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

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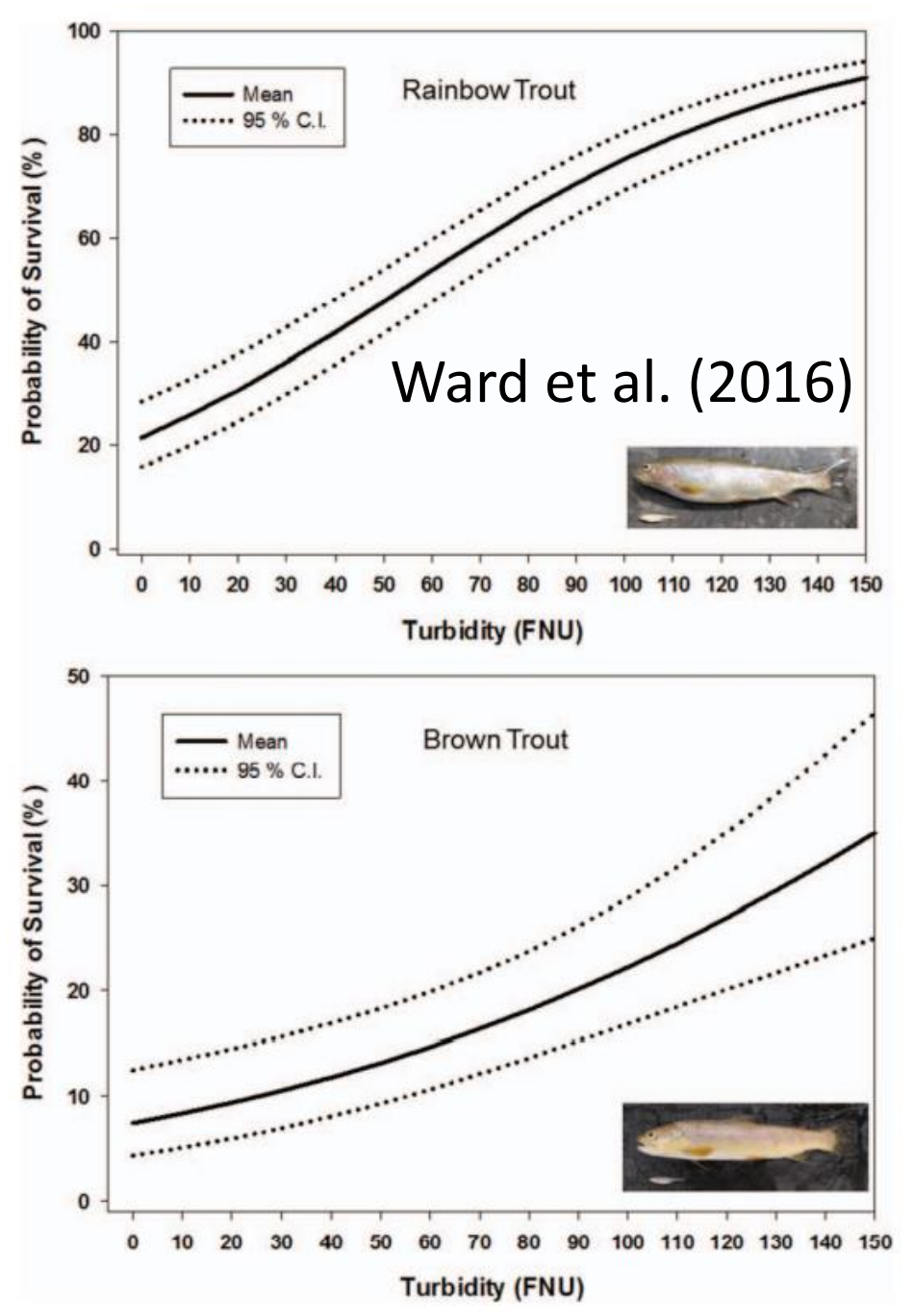
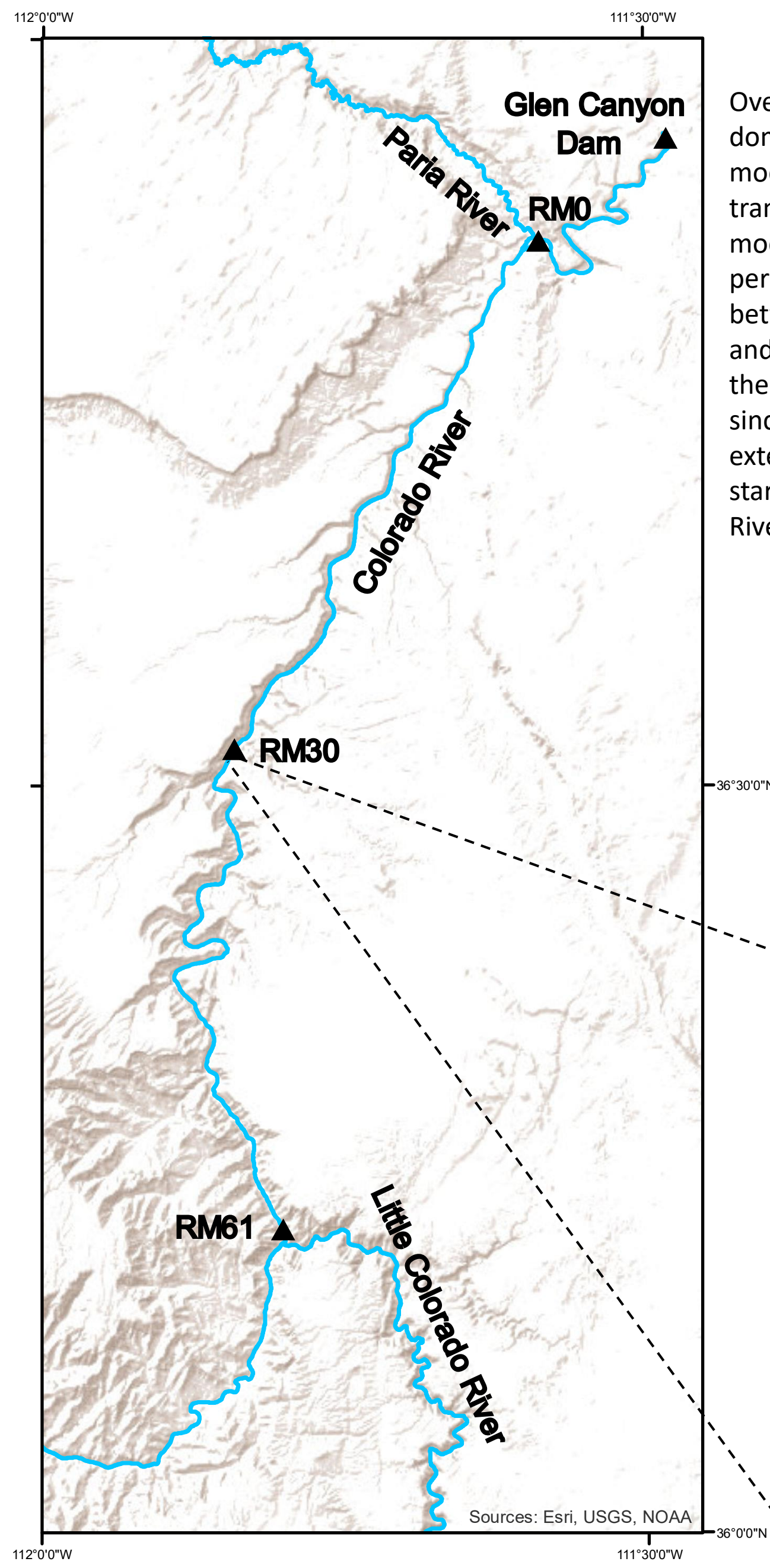
## 1. Introduction

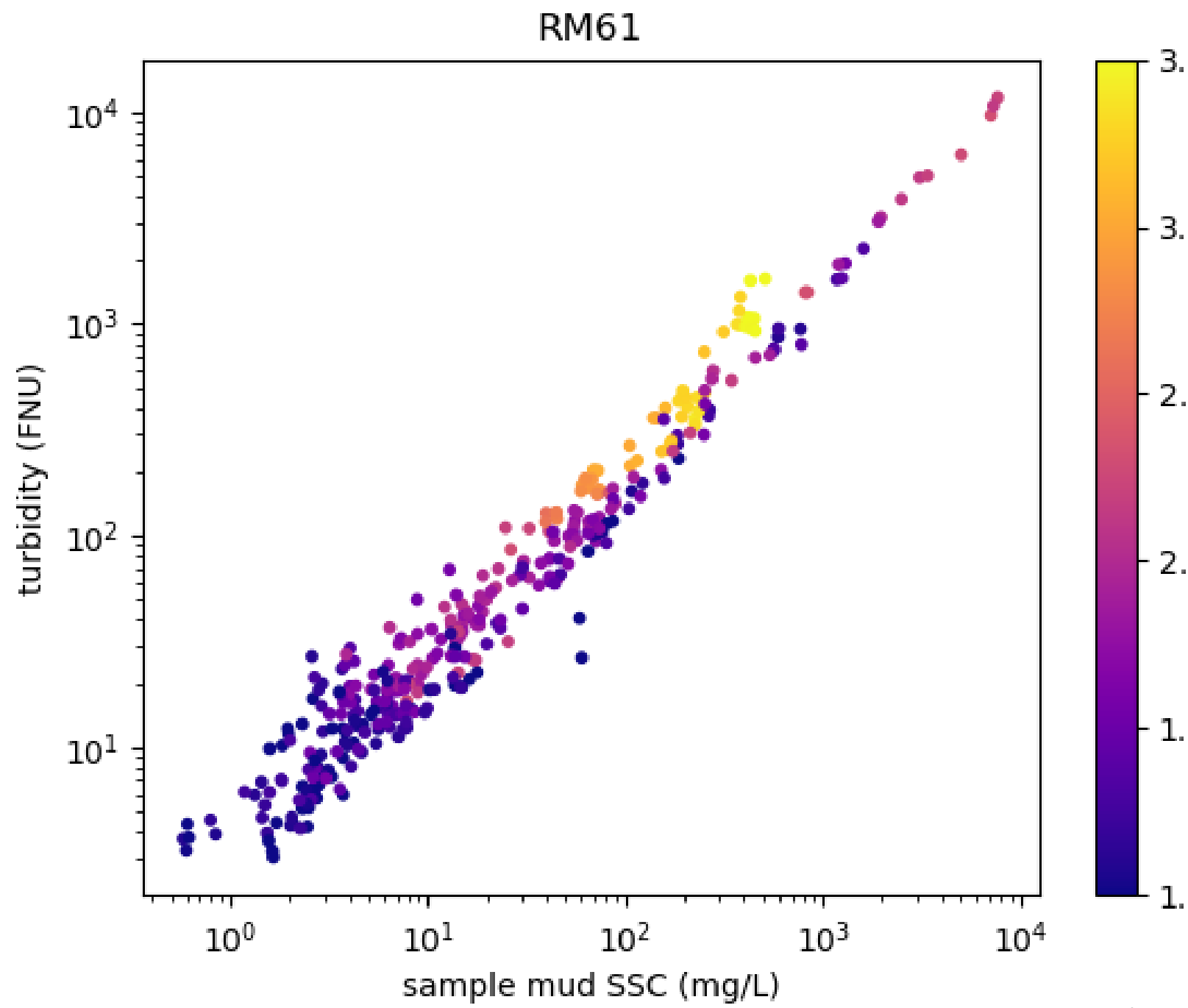
- Mud (silt and clay) is the primary control on **turbidity**, which has been shown to affect native and non-native fish (Ward et al. 2016), and can affect gross primary productivity (Deemer et al. 2022).
- The Colorado River downstream of Glen Canyon Dam is a natural laboratory for learning how fine **sediment pulses** travel downstream, **exchanging** with the **bed, eddies, and bars**.
- Although **most mud washes downstream** following tributary inputs**, some is trapped** in bars and the bed, and potentially **released later**.
- Existing models focus on sand; this new model will be used to predict suspended sediment concentrations (**SSC**) of both **mud and sand**.



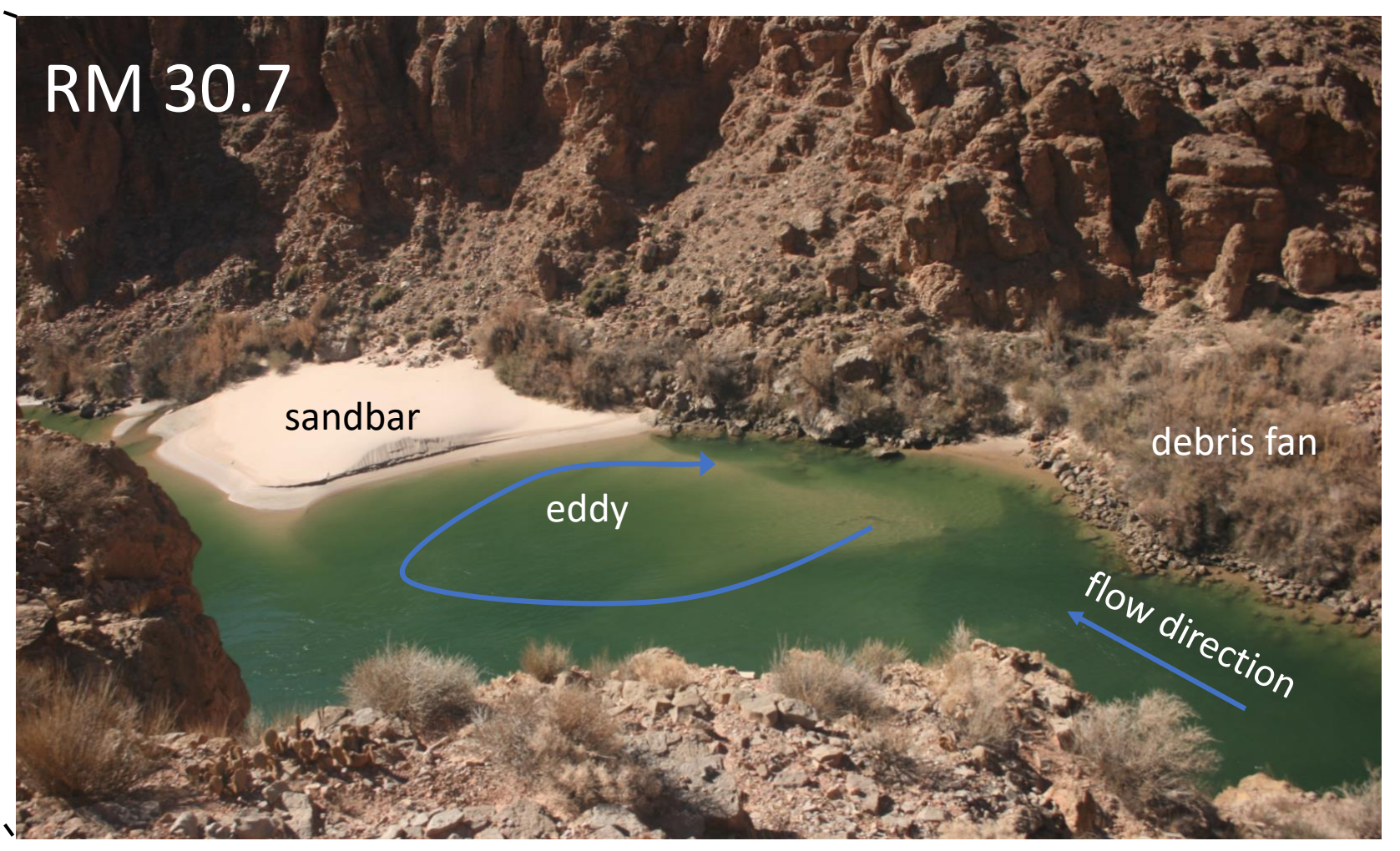
Laboratory experiments by Ward et al. (2016) show that higher turbidity increases the survival rate for juvenile humpback chub from predation by trout (bonytail *Gila elegans* used here as a proxy for humpback chub *Gila cypha*).



Overview of domain used for modeling mud transport. Pilot model runs were performed between RM30 and RM61, and the domain has since been extended to start at the Paria River.



Tight relationship between mud suspended sediment concentration (SSC) and turbidity, although fine sand can also contribute to turbidity.



Sandbar within a fan/eddy complex near River Mile (RM) 30. Although most of the sediment in the bed and bars is sand, exchange of mud between the flow and these deposits is an important control on mud transport in Grand Canyon.

## 2. Model Framework

**suspended sediment concentration (SSC) by grain size class *i***

depth[1]

width

depth-averaged velocity[1]

Settling velocity of grain size class *i*

bed sediment entrainment[3]

near-bed SSC[5]

eddy exchange coefficient

eddy width

eddy depth

eddy SSC

$$\underbrace{\frac{\partial hBc_i}{\partial t}+\frac{\partial uhBc_i}{\partial x}}_{\textbf{sediment advection}}=\underbrace{Bw_{si}(E_i-c_{bi})}_{\textbf{bed exchange}^2}+\underbrace{\lambda B_e h_e(c_{ei}-c_i)}_{\textbf{eddy exchange}^4}$$

[1] Separate 1D hydrodynamic model, e.g. SWMM (Mihalevich et al. 2021); one-way coupling (i.e. hydrodynamics affect bed; bed change does not affect hydrodynamics)

[2] Bed composition is updated via a submodel that tracks mass conservation of each grain size within layers of the bed. We have implemented multiple versions of the bed model, which are variants on the Hirano (1970) active layer concept.

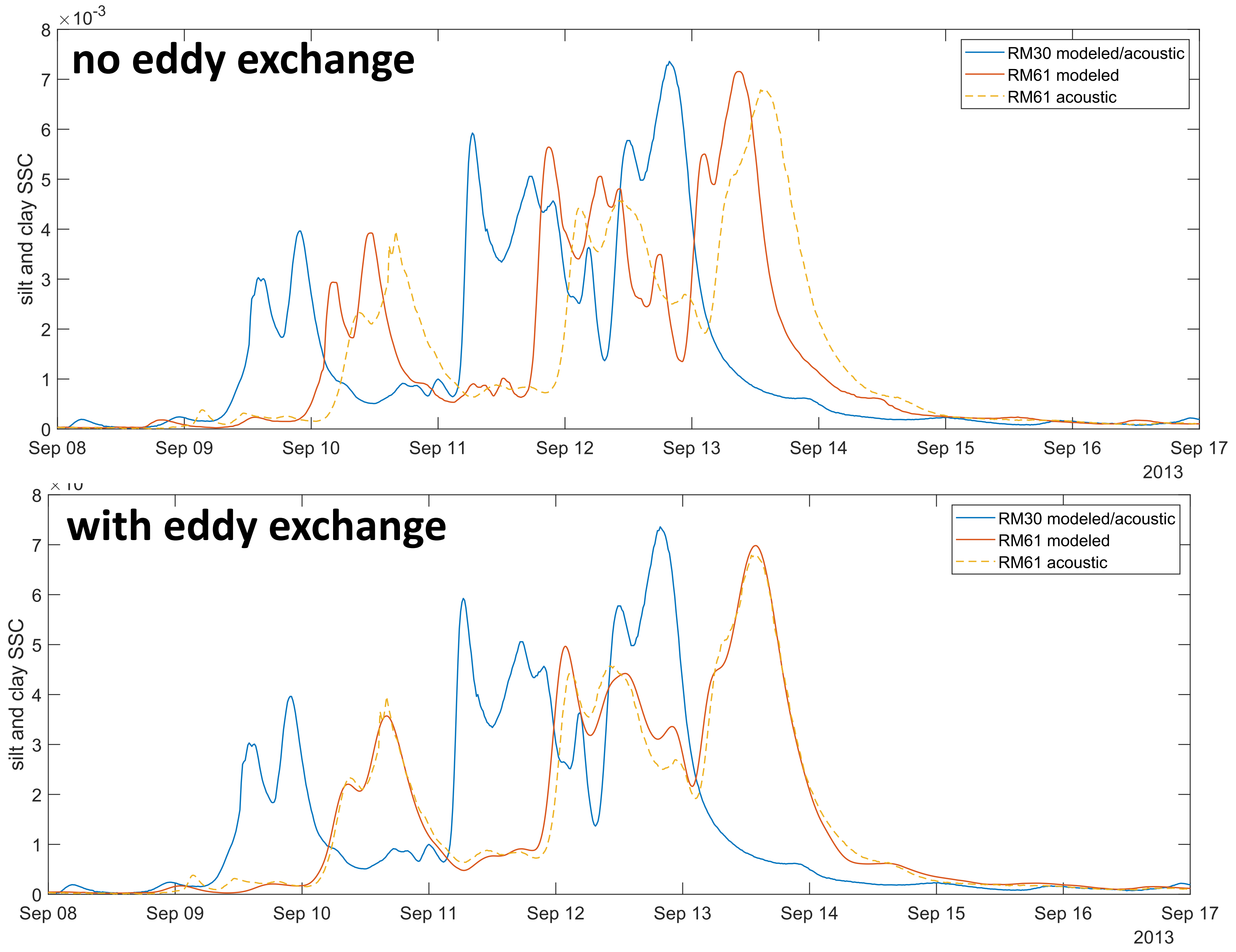
[3] Entrainment submodel, e.g. Wright and Parker (2004)

[4] Eddy exchange is modeled as spatially continuous, with eddy SSC controlled by the mass balance of exchange with the main channel and exchange with the associated bar deposit. A separate submodel tracks the bar deposit composition.

[5] The near-bed SSC is calculated from the depth-averaged SSC using a Rouse (1937) submodel, assuming that the vertical profile is at equilibrium but allowing for disequilibrium between entrainment and settling.

## 3. Importance of eddy exchange

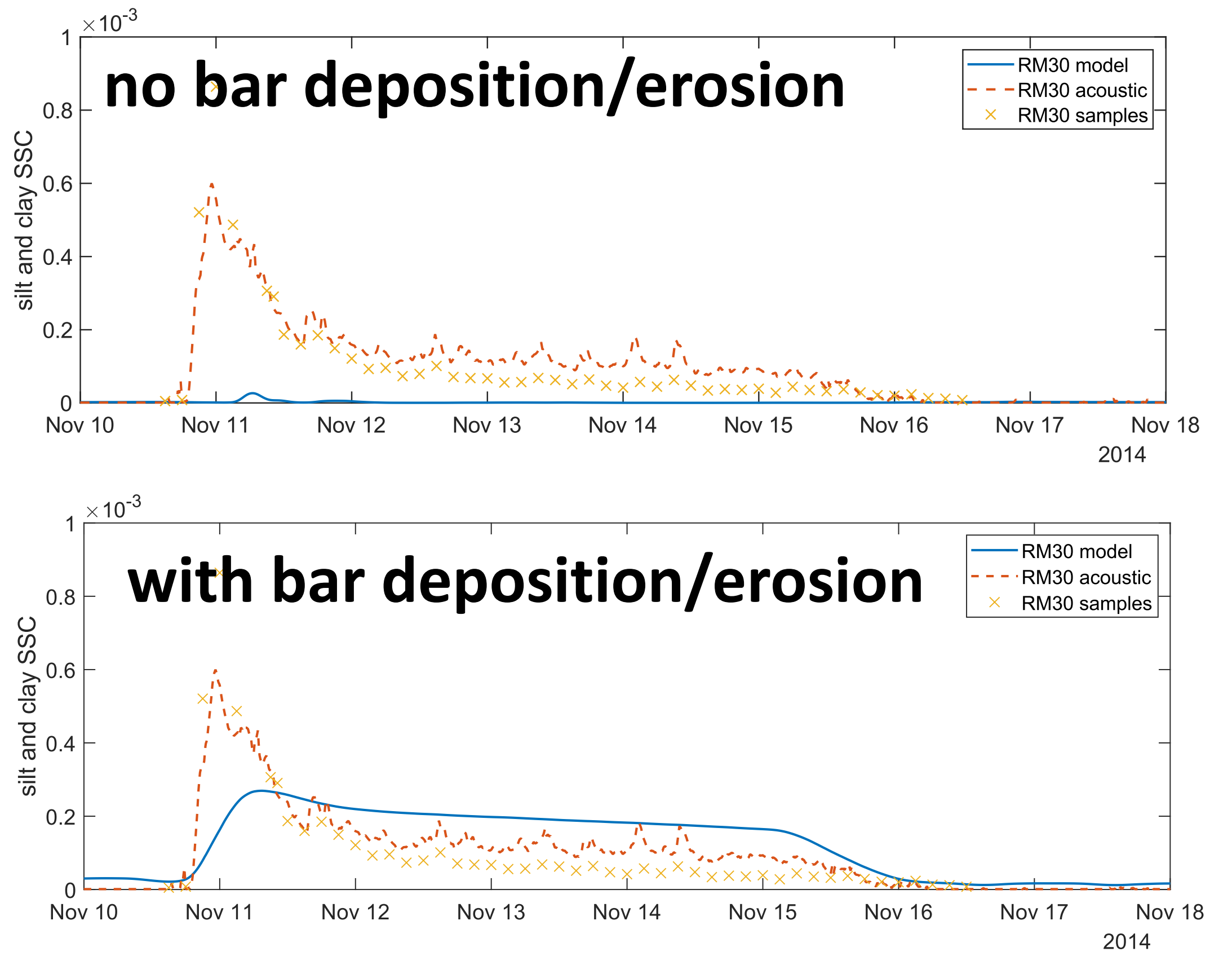
Eddy exchange is necessary for capturing the timing and attenuation of mud pulses as they travel downstream.



Model results with and without eddy exchange ($\lambda=10^{-3}$ s$^{-1}$). Acoustic-derived mud SSC at RM30 is used as the model boundary condition. Acoustic-derived mud SSC at RM61 is compared to the model prediction. Notice that eddy exchange slows down the mud pulse and attenuates the secondary peaks in the pulse.

## 4. Modeling Storage and Release

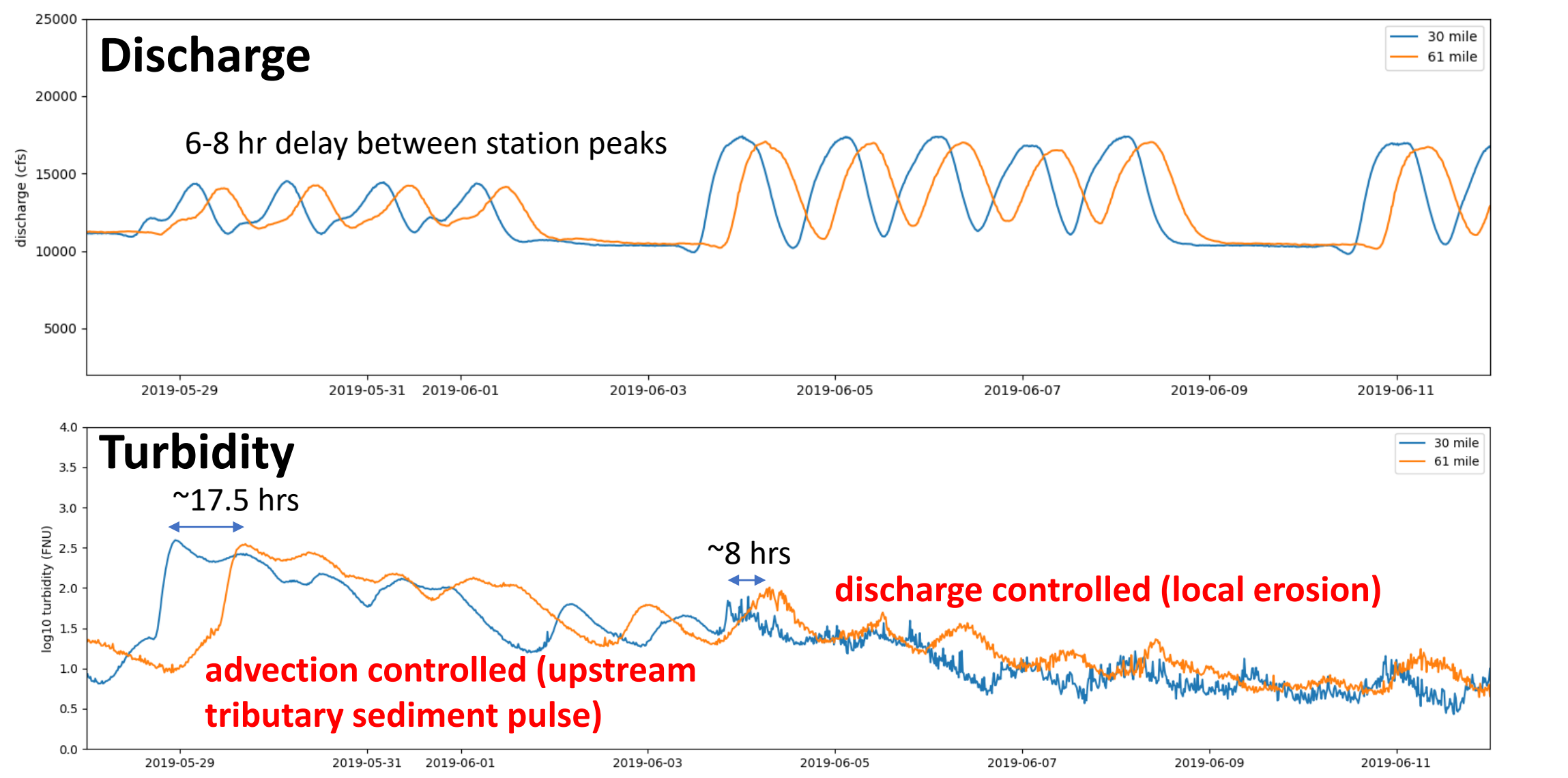
- Mud pulse propagation is ***not*** strongly sensitive to exchange of silt and clay between eddies and their associated sandbars
- However, model drastically underpredicts mud SSC during HFE's when sandbar deposition is turned off
- Modeling **mud storage in sandbars** is critical for predicting **mud release** associated with dam operations



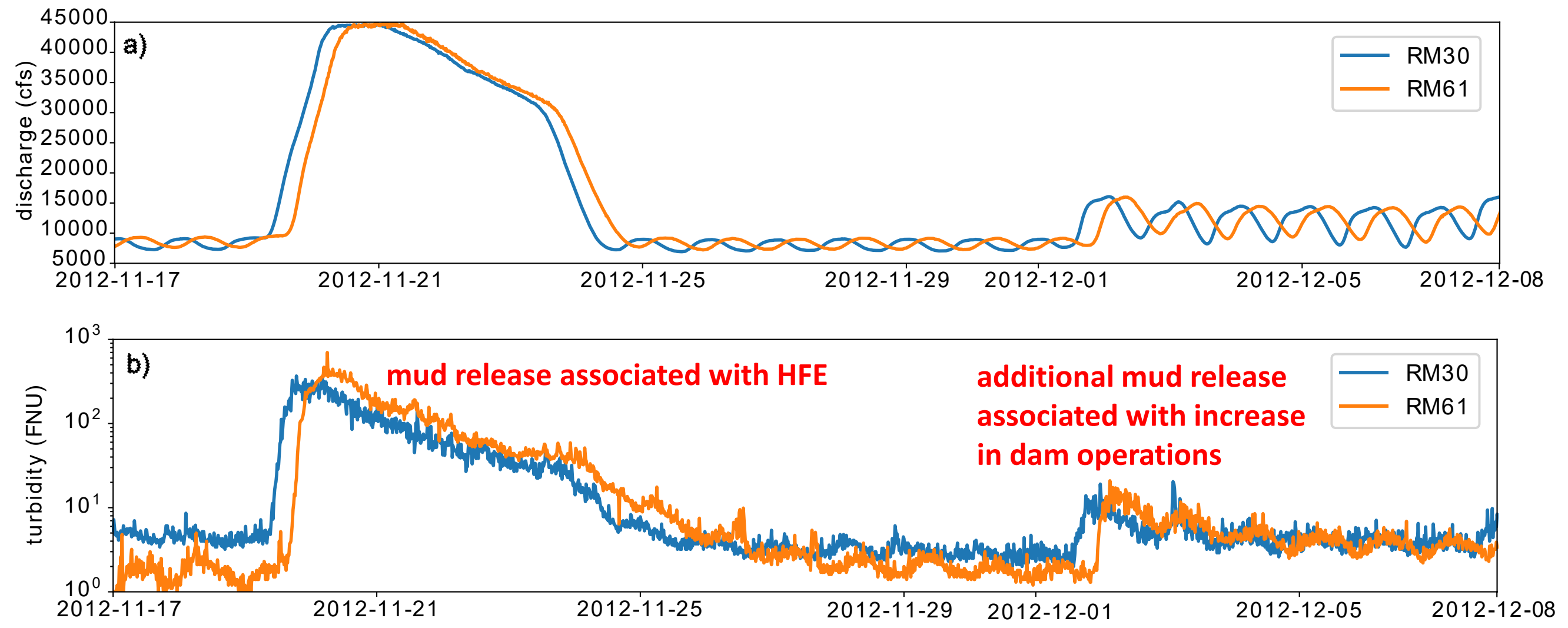
Comparison of model results during the Fall 2014 HFE with and without bar deposition/erosion. Both model runs include eddy/channel exchange. Modeling domain is from the Paria to RM30. There are no Paria inputs over this timeframe, so the mud SSC at RM30 is completely associated with release of previously deposited mud from the bed and sandbars. Results without bar exchange show that bed storage/release is not sufficient to generate the observed mud SSC.

## 5. Storage and Release: Data Analysis

We can differentiate between mud pulses produced by **tributary inputs** and those due to **local erosion** associated with dam operations by taking advantage of the **difference in travel time** between discharge waves and the water itself.

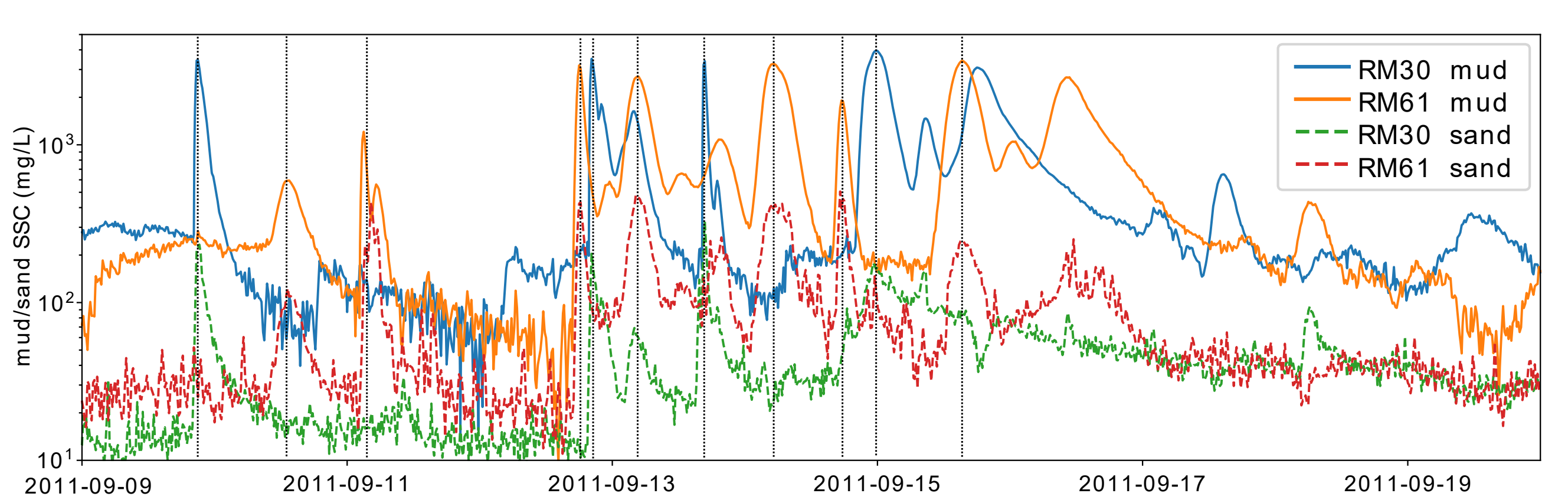


Discharge and turbidity time series at RM30 and RM61. Turbidity is closely associated with mud SSC but is less noisy at low values. Note that the y-axis shows $\log_{10}$ of turbidity. Discharge waves travel faster than the water itself. Mud pulses associated with tributary inputs are expected to travel at the water speed. Therefore, tributary pulses will have a longer time lag between stations than pulses associated with local erosion due to dam operations.



High Flow Experiments (HFE's) are associated with an increase in turbidity associated with local erosion of mud trapped in storage. This could be expected to lead to clearer water after the HFE because the mud has been flushed from the system. Notwithstanding, this example shows an increase in turbidity in December associated with the change in dam operations, showing that mud was still present in the system despite the earlier HFE.

## 6. Long-range sand advection: a puzzle



Acoustic-derived mud and sand SSC at RM30 and RM61. Alignment between peaks in mud and sand SSC and the time lag between peaks at RM30 and RM61 show that mud and sand are both traveling at a speed close to the water velocity. Discharge over this time period was relatively steady at ~16,000 cfs.

- **Advection length** $L_{adv}=\frac{hu}{w_s}$ is the distance a particle travels on average before interacting with the bed*. For 63 μm sand, this is ~1 km, vs. hundreds of km for mud.
- However, some sand travels at a similar velocity to the water for many km, suggesting minimal interaction with the bed.
- We hypothesize that this is facilitated by a **thin bed surface layer** that equilibrates quickly to sand supply.

*This is an upper-end estimate, since the advection length is also affected by the vertical SSC profile, which is skewed towards the bed (see Ganti et al. 2014).

## 7. Ongoing and Future Work

- Expanding the **model domain** and running larger-scale simulations, both within Grand Canyon and applying the model to the Upper Basin
- Refining the bed and bar submodels to **reproduce sand pulses** traveling near the water velocity for long distances
- Prediction of **turbidity at low values** of biological interest (e.g. 10-100 FNU) and exploring how dam operations affect turbidity
- Developing a scientific understanding of **washload** and the transition to bed material load

### References

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**Data sources:**
- Sediment monitoring data: https://www.gcmrc.gov/discharge_qw_sediment/
- Sandbar images: https://www.usgs.gov/apps/sandbar/