Modeling bed-material sediment transport on a river network

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ABSTRACT: Understanding how river-channel processes aggregate at the watershed scale is becoming increasingly important for watershed managers. Here we describe a network-based framework for modeling sediment transport in a watershed that involves (1) decomposing the landscape into a connected network of elements including river channels, lakes, etc., (2) spatially and temporally distributing inputs of sediment according to a sediment budget, and (3) tracking these inputs through individual landscape elements via process-based time delays. The resulting bed-material sediment transport model described herein includes recurrent inputs informed by a sediment budget and also lake and in-channel storage with feedback between in-channel storage and channel slope. The model was used to simulate spatial and temporal bed-sediment depths on an entire river network at the watershed scale.

1 INTRODUCTION

Detailed sediment budgets for many agricultural watersheds are revealing a surprising story—that sediment is no longer primarily sourced from upland fields, but instead from near-channel sources. This is the case for the Minnesota River Basin (MRB) where an intensification and expansion of agricultural drainage combined with increased precipitation has (1) reduced surface runoff and erosion, (2) amplified streamflows, and (3) accelerated both near-channel sediment generation and sediment transport (Belmont et al., 2011; Schottler et al. 2014, Foufoula-Georgiou et al. 2015). The resulting increase in suspended sediment concentrations may be partly responsible for recent declines in native mussel populations (e.g., Hansen et al. 2016).

Bluffs and streambanks in the MRB are now the dominant sources of sediment (Gran et al. 2011, Belmont et al. 2011, Bevis 2015), but these features are not easily incorporated into traditional watershed-scale, sediment-transport models. We are advancing a network-based modeling framework that explicitly considers sediment sources, transport, and storage along a river network. We apply this framework to bed-material sediment transport in the Greater Blue Earth River Basin (Fig. 1), the major sediment-generating subbasin of the MRB, where a recent sediment budget has quantified the locations and rates of erosion and deposition of major sediment sources and sinks (i.e., bluffs, streambanks/floodplains, agricultural fields, and ravines) over millennial and decadal timescales (Gran et al. 2011, Belmont et al. 2011, Bevis 2015).

With the river network as the basis of a simple model, inputs of sediment to the network are informed by the sediment budget and these inputs are tracked through the network using process-based time delays that incorporate uniform-flow hydraulics and at-capacity sediment transport. The result is a map of bed-material sediment depths throughout
a network. Often the pattern that emerges concentrates bed-material sediment into hotspots dispersed throughout the network as the result of hierarchical ordering by the network, spatial and temporal distribution of inputs, and local channel characteristics.

2 BRIEF DESCRIPTION OF THE MODEL

The model formulation described very briefly herein advances the network-based framework of Czuba & Foufoula-Georgiou (2014, 2015) which involves (1) decomposing the landscape into a connected network of elements including river channels, lakes, etc., (2) spatially and temporally distributing inputs of sediment according to a sediment budget, and (3) tracking these inputs through individual landscape elements via process-based time delays. The resulting bed-material sediment transport model described herein includes recurrent inputs informed by a sediment budget and also lake and in-channel storage with feedback between in-channel storage and channel slope (Gran & Czuba 2016).

The travel time for an input to move through a given channel link of the network is based on an analysis of sand transport assuming: (1) uniform (normal) flow hydraulics, (2) that Engelund & Hansen’s (1967) sediment-transport formula represents the sand-transport process (neglecting the shear stress partition for bedforms), (3) hydraulic geometry scaling of streamflow depth, width, and velocity, (4) an intermittency of flows that transport the majority of sediment, (5) that sediment supply does not exceed transport capacity (this is handled mechanistically as an additional storage delay; see Gran & Czuba 2016 for details), and (6) that sediment does not enter long-term floodplain storage (future work is to include this dynamic as an additional storage delay).

Temporally recurrent inputs were added to the network at the locations of bluffs, ravines, and uplands with exponentially distributed interarrival times with mean of one year. This assumes sediment sourcing from these features is dictated by extreme storms and floods which are independent (extreme) events and thus can be assumed to follow a Poisson process. The amount of sand generated by each feature was given by a sand budget derived from source information originally compiled for the fine sediment budget (Gran et al. 2011, Belmont et al. 2011, Bevis 2015). The result was an annual input of roughly 350,000 Mg/yr of sand to the basin. Lakes within the river network act as coarse sediment sinks, and whenever supply to a channel of the network exceeded transport capacity, a fraction of that sediment entered in-channel storage which altered the slope and thus the transport of sediment through the reach. The simulation was run for 600 years. For more details on the model refer to Czuba & Foufoula-Georgiou (2014, 2015) or Gran & Czuba (2016).

The proposed network-based framework for sediment transport at the watershed scale has the potential to (1) trace sediment as it moves through a river network, (2) provide estimates of timescales of movement of sediment through the river network, (3) explore synchronizations (Czuba and Foufoula-Georgiou 2014), (4) identify the emergence of hotspots of change (Czuba and Foufoula-Georgiou 2015), (5) quantify fluctuations in bed elevation as a result of sediment entering from upstream tributaries, (6) aggregate spatially explicit inputs into a variable sediment load at the watershed outlet, and also (7) test alternative scenarios for management decisions aimed at reducing the detrimental effects of sediment.

3 RESULTS

Simulated bed sediment depths mapped throughout the Greater Blue Earth River Basin are shown in Figure 2. Bed sediment depths ranged from on the order of millimeters to upwards of nearly one meter. In reality a bed sediment depth on the order of one millimeter suggests a reach with essentially no sand and a bed of a coarser gravel lag or exposed till or bedrock. The simulated bed sediment depths in these reaches can also be quite variable because short-lived local increases in sediment load can substantially increase bed sediment depths.

“Hotspots” of relatively thicker bed sediment depths emerge (Fig. 2). While most sediment is generated in the knickzone, there are many bluffs (which are the largest contributors of sediment) that line the major rivers throughout the network. This results in a pattern of relative sediment depths along mainstem rivers that are not completely different from the

Figure 2. Bed sediment depths throughout the Greater Blue Earth River Basin at the end of a 600 year simulation period with inputs derived from a sediment budget and incorporating lake and in-channel storage. The color breaks are at the 0.99, 0.95, 0.90, and 0.75 quantile. The approximate extent of the knickzone, a steeper rapidly incising portion of the basin, is shown as a dashed line.
Hierarchical ordering of uniform inputs (described in Gran & Czuba 2016). What emerges is that the spatial pattern of sediment depths is driven by a combination of spatial pattern of inputs, hierarchical ordering by the network structure, and local channel characteristics that dictate how sediment moves through a given reach (see Gran & Czuba 2016).

The resulting bed-material sediment load was recorded at the outlet of the Greater Blue Earth River Basin during the 600 year simulation period (Fig. 3). The first 100 years of the simulation period are part of the model spin-up time where the farthest inputs have not yet arrived at the outlet and bed elevations are still adjusting to the sediment supply.

The average bed-material sediment load was around 330,000 Mg/yr, less than the 350,000 Mg/yr input to the basin due to storage of 20,000 Mg/yr of sand in lakes. The variability in the simulated annual sediment load ranged between roughly 240,000 Mg/yr and 440,000 Mg/yr with a standard deviation of 34,000 Mg/yr. While the average loads agree well with values from the sediment budget (because they are directly specified), the variability in the loads are much less than might be expected when computing loads from daily streamflow hydrographs and a power law relating flow to sediment load. This is driven by the exponential distribution of interarrival times of inputs and the long-term average flow conditions driving transport. It is likely that in order to accurately capture a more realistic year-to-year variability in sediment loads, the flows and the sediment generated by those flows would need to be simulated as being higher in some years and lower in others, consistent with the variations in the underlying climatic forcing.

4 CONCLUSIONS AND FUTURE WORK

This work briefly describes a watershed-scale model of bed-material sediment transport on a river network. Simulated bed sediment depths throughout a river network and annual bed-material sediment loads are shown as examples of results produced by the model. These results highlight the role of the network structure, temporal and spatial patterns of inputs, and local channel characteristics in dictating the temporal and spatial pattern of bed sediment depths on a network.

Ongoing work is exploring how sediment might move through a river network and affect the variability of bed elevations under cases where the mechanisms of in-channel and floodplain storage are turned on and off. Additionally, ongoing work includes understanding timescales of movement of sediment through the system to better inform legacy effects and hysteresis, and also identifying targeted management actions that will most effectively reduce the detrimental effects of excess sediment.

REFERENCES


Bevis, M. 2015. Sediment budgets indicate Pleistocene base level fall drives erosion in Minnesota’s greater Blue Earth River basin, M.S. thesis, Dept. of Earth and Environmental Sciences, Univ. of Minnesota, Duluth, Minnesota.


