Numerical Modeling of Mud Transport, Storage, and Release on the Colorado River, Arizona

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Extended Abstract

Introduction

Glen Canyon Dam on the Colorado River has had major impacts on downstream hydrology, sediment transport, and geomorphology, thereby impacting the aquatic and riparian ecosystems. Predictive models are currently used to estimate the accumulation and evacuation of sand and to design controlled floods to redistribute sand from the riverbed and rebuild sandbars (Wright et al., 2010; Mueller et al., 2021). Although sand is the primary component of most fine-sediment deposits, there is increasing interest in mud (silt and clay) transport in Grand Canyon due to its effect on turbidity, which has been shown to affect native and non-native fish (Ward et al., 2016). Mud is predominantly supplied by tributary floods. While most of the mud washes downstream, some mud is trapped within the bed and in bar deposits and potentially released later, increasing turbidity (Deemer et al. 2022). Here we present preliminary results from a one-dimensional model being developed for predicting fine sediment concentrations (sand, silt, and clay) in the Colorado River downstream of Glen Canyon Dam.

Methods

The model includes sediment advection, eddy exchange, exchange with the bed, and storage/release from bar deposits. The mass conservation equation for suspended sediment can be written:

$$\frac{\partial hBc_i}{\partial t} = -\frac{\partial uhBc_i}{\partial x} + Bw_{si}(E_i - c_{bi}) + S_{ei}\ , \tag{1}$$

where c_i is the suspended sediment concentration (SSC) of grain size class i, h is the flow depth, B is channel width, u is depth-averaged flow velocity, w_{si} is the settling velocity, E_i is bed sediment entrainment, c_{bi} is near-bed suspended sediment concentration, S_{ei} is a source/sink term associated with channel/eddy exchange, t is time, and x is down-channel distance. We modeled eddy exchange as a spatially continuous process, governed by:

$$S_{ei} = \lambda B_e h_e (c_{ei} - c_i) \tag{2}$$

and

$$\frac{\partial h_e B_e c_{ei}}{\partial t} = \lambda(c_i - c_{ei}) + S_{Bi} \tag{3}$$

where λ is the eddy exchange coefficient, B_e is a characteristic eddy width, h_e is a characteristic eddy depth, c_{ei} is the eddy SSC, and S_{Bi} is a source/sink term for exchange between the eddy and the eddy bar deposit.

We explored several models for bed/flow exchange in the main channel, the simplest of which is the Hirano (1971) active layer model with a fixed active layer thickness:

$$\frac{\partial F_i}{\partial t} = \frac{1}{L_a(1-p)}\left((c_{bi} - E_i)w_{si} - \frac{\partial q_{bi}}{\partial x}\right) - f_{li}\frac{\partial \eta}{\partial t} \quad , \tag{4}$$

where F_i is the fraction of the bed active layer belonging to grain size class i, L_a is the active-layer thickness, p is the bed porosity, q_{bi} is the bed load flux, f_{li} is the bed grain size fraction of class i at the interface between the bottom of the active layer and the substrate below, and η is the bed elevation. During deposition ($\frac{\partial \eta}{\partial t} > 0$), f_{li} is equal to the active layer fraction F_i, whereas during erosion ($\frac{\partial \eta}{\partial t} < 0$), it is based on the grain size distribution of the substrate, which is tracked with a stratigraphy submodel. Bed elevation change is calculated according to mass conservation (Parker et al. 2004):

$$\frac{\partial \eta}{\partial t} = \frac{1}{1-p}\sum_i\left((c_{bi} - E_i)w_{si} - \frac{\partial q_{bi}}{\partial x}\right). \tag{5}$$

Solving equation (1) requires expressions for entrainment E_i and near-bed concentration c_{bi}. A common approach in modeling suspended sediment is to assume local equilibrium between E_i and c_{bi} and compute the bed/flow exchange based on the divergence of the suspended sediment flux in the streamwise direction. However, this approach fails for modeling advection of mud and very fine sand, as it incorrectly predicts that sediment pulse propagation is entirely mediated via the bed (An et al. 2018), whereas fine sediment can potentially be advected kilometers downstream with minimal interaction with the bed (i.e. washload). Instead, we allow for the possibility of disequilibrium between c_{bi} and E_i. Results shown in this abstract use Wright and Parker (2004) to compute E_i, but we have obtained similar results with formulae such as De Leeuw (2020). In order to compute c_{bi}, we assumed that the vertical concentration profile followed a Rouse distribution. Although this assumption is not strictly valid in the presence of spatial and temporal gradients in SSC, tests with a 2D (x-z) model (e.g. Stansby et al. 1998) indicated that this assumption is reasonable for the time and spatial scales of interest, and using a 1D model allows for much faster computation. Finally, the bedload transport rate was computed with Wong and Parker (2006) correction to the Meyer-Peter Muller formula:

$$q_{bi} = 3.97F_i d_i\sqrt{Rgd_i}(\tau_{*sk} - 0.0495\xi_i), \tag{6}$$

where q_{bi} is the bedload flux, d_i is the grain size of fraction i, $R = 1.65$ is the submerged density of quartz, g is gravitational acceleration, τ_{*sk} is the skin friction shear stress, and ξ_i is a hiding function.

To drive the sediment transport components above, we used the 1D hydrodynamic model EPA SWMM (Storm Water Management Model; Rossman, 2006), applied to the Colorado River by Mihalevich et al. (2020). The model solves the complete unsteady form of the 1D St. Venant equations (Chow 1959), and uses the channel cross sections of Magirl et al. (2008). The SWMM model is used to generate the shear stresses, velocities, and depths used to drive the sediment model. We used a one-way coupling, i.e. the hydrodynamics affect the sediment transport but we did not include changes in channel cross section due to deposition or erosion that could feed back on the hydrodynamics. This approximation is likely reasonable in a supply-limited canyon like the Colorado River and over the short time scales of interest (< 1 year).

Results and Discussion

We used acoustic-derived sand and mud concentrations to provide the model boundary condition at River Mile (RM; miles downstream of Lees Ferry) 30, and to test the model sediment routing at RM61 (U.S. Geological Survey, 2023). Acoustic-derived sand concentration measurements made following tributary floods show that the finest sand fractions supplied during these floods travel only slightly slower than the tributary-generated mud pulse in the Colorado River for hundreds of kilometers, despite estimated advection lengths (characteristic distance a particle travels in suspension before exchanging with the bed) of less than a kilometer. This fast-moving component of a sand pulse is termed “Packet A” by Topping et al. (2018), in contrast to the slower-moving “Packet B” which works its way down canyon in the months following a tributary flood (Topping et al., 2021). Acoustic-derived sediment concentrations show evidence of Packet A. For instance, as shown in Figure 1a, during periods of relatively steady dam operations, peaks in mud and sand traveling through RM30 arrive downstream at RM61 at nearly identical times. Although this effect is often concealed by sand concentration variation induced by daily discharge fluctuations, it is confirmed by cross-covariance analysis (Figure 1b). We hypothesize that the existence of a fast-moving sand component is a result of exchange of sand between the flow and the bed facilitated by a thin bed surface layer immediately following tributary floods, with deeper bed mixing occurring over longer time-scales due to bedform migration. We have implemented 2-layer versions of the bed exchange model to try to capture this effect; however, calibration of the 2-layer version is ongoing.

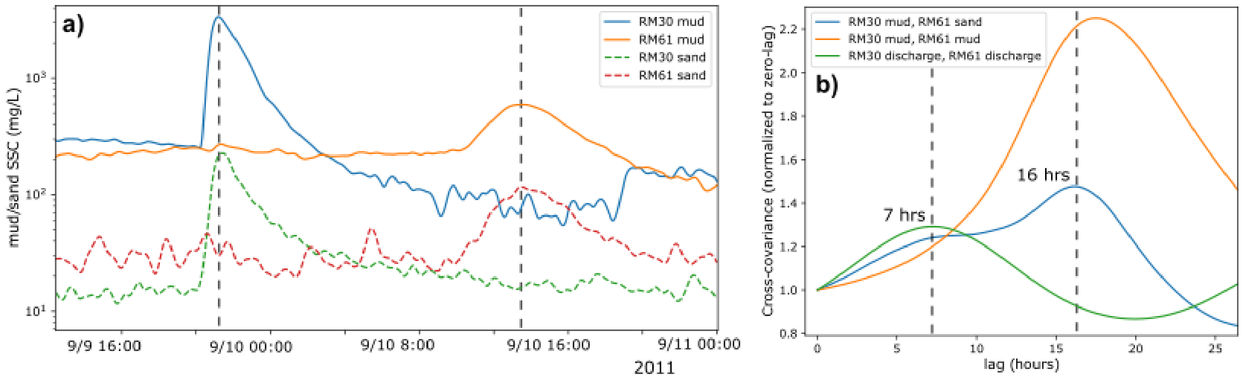

Figure 1: a) Acoustic-derived mud and sand concentrations at RM30 and RM61. Lines highlight the alignment between concentration spikes. These spikes typically take ~16 hours to reach RM61 from RM30. Mud and sand components of the tributary-derived sediment pulse travel between RM30 and RM61 at similar speeds. This example occurred during a period of relatively high and steady discharge (~16,000 cfs with minimal fluctuations). b) Cross-covariance analysis between RM30 and RM61. Blue line shows cross-covariance between mud at RM30 and sand at RM61, showing a peak at 16 hours corresponding to the time for a tributary sediment pulse to travel between the two gages. By using mud at RM30 and sand at RM61 rather than sand at both gages, we isolate the propagation of tributary-derived sediment pulses rather than discharge-driven fluctuations, which are much larger in sand than mud. The orange line shows the cross-covariance of mud SSC between the two gages, and the green line shows the cross-covariance of discharge between the two gages. Discharge waves travel significantly faster (~7 hrs) than the water itself (~16 hours indicated by the travel time of sediment pulses). A potential explanation for the slight difference in lag between the mud/sand and mud/mud peaks is that sand can only travel as washload when the discharge (and hence water velocity) is sufficiently high.

Comparison between model results and acoustic-derived time series of silt/clay concentration indicate that including exchange between the main channel and flow recirculation zones (eddies) is essential for accurately modeling the timing and attenuation of mud pulses as they travel downstream (Figure 2). We find that eddy exchange both slows and attenuates mud pulses.

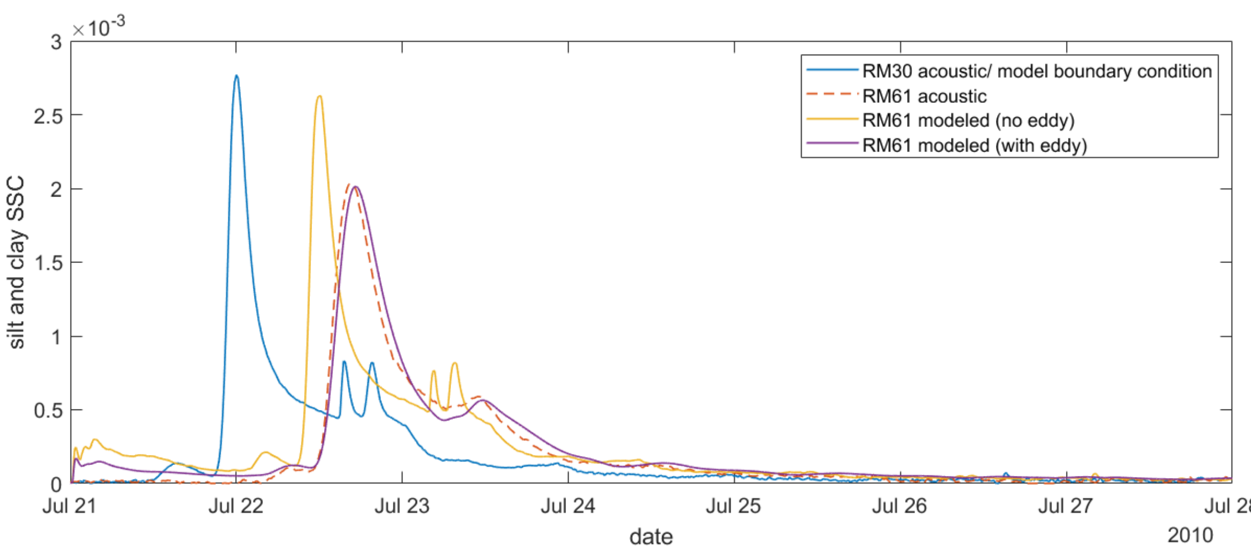

Figure 2: Comparison of modeled and acoustic-derived mud SSC for the River Mile 30 to 61 reach. Model results with and without eddy exchange (exchange rate = 10^{-3} s^{-1}) are shown.

Finally, analysis of acoustic-derived silt/clay measurements indicates that a small percentage of the mud from tributary pulses is trapped within bed and bar deposits and gradually released. Discharges above 15,000 cfs are associated with faster release of silt/clay from bed and bar deposits. For instance, as shown in Figure 3, the 2012 High Flow Experiment (HFE) caused a spike in turbidity, presumably due to erosion of mud from the bed and bars (U.S. Geological Survey, 2023). Nevertheless, the increase in peak flows caused by the change in dam operations on December 1 led to an increase in turbidity, suggesting that some mud is retained even after high flows. Taking the 2013 HFE as an example, model results are consistent with the observation that dam operations such as HFE's release mud, but underestimate the magnitude of mud release (Figure 4). We hypothesize that this is due to an inadequate treatment of sandbar erosion in the model. We are working to implement a discharge-dependent erosion rule which will better capture the magnitude of mud release associated with discharge increases.

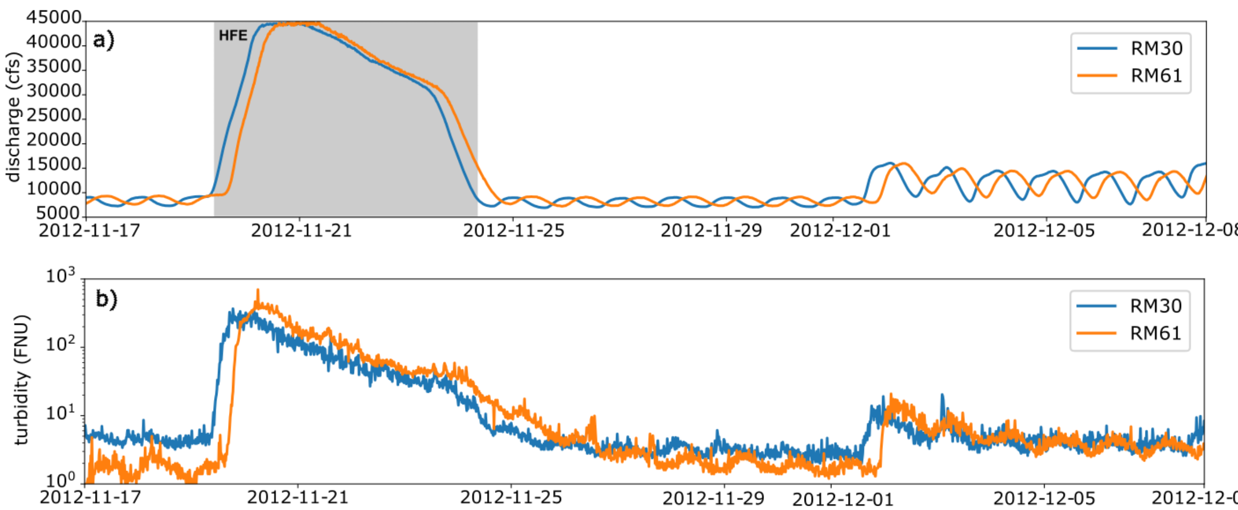

Figure 3: a) Discharge (HFE indicated with gray rectangle) and b) turbidity during 2012 HFE. Note the turbidity increase in response to the HFE, and smaller turbidity increase following the change in dam operations on December 1.

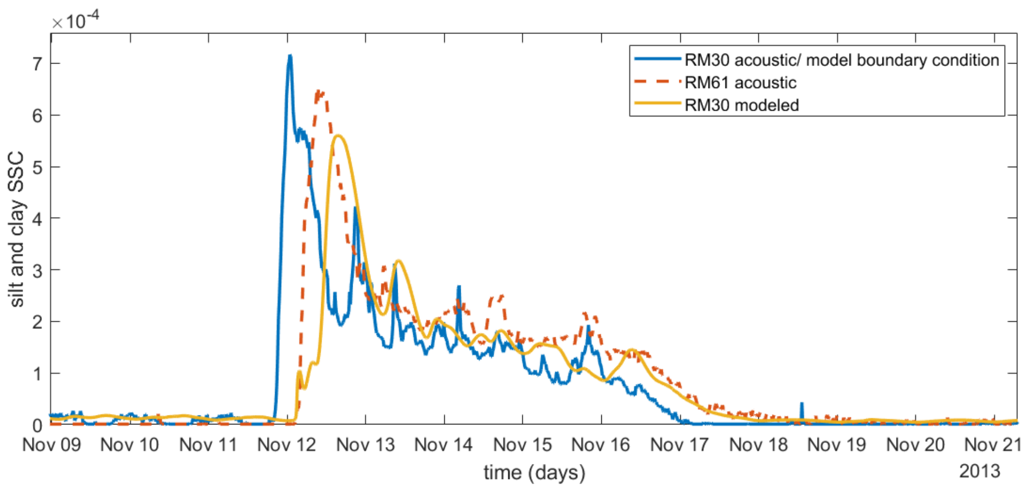

Figure 4: Comparison of modeled and measured (acoustic) mud SSC for the River Mile 30 to 61 reach during the 2013 HFE. Model results at RM61 underpredict the initial spike in mud concentration with the arrival of the discharge wave.

Our results indicate that while mud concentrations are primarily controlled by summer thunderstorm and winter tributary inputs, which reset the system by reloading bed and bar deposits with mud, discharge plays a secondary but important role in regulating mud concentrations and turbidity in the Colorado River. This work will lead to improved prediction of mud release due to discharge fluctuations, which while much smaller in magnitude than mud supplied by tributary events, can elevate turbidity to biologically significant levels. Additionally, this work sheds light on more basic sediment transport mechanics, taking advantage of a highly-monitored canyon-bound system where sediment inputs and discharge fluctuations occur independently. On one hand, although mud primarily washes through the system, some is trapped in deposits and subsequently entrained. On the other hand, the transport of sand is mediated by exchange with the bed and bars over relatively short distances, and yet we find that a fraction of the sand at time acts more like washload. These observations suggest that rather than a sharp discontinuity between washload and bed-material load, there exists a continuum between the two. Our modeling framework shows that both endmembers can be captured with similar sediment transport physics, and provides new insight into how sediment pulses propagate in canyon-bound systems.

References

An, C., Moodie, A. J., Ma, H., Fu, X., Zhang, Y., Naito, K., & Parker, G. (2018). Morphodynamic model of the lower Yellow River: Flux or entrainment form for sediment mass conservation?. *Earth Surface Dynamics*, *6*(4), 989-1010. https://doi.org/10.5194/esurf-6-989-2018

Chow V.T., 1959. Open Channel Hydraulics. Blackburn Press, Caldwell, NJ.

De Leeuw, J., Lamb, M. P., Parker, G., Moodie, A. J., Haught, D., Venditti, J. G., & Nittrouer, J. A. (2020). Entrainment and suspension of sand and gravel. Earth Surface Dynamics, 8(2), 485-504. https://doi.org/10.1038/s41561-020-0602-5

Deemer, B. R., Yackulic, C. B., Hall Jr, R. O., Dodrill, M. J., Kennedy, T. A., Muehlbauer, J. D., ... & Yard, M. D. (2022). Experimental reductions in subdaily flow fluctuations increased gross primary productivity for 425 river kilometers downstream. *PNAS Nexus*, *1*(3), pgac094. https://doi.org/10.1093/pnasnexus/pgac094

Hirano, M. (1971). River bed degradation with armoring. *Proceedings of the Japan Society of Civil Engineers*, *195*, 55–65. https://doi.org/10.2208/jscej1969.1971.195_55

Magirl, C. S., R. H. Webb, and P. G. Griffiths (2008), Modeling water surface elevations and virtual shorelines for the Colorado River in Grand Canyon, Arizona, U.S. Geological Survey Scientific Investigations Report 2008-5075, 32 pp. https://doi.org/10.3133/sir20085075

Mihalevich, B. A., Neilson, B. T., Buahin, C. A., Yackulic, C. B., & Schmidt, J. C. (2020). Water temperature controls for regulated canyon-bound rivers. Water Resources Research, 56(12), e2020WR027566. https://doi.org/10.1029/2020WR027566

Mueller, E. R., & Grams, P. E. (2021). A Morphodynamic Model to Evaluate Long-Term Sandbar Rebuilding Using Controlled Floods in the Grand Canyon. *Geophysical Research Letters*, *48*(9), 1–10. https://doi.org/10.1029/2021GL093007

Parker, G. (2004). 1D Sediment Transport Morphodynamics with Applications to Rivers and

Turbidity Currents, available at: http://hydrolab.illinois.edu/people/parkerg/morphodynamics_e-book.htm (last access: 4/7/2023).

Rossman, L. A. (2006). Storm water management model quality assurance report: Dynamic wave flow routing. In *National risk management research laboratory, Office of Research and Development, U.S. Environmental Protection Agency* (pp. 1–115). Cincinnati, OH: U.S. Environmental Protection Agency.

Stansby, P. K., & Omar Awang, M. A. (1998). Response time analysis for suspended sediment transport. *Journal of Hydraulic Research*, *36*(3), 327-338. https://doi.org/10.1080/00221689809498622

Topping D. J., Wright S. A. 2016. Long-term continuous acoustical suspended-sediment measurements in rivers – theory, application, bias, and error. *US Geological Survey Professional Paper 1823*. https://doi.org/10.3133/pp1823.

Topping, D. J., Mueller, E. R., Schmidt, J. C., Griffiths, R. E., Dean, D. J., & Grams, P. E. (2018). Long-term evolution of sand transport through a river network: Relative influences of a dam versus natural changes in grain size from sand waves. *Journal of Geophysical Research: Earth Surface*, *123*(8), 1879-1909.

Topping, D. J., Grams, P. E., Griffiths, R. E., Dean, D. J., Wright, S. A., & Unema, J. A. (2021). Self-Limitation of Sand Storage in a Bedrock-Canyon River Arising From the Interaction of Flow and Grain Size. *Journal of Geophysical Research: Earth Surface*, *126*(5), 1–37. https://doi.org/10.1029/2020jf005565

U.S. Geological Survey, 2023, Discharge, sediment, and water quality monitoring data: Flagstaff, Ariz., U.S. Geological Survey, Southwest Biological Science Center, Grand Canyon Monitoring and Research Center, accessed March 1, 2023, at http://www.gcmrc.gov/discharge_qw_sediment/.

Ward, D. L., Morton-Starner, R., & Vaage, B. (2016). Effects of turbidity on predation vulnerability of juvenile humpback chub to rainbow trout and brown trout. *Journal of Fish and Wildlife Management*, *7*(1), 205–212. https://doi.org/10.3996/102015-JFWM-101

Wong, M., & Parker, G. (2006). Reanalysis and correction of bed-load relation of Meyer-Peter and Müller using their own database. *Journal of Hydraulic Engineering*, *132*(11), 1159-1168. https://doi.org/10.1061/(ASCE)0733-9429(2006)132:11(1159)

Wright, S., & Parker, G. (2004). Flow resistance and suspended load in sand-bed rivers: simplified stratification model. Journal of Hydraulic Engineering, 130(8), 796-805. https://doi.org/10.1061/(ASCE)0733-9429(2004)130:8(796)

Wright, S. A., Topping, D. J., Rubin, D. M., & Melis, T. S. (2010). An approach for modeling sediment budgets in supply-limited rivers. *Water Resources Research*, *46*(10), 1–18. https://doi.org/10.1029/2009WR008600