, it is a substantial improvement over a stable sand rating curve which underestimates this flux by 37% because it cannot incorporate bed fining due to large Paria River flooding in October 2006. A variety of reasons could explain the model overestimates 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 Figure 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.* [2000], and this envelope is included in Figure 7.

5.1. Monthly Sand Flux and Annual Sand Budgets

[30] Water discharge varies substantially on a monthly basis below Glen Canyon Dam 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 Figure 8 for both calibration and validation periods. While the model captures the general behavior well, there is substantial variability and some indication of model overestimation 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

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)[a]	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

[a]First value is calibration, value in parentheses is validation.

better than at RM61). The agreement during the calibration period is generally slightly better than during the validation period, as expected, although 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.

[31] 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, Figure 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 (Figure 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.

5.2. Accumulation/Fining and Erosion/Coarsening

[32] 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 Figure 10 that shows the modeled sand thickness (top), median bed particle size (D_{50}, middle), and cumulative sand budget (bottom) for the upper Marble Canyon reach. Figure 10 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 Figure 2), which resulted in more than 1×10^6 metric tons of sand accumulation in the reach (Figure 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 (Figure 10, top and middle). The measurements exhibit greater variability, particularly in the period leading up to and following the November 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 (Figure 10, top) and bed D_{50} (Figure 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 second tributary flood would result in the same increase in sand thickness as the first flood but proportionately less fining since it's mixing with an initially finer bed).

[33] The controlled flood releases in November 2004 (during the calibration period) and March 2008 (during the validation period) provide excellent tests of the model's ability to simulate sand erosion and coarsening of the bed. Although 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 Figure 11 that 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 that 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 March 2008 hydrograph is shown in Figure 2; the November 2004 hydrograph was nearly identical). There is a general tendency, however, for the model to underestimate 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

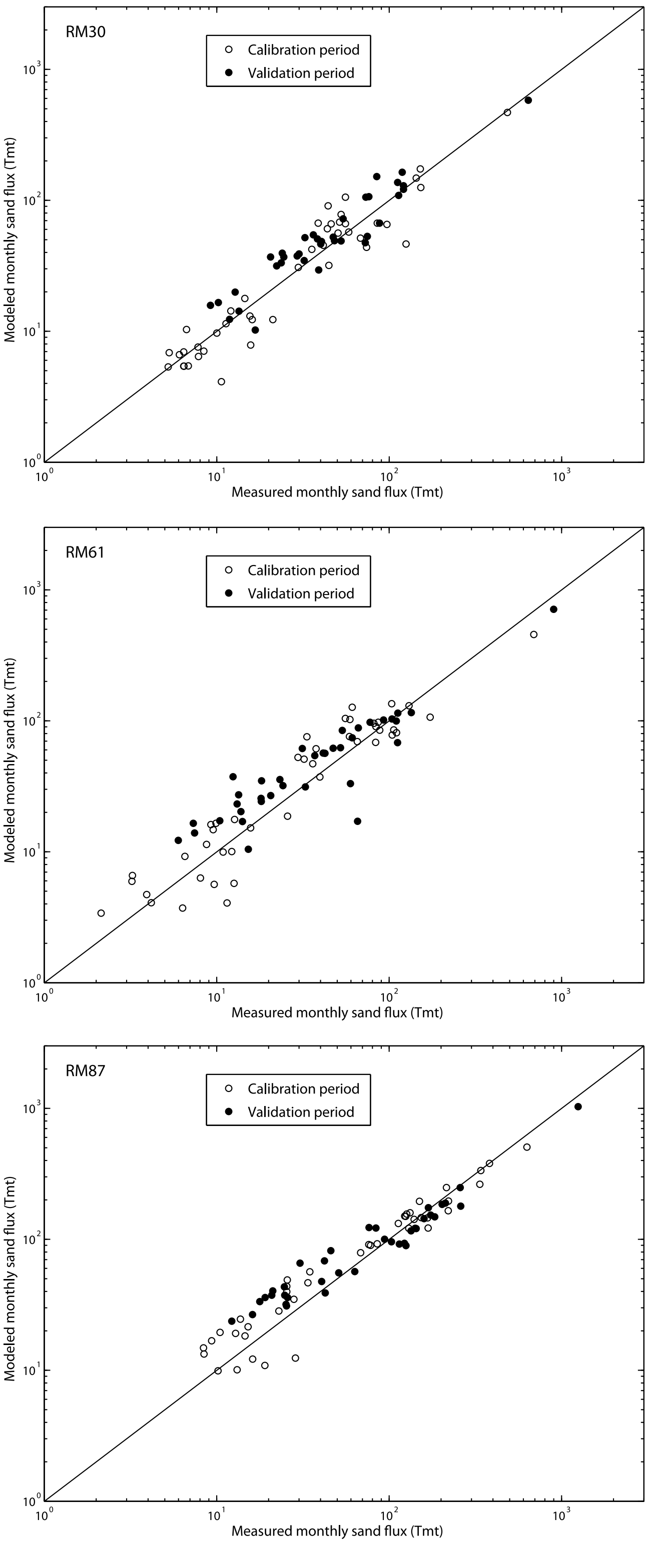

Figure 8. Comparison of measured and modeled monthly sand fluxes at the three monitoring sites ((top) RM30; (middle) RM61; (bottom) RM87) for the calibration and validation periods; line indicates perfect agreement. Statistics are given in Table 2.

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 distributions 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.

6. Sensitivity Analysis

[34] 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 equation (2)), (6) discharge exponent (L in equation (2)), (7) bed-sand particle size exponent (K in equation (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 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.

[35] 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 (September 2002 through March 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 Figure 12, it is immediately apparent that the rating-curve exponents (L and K in equation (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% to 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%).

[36] It is perhaps not surprising that the exponents exert such strong influence, given that they are substantially greater than one resulting in a highly nonlinear 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

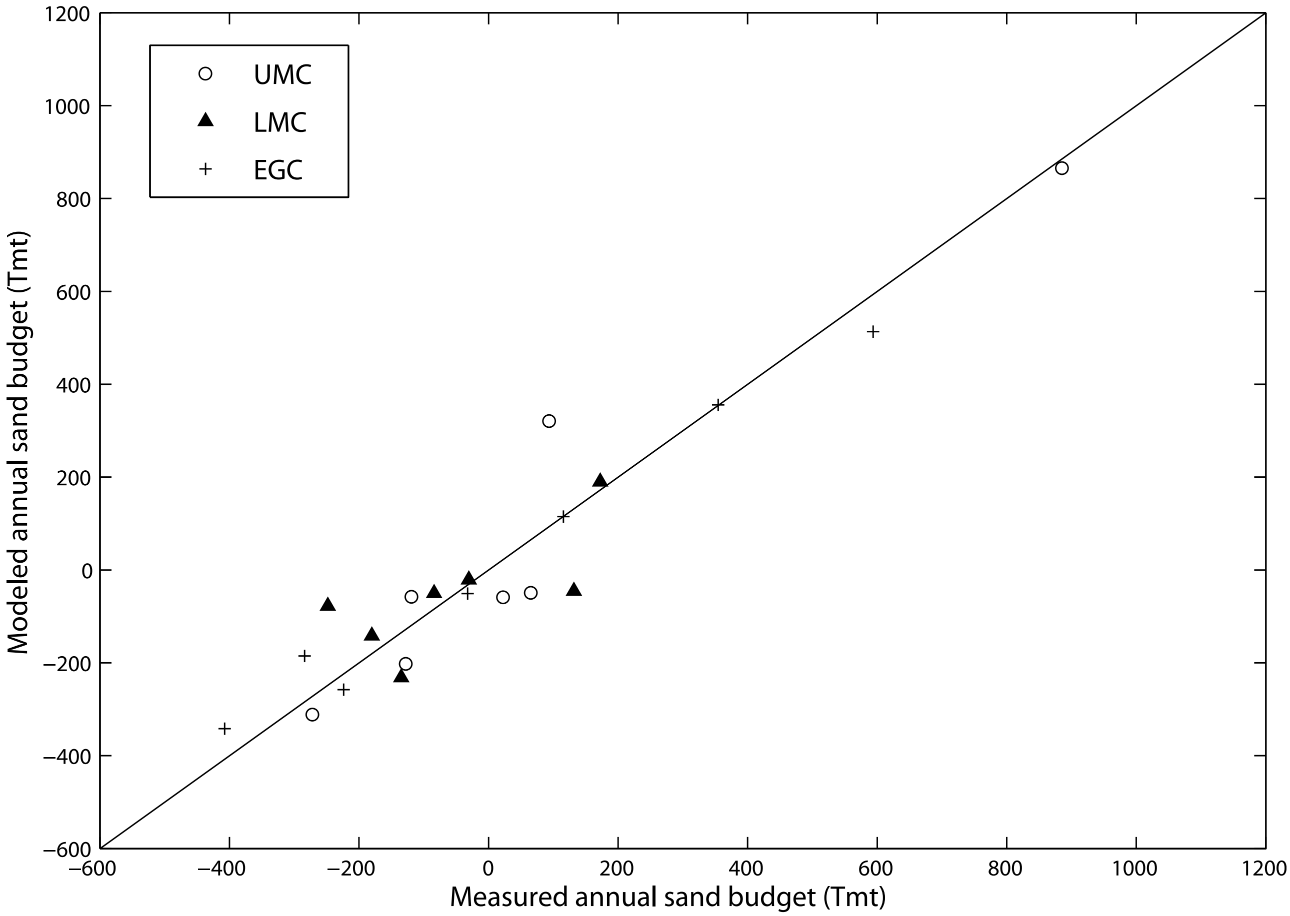

Figure 9. Comparison of measured and modeled annual sand budgets for the three reaches. The annual sand budget is defined as sand inputs minus export from the reach (based on water year), i.e., the change in storage on a mass basis.

similar sediment-transport formula whereby concentration or flux is dependent on hydraulic variables (and particle size) in a highly nonlinear 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.

7. Limitations of the Approach

[37] 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:

[38] •Although 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.

[39] •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.

[40] •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.

[41] •Although the model uses a short (15 min) time step to capture the subdaily 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., Figure 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 Figure 3 (squares), an unsteady, advection-dispersion approach for suspended sediment would likely be required.

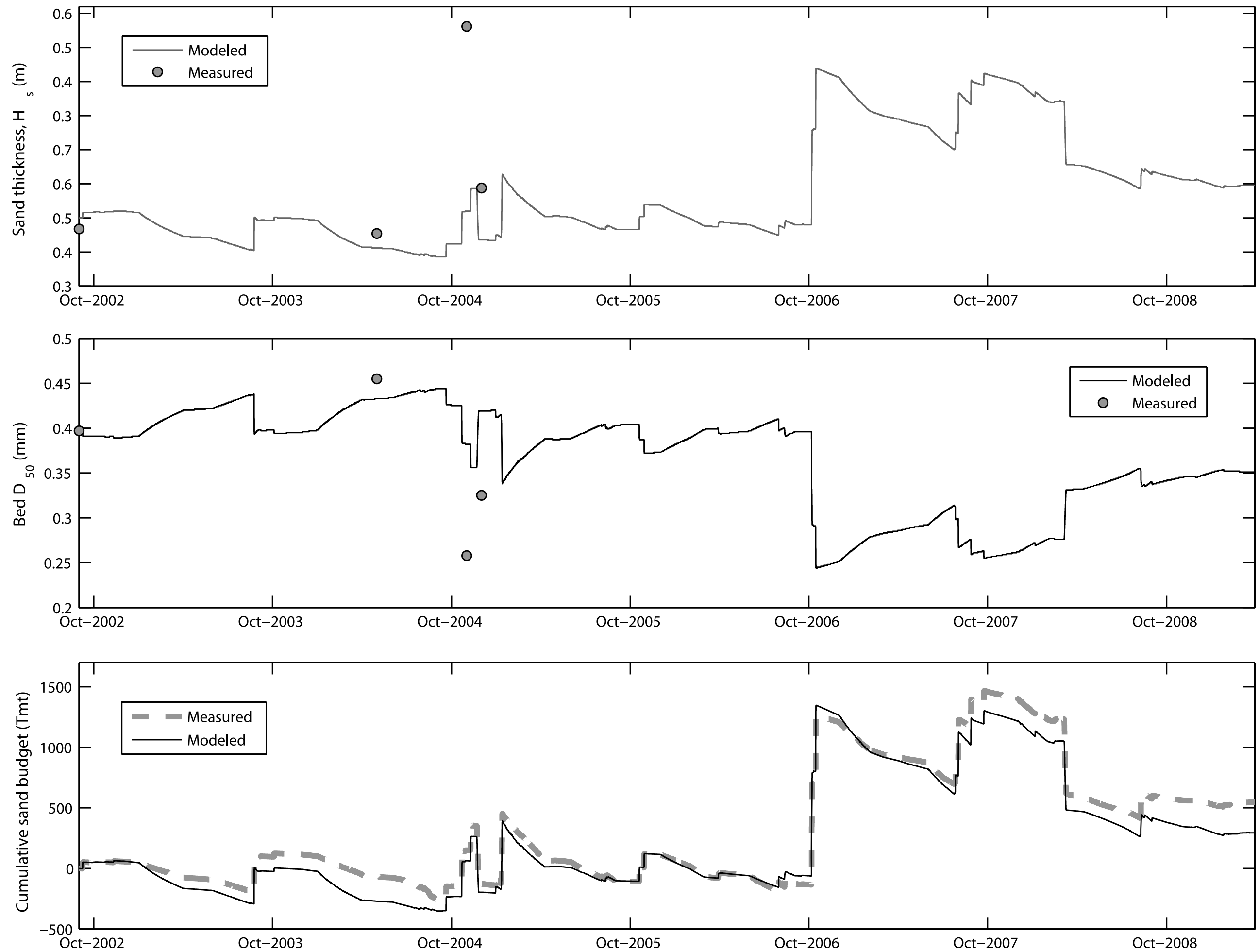

Figure 10. Time series of (top) measured and modeled sand thickness, (middle) bed median particle size, and (bottom) cumulative sand budget for the upper Marble Canyon (UMC) reach. Data sources are described in the text.

[42] •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.

[43] •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.

[44] 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 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.

8. Conclusions

[45] The modeling approach described herein represents a compromise between a desire for model simplicity, 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

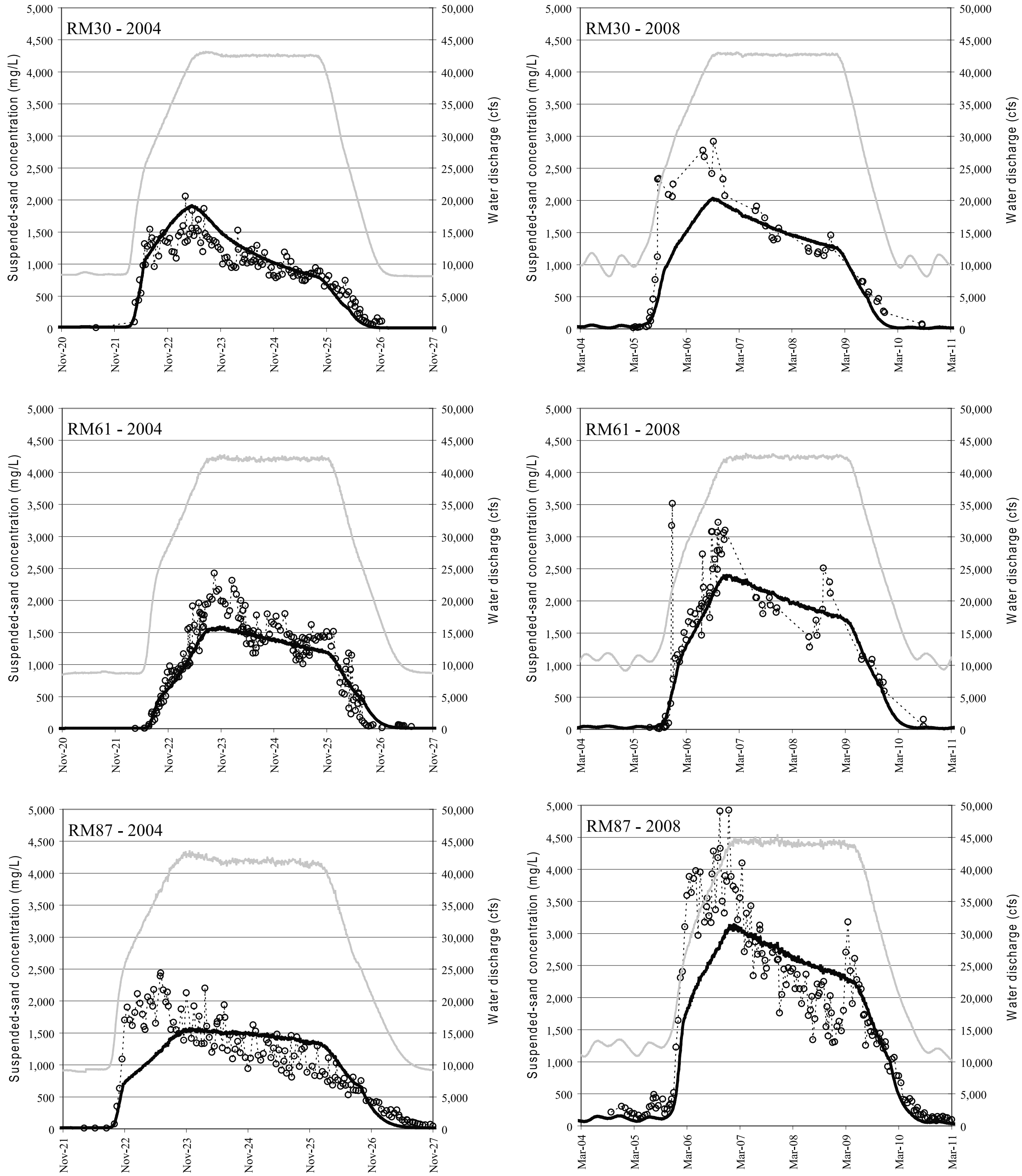

Figure 11. Comparison of measured (circles) and modeled (solid black lines) suspended sand concentration at the three monitoring sites during high-flow releases in November 2004 (during calibration period) and March 2008 (during validation period). The high-flow hydrographs are shown light solid lines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

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 s on a standard desktop computer.

[46] The model was applied to the reach of the Colorado River below Glen Canyon Dam for the period September 2002 through March 2009. The model was calibrated such

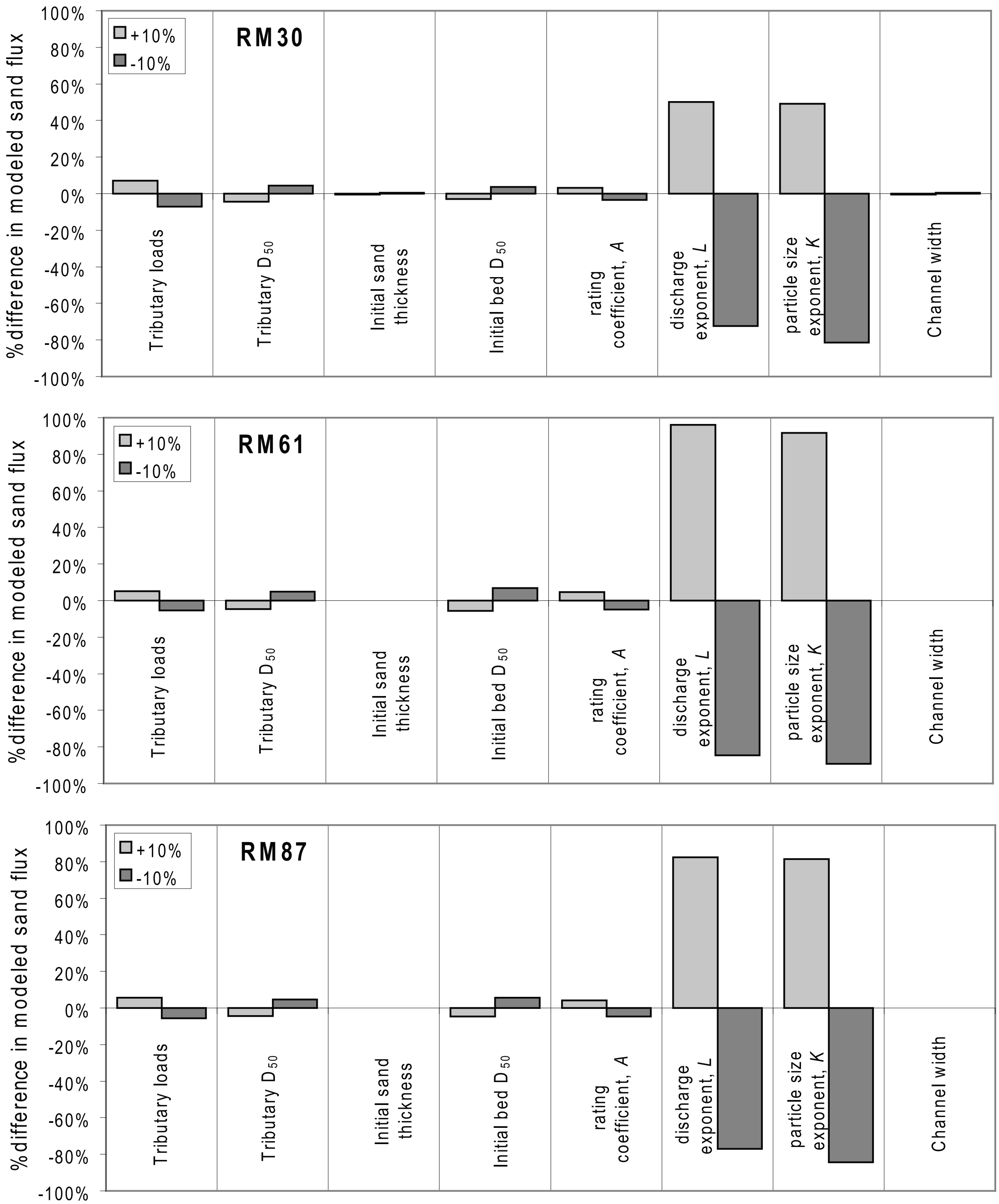

Figure 12. Results of model sensitivity analyses for the three gage sites. The *y* axis portrays the percent difference between the given scenario and the fully calibrated model, for variations in each parameter of ±10%.

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 November 2004 and March 2008 indicate that the model can adequately simulate bed coarsening during the peak flows but tends to underestimate 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.

[47] 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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T. S. Melis and D. J. Topping, U.S. Geological Survey, Grand Canyon Monitoring and Research Center, Flagstaff, AZ 86001, USA.

D. M. Rubin, U.S. Geological Survey, Pacific Science Center, Santa Cruz, CA 95060, USA.

S. A. Wright, U.S. Geological Survey, California Water Science Center, Sacramento, CA 95819, USA. (sawright@usgs.gov)