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Watershed scale impacts of upstream sediment supply on the mainstem of a river network

Muneer Ahammad & Jonathan A. Czuba
Department of Biological Systems Engineering, Virginia Tech, USA

Allison Pfeiffer
Department of Geology, Western Washington University, USA

Brendan P. Murphy & Patrick Belmont
Department of Watershed Sciences, Utah State University, USA

ABSTRACT: Sediment pulses delivered to a river affect downstream reaches of the river network. The movement of sediment depends on the flow, grain size distribution, interactions among grain sizes, bed morphology, as well as the geometry of the channel and the network. This study serves as essential validation for a model of the space-time evolution of sediment pulses and the physical disturbances to downstream reaches of a channel network. The 1D model builds on a previous Lagrangian, bed-material sediment transport model, which is applied to a 27-kilometer reach of the mainstem Nisqually River (WA) draining Mt. Rainier and terminating in Alder Lake. We utilize measured flow and grain size as inputs, and measurements of bed-elevation change and sediment accumulation rates in Alder Lake to validate the model. This study is important because it allows us to better characterize the fluvial geomorphic response of river networks to variations in sediment supply.

1 INTRODUCTION

Sediment pulses are discrete inputs of sediment to river networks from natural processes, such as from landslides, debris flows, or bank and hillslope erosion, as well as anthropogenic activities, such as dam removal or gravel augmentation. When these processes deliver sediment to a river they can affect channel morphology, habitat conditions, and channel-floodplain connectivity in both the local and downstream reaches of a river network. The transport of sediment depends on streamflow, the grain size distribution, interactions among grain sizes, bed morphology, and the geometry of the channel and network. Predicting how sediment pulses move downstream and the timing and magnitude of downstream impacts (i.e., aggradation, changes in grain size distribution, and changes in channel characteristics) is important for understanding river systems and their management.

Modeling frameworks exist for making these predictions in gravel-bedded rivers at the network scale (Czuba, 2018; Murphy et al., 2019). The present work builds upon these models with the incorporation of additional dynamic processes of bedload transport. Specifically, advancements include supplying upstream sediment in different ways, calculating water depth from channel resistance, automated methods for initializing grain size throughout the network, considerations of stress partitioning, and abrasion. The model is applied to the upper Nisqually River in Washington State to validate the approach and investigate the spatiotemporal changes in morphologic characteristics of the river network.

2 METHODS

2.1 *Two-layer model*

The model builds on a previous one-dimensional Lagrangian, bed-material sediment transport model (Czuba, 2018). Here sediment is conceptualized as a combination of discrete individual parcels, where each parcel has its volume and mean grain size. The river network is conceptualized as interconnected links, each with topologic (elevation, slope), physical (length, width), hydrodynamic (flow discharge) and sedimentologic (sediment size and distribution) attributes. Sediment in any link at any time is separated into two layers: active surface layer and subsurface layer.

Active layer volume for any link is determined by the transport capacity (χ) where

$$\chi = \ell \mathrm{B}\ \mathrm{L} \tag{1}$$

and ℓ is the link length, B is the channel width, and L is the active layer thickness in that link. Active layer thickness is kept constant in the model and estimated as twice the median particle diameter. If sediment volume in any link increases beyond the capacity, the excess sediment is stored in the subsurface layer, which consequently adjusts the slope of upstream and downstream links. The total parcel volume in any link at any time (V) is the sum of the volumes of all parcels within that link at that particular time.

The total sediment volume in the active surface layer of any link at any time (V_{act}) is dependent on transport capacity

$$V_{\mathrm{act}} = V \text{ if } V < \chi \tag{2}$$

$$V_{\mathrm{act}} = \chi \text{ if } V > \chi \tag{3}$$

Each parcel is tracked as it moves through the network. The arrival and departure of sediment parcels from links follow a first-in, last-out rule, i.e., the last parcels to arrive to a link are positioned in the active surface layer (when incoming cumulative volume is less than the link capacity). With this movement of sediment, bed elevation is updated accordingly at each timestep throughout the network.

2.2 *Bedload transport equation*

The transport time (t) of sediment parcels (Czuba and Foufoula-Georgiou, 2014) is calculated from

$$\mathrm{t} = \frac{\rho^{3/2} g R \ell \mathrm{L}}{\mathrm{W}^{*} \tau^{3/2} F} \tag{4}$$

Where ρ is the density of water, g is the acceleration due to gravity, R is the submerged specific gravity of sediment, τ is the bed shear stress, and F is the fraction of the parcel in the active surface layer of that link at that time. The dimensionless transport rate, W^{*}, is calculated for each parcel and comes from surface-based mixed-size bedload transport equation of Wilcock and Crowe (2003). This formulation takes into consideration that the presence of sand increases the mobility of all sediment.

2.3 *Key advancements*

The median channel sediment size (D_{50}) is initialized throughout the network as a function of channel width (B) and slope (S) following Snyder et al., (2013)

$$D_{50} = \frac{\rho g n^{3/5}\ Q_2^{3/5} B^{-3/5} S^{7/10}}{(\rho_s - \rho) g \tau_{c*}} \tag{5}$$

Where n is the Manning roughness coefficient, Q_2 is the 2 year recurrence interval flow, ρ_s is sediment density, and $\tau_c{*}$ is the critical Shields parameter to mobilize D. Q_2 is used in Equation 5 as an approximation of bankfull discharge when bed sediment mobilizes in single-thread coarse gravel-bedded rivers (Snyder et al., 2013). We find that modeled median sediment sizes exhibit strong agreement with median sizes collected at four locations in the network (results not shown).

Water depth in each link is calculated as

$$H = \left(\frac{Q\ k_s^{1/6}}{8.1\ B\ \sqrt{gS}} \right)^{3/5} \tag{6}$$

This formulation of equation 6 allows water depth to change with variations in discharge (Q) and channel flow resistance. The roughness height k_s is assumed here as twice the mean particle size.

The present model allows for the incorporation of particle abrasion. The sediment size and volume will vary in time when sediment breaks down via attrition.

$$V_{new} = V_{init} * e^{-\alpha * d} \tag{7}$$

Where V_{new} is the new volume, V_{init} is the original material volume, α is the abrasion rate, and d is the travelled distance. The value of α can range from $2X10^{-3}$ to $2X10^{-1}$ km^{-1} (Kodama, 1994).

The presence of large immobile grains reduces flow energy and the shear stress available to move sediment. This effect is considered here with stress partitioning from Rickenmann (2012). This method uses a reduced energy slope S_0, instead of actual S. S_0 is calculated in this work by relating S to the Darcy–Weisbach friction coefficient f. With the partitioning between base level, f_o (defined by Manning–Strickler-type approach) and total resistance, f_{tot} (from variable power equation (VPE) of Ferguson (2007)) and exponent $e \approx 1.5$ (Rickemann, 2012), it is then can be expressed as:

$$\frac{S_0}{S} = \sqrt{\left(\frac{f_0}{f_{tot}} \right)}^{e} \tag{8}$$

The model has provision to supply sediment at upstream or intermediate locations within the river network. The various methods include: (1) keeping the link always at its capacity, (2) using a sediment rating curve, or (3) maintaining an effectively infinite reservoir of sediment and letting the flow continually erode the deposit but still maintain a fixed bed elevation.

3 APPLICATION TO THE NISQUALLY RIVER

The model was applied to the 27-km reach of upper Nisqually River, just upstream of Tahoma Creek to Alder Lake. We limit the simulation of transport to the mainstem of the river network with major tributary inflows in order to validate the Lagrangian framework against detailed field observations.

The river was discretized and modeled as 68 connected links, each of which was 400 m in length. The longitudinal profile was obtained from LiDAR elevations, by approximating shallow water levels. The average active channel width for each link ranged from 29 m to 291 m, with a mean value of 175.7 m (Czuba et al., 2012a). A long-term daily streamflow record of 1945-2011 from the USGS gage (12082500 Nisqually River at National, WA) was applied in the model. Surface grain-size distribution was measured at 4 locations within the study reach. The initial median sediment size was calculated using equation 5 for each link, and the initial distribution was set by interpolating the observed distributions. Subsurface grain-size distribution was kept the same as the surface grain-size distribution.

Using the Bedload Assessment in Gravel-bedded Streams (BAGS) (Pitlick et al., 2009) software, a sediment rating curve was developed for upstream sediment supply. Thus, sediment load by grain size was varied with streamflow. The model-conditioning process consisted of running the model for 66 years (1945-2011) to get a stabilized model output.

The model requires flow data, channel/link data (length, width, initial elevation), and initial sediment data as inputs. The simulation procedure at each timestep can be summarized as:

(i) compute sediment transport volume at capacity (Eq. 1),
(ii) compute bed elevations from sediment volume within a link,
(iii) compute D_{50} of the active layer sediment parcels in each linkfor mixed-sized sediment transport,
(iv) compute transport time (Eq. 4) and then location of each parcel within a link,
(v) move parcels to a new location within a link or to downstream link,
track sediment parcels and update slope/elevations.

Thus, model outputs are spatially and temporally explicit attributes of sediment depth, elevation, sediment size, sediment distribution and volume that reaches the watershed's downstream outlet.

4 RESULT AND DISCUSSION

4.1 *Model validation*

The observed variance in bed elevations at the USGS gage location (in Figure 1) was ~1.7 m between 1985 and 2011 (Czuba et al., 2012a; Pfeiffer et al., 2019). The model predicted that bed elevations varied within 0.7 m from equilibrium during this same period. However,

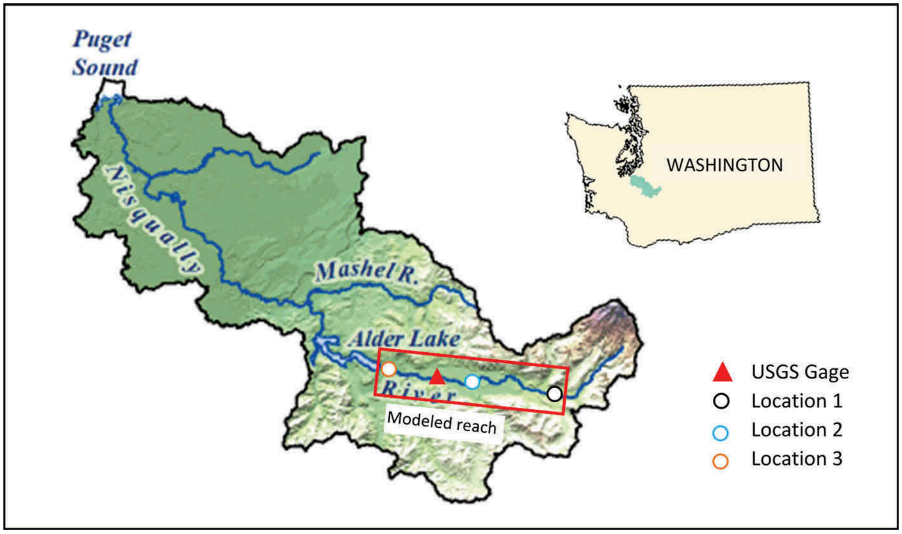

Figure 1. Study area map of the Nisqually River in Washington State, USA. The USGS gage and the locations of simulation results are also marked within the modeled reach.

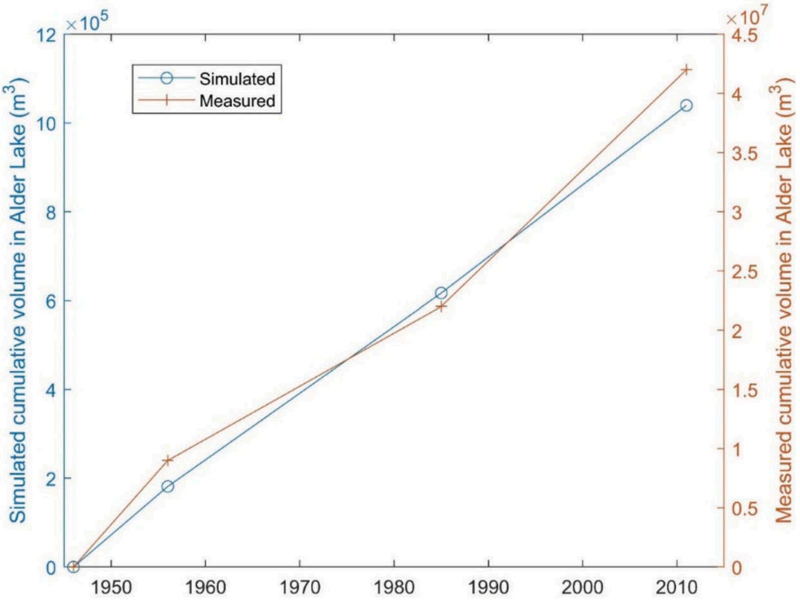

Figure 2. Simulated and measured outlet volumes in Alder Lake. While temporal trends are consistent, note the different orders of magnitude in y-axes scales.

this was under a constant simulated sediment supply, thus, not including sediment pulses that likely contributed to real variations observed in the gage data.

The model exhibited a similar temporal trend (Figure 2) with observed outlet volume in Alder Lake (Czuba et al., 2012b), however, the total simulated volume is around 2.5% of the measured outlet volume. In the White River (a comparable river draining Mt. Rainier), the bedload contribution to the total load is very low (around 10%; Czuba et al., 2012a), and most of the material reaching the outlet is in suspension. We did not include fine materials (<2 mm) in the modeled grain sizes, likely contributing to the low predictions of volume delivered to Alder Lake as compared to observations of deposition in the delta in Alder Lake.

4.2 *Simulation result*

The model results are presented at 3 different locations (Location 1: upstream link; Location 2: mid-network link; and Location 3: downstream link) shown in Figure 1. The results (Figure 3) demonstrate relatively stable sedimentologic characteristics with short-lived high flow fluctuations. Gradual coarsening of the river bed is observed due to flushing of sand from the bed. The long-term trends in grain size are adjusted primarily during high flow events. Coincident adjustments are observed for sediment depths, where large flow events result in decreases in the long-term condition of sediment depth. The detailed result, however, showed strong control of bed slope and width on the morphological response in the river network.

5 CONCLUSION

In this work, a 1-dimensional Lagrangian sediment routing model was built off of an existing framework with some key advancements and applied to understand the behavior of a 27-km mainstem reach of the upper Nisqually River in Washington State between 1945 and 2011. The model was capable of routing upstream supplied sediment through the network and simulating spatiotemporal changes in elevation, sediment size and

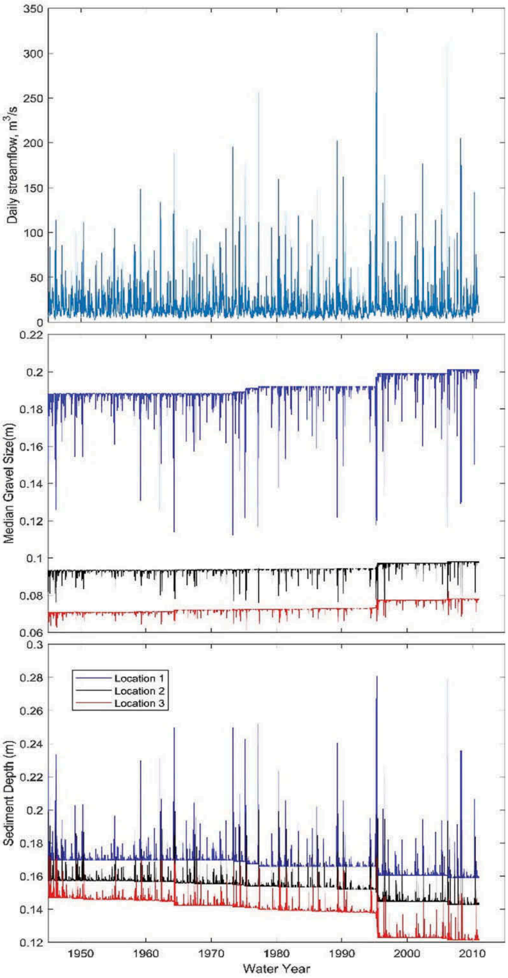

Figure 3. Time series of flow, median gravel size, and sediment depth for three links shown in Figure 1: Location 1 (upstream link), Location 2 (mid-network link), and Location 3 (downstream link).

distribution. The approach was validated with field measurement and the model performance was found to be acceptable. This modeling framework allows us to understand how upstream sediment inputs are transported through and influence river networks, and provides an approach to predict watershed-scale sedimentological processes and downstream impacts in gravel-bedded rivers.

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