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A Lagrangian framework for exploring complexities of mixed-size sediment transport in gravel-bedded river networks

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ABSTRACT

The movement of sediment from source to sink in a watershed is a complex process with multiple interactions and feedbacks across scales. At small scales, the size characteristics of a sediment mixture affect the transport of that sediment through hiding and through the nonlinear effect of sand content on gravel transport. At large scales, the channel network itself, through network geometry and the spatial pattern of transport capacity, adds additional complexity in organizing sediment moving through the system such that aggradational hotspots can emerge. The purpose of this paper is to present a Lagrangian framework for exploring complexities of mixed-size sediment transport in gravel-bedded river networks. The present model builds off of previous network-based, bed-material sediment transport models; but key advancements presented herein (i) allow for a mixture of sediment sizes in the river network, (ii) incorporate a mixed-size sediment transport equation, and (iii) utilize a daily flow hydrograph to drive intermittent transport. The model is applied to the roughly 4700 km^2 Methow River Basin in Washington State, USA, using simplified model inputs with the goal of illustrating the utility of the model for motivating future work.

1. Introduction

The movement of sediment from source to sink in a watershed is a complex process with multiple interactions and feedbacks across scales. For example, the sediment size distribution supplied by hillslopes to channels depends on lithology, climate, life, erosion rate, and topography (Sklar et al., 2017). Furthermore, the frequency-magnitude characteristics of the sediment supply are inherently stochastic because of rainstorms, topography, colluvial properties, and recovery from past events (Benda and Dunne, 1997b). Once emplaced, spatially variable, local channel properties transform the flow of water into a driving force for moving sediment downstream. Mixing, hiding, and grain-size specific transport of sediment affect how an individual rock moves downstream (Parker, 2008). This already complex transport process is further confounded by additional granular interactions that lead to imbrication, armoring, patch formation, and the creation of force chains (Frey and Church, 2011) as well as stress history, which results in vertical settlement, changes in roughness, particle repositioning, and changes in the entrainment threshold (Ockelford and Haynes, 2013). At larger scales, the channel network itself, through network geometry and the spatial pattern of transport capacity, adds additional complexity in organizing sediment moving through the system such that aggradational hotspots can emerge (Benda et al., 2004; Czuba and Foufoula-Georgiou, 2015; Czuba et al., 2017; Gran and Czuba, 2017; Rice, 2017; Schmitt et al., 2018; Walley et al., 2018).

Incorporating all of these process dynamics across multiple scales into a single modeling framework seems computationally prohibitive at present. Instead, exploring a subset of this complexity is common based on a scale or component of interest. Herein, the interest is in exploring mixed-size sediment transport on a river network. Relevant to this scope, one dimensional (1D) sediment transport models have been developed that incorporate mixed-size sediment dynamics. The Unified Gravel-Sand (TUGS) model incorporates transport dynamics of a sand-gravel grain size distribution via a surface-based bedload equation, three conceptual layers (bedload, surface, and subsurface), transfer functions between layers, and abrasion (Cui, 2007). The Morphodynamics and Sediment Tracers in 1D (MAST-1D) model also incorporates mixed-size transport, but its key contribution is in its handling of size-specific exchange between sediment in the channel and floodplain (Lauer et al., 2016). However, these 1D models cannot suitably explore additional complexities that arise from channel network structure.

River network models have been created to explicitly explore network structure, although they have not yet sufficiently advanced to incorporate the dynamic processes of their 1D model counterparts (e.g., TUGS, MAST-1D). One major shortcoming of existing river network models is that they do not incorporate physically based dynamics of mixed-sized sediment transport (Benda and Dunne, 1997a; Jacobson and Gran, 1999; Wilkinson et al., 2006; Czuba and Foufoula-Georgiou,

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2014, 2015; Schmitt et al., 2016; Czuba et al., 2017; Gran and Czuba, 2017; Schmitt et al., 2018). It remains to be seen how multiple size fractions interact during transport on river networks (e.g., via the incorporation of a mixed-size sediment transport equation such as Wilcock and Crowe, 2003).

The purpose of this paper is to present a Lagrangian framework for exploring complexities of mixed-size sediment transport in gravel-bedded river networks. The present model builds off of previous work by Czuba and Foufoula-Georgiou (2014, 2015), Czuba et al. (2017), and Gran and Czuba (2017), but key advancements herein allow for a mixture of sediment sizes in the river network, incorporate the mixed-size sediment transport equation of Wilcock and Crowe (2003), and utilize a daily flow hydrograph to drive intermittent transport. The model is applied to the roughly 4700 km^2 Methow River Basin in Washington State, USA, using simplified model inputs. The goal is to illustrate the utility of the model for motivating future work rather than to provide a detailed case study for the Methow River Basin.

2. Network-based modeling framework for mixed-size sediment

2.1. Network of river channels

The basis of the model is a river network that is conceptualized as a set of connected links. Each link i represents a segment of river channel with a set of unique, and possibly time-variable, topologic, physical, and hydrodynamic attributes. The spatial extent of a link is between tributaries (so attributes of a link remain constant throughout the length of a link) and no longer than a given length. That is, long reaches between tributaries can be broken into multiple links to ensure an upper limit to the maximum link length.

2.2. Sediment conceptualization

Sediment is conceptualized in the model as discrete units referred to as parcels p. An individual parcel represents an arbitrary volume of sediment that moves downstream as a coherent unit. Each parcel has a set of unique geometric, sedimentologic, and lithologic attributes including: volume V_p [L^3] and grain size d_p [L]. The model is capable of allowing parcel volume and parcel grain size to vary in time as sediment is broken down via attrition, but these dynamics are not incorporated in the present model. The spatiotemporal distribution of sediment parcels input to the network will depend on the specific basin under study. The model itself is flexible enough to allow for sediment parcel input anywhere along the length of a link and at any point in time.

2.3. Two-layer model

At any time t [T] multiple parcels can be present with different volumes and grain sizes within a given link i. The total parcel volume in each link i at time t or $V_{i,t}$ [L^3] is the sum of the volumes of all parcels within that link at that particular time given as

$$V_{i,t} = \sum_{\substack{\text{all parcels } p \\ \text{in link } i \\ \text{at time } t}} V_p \quad (1)$$

The total volume of sediment in a link is separated into an active/surface layer and a storage/subsurface layer (see Czuba et al., 2017). The volume of sediment in the active/surface layer at transport capacity $\chi_{i,t}$ [L^3] is given by

$$\chi_{i,t} = \ell_i B_{i,t} L_{a,i,t} \quad (2)$$

where ℓ_i [L] is the length, $B_{i,t}$ [L] is the channel width, and $L_{a,i,t}$ [L] is the active layer thickness in link i. Thus, the total parcel volume in the active/surface layer of link i at time t or $V_{i,t}^{act}$ [L^3] is given by

$$V_{i,t}^{act} = \begin{cases} \chi_{i,t}, & \text{for } V_{i,t} > \chi_{i,t} \\ V_{i,t}, & \text{for } V_{i,t} \leq \chi_{i,t} \end{cases} \quad (3)$$

Any volume of sediment within a link beyond what can be moved at capacity is placed in the storage/subsurface layer, is not transported at that time, and acts to increase the slope in the link and decrease the slope(s) in the immediately upstream link(s) (see Czuba et al., 2017, for further details). The order of arrival of parcels is preserved in the model and each parcel is tracked as it moves through a link. Following first-in, last-out, the last parcels to arrive to a link and whose cumulative volume is $\leq \chi_{i,t}$ are placed in the active/surface layer.

The active/surface layer and storage/subsurface layer are only formed if enough parcels reside in that link. When no parcels are within a link, nothing is transported, and the link is treated as bedrock floored. As a few parcels enter a link (whose total volume within the link is less than the volume transported at capacity), the link is still treated as bedrock floored, no storage/subsurface layer exists, and all the parcels within the link are within the active layer. When more parcels than can be moved at capacity reside in a link, only then does the storage/subsurface layer exist. In this Lagrangian framework, bed elevation is computed from the total number of parcels over the link surface area (length times width), including porosity (see Czuba et al., 2017, for further details). Thus, as parcels enter and exit a link, the bed elevation is updated accordingly.

2.4. Mixed-size sediment transport

2.4.1. Sedimentologic characteristics of a link

The transport calculation begins by first computing the sedimentologic characteristics of a link at a particular time from the parcels within that link. Within the active/surface layer of link i at time t, the mean size of the bed surface sediment $d_{i,t}$ [L] (including sand and gravel grain size classes) is computed as

$$d_{i,t} = \frac{1}{V_{i,t}^{act}} \sum_{\substack{\text{all parcels } p \\ \text{in active layer} \\ \text{of link } i \\ \text{at time } t}} d_p V_p \quad (4)$$

The fraction of sand in the active/surface layer of link i at time t or $F_{s,i,t}$ is computed as

$$F_{s,i,t} = \frac{1}{V_{i,t}^{act}} \sum_{\substack{\text{sand parcels } p \\ \text{in active layer} \\ \text{of link } i \\ \text{at time } t}} V_p \quad (5)$$

and the fraction of parcel p in the active/surface layer of link i at time t or $F_{p,i,t}$ is computed as

$$F_{p,i,t} = \frac{V_p}{V_{i,t}^{act}} \quad (6)$$

2.4.2. Surface-based transport equation of Wilcock and Crowe (2003)

The transport of mixed-size sediment follows the surface-based, bedload equation of Wilcock and Crowe (2003). Under this