Relative importance of climate and floodplain management on the morphodynamic evolution of a gravel-bed river: numerical simulations using MAST-1D

Sarah Harbert, Northwest Hydraulic Consultants, Tukwila, WA, SHarbert@nhcweb.com
J. Wesley Lauer, Seattle University, Seattle, WA, lauerj@seattleu.edu
Andrew Nelson, Northwest Hydraulic Consultants, Bellingham, WA, ANelson@nhcweb.com

Extended Abstract

Simulating geomorphic change on rivers over the decadal timescales relevant to river management often requires consideration of river discharge, sediment transport, and, critically, the channel/floodplain processes that maintain the channel. In addition, the adjustment of channel geometry to changing flow and/or sediment supply regimes – if such adjustment is possible given floodplain management – is important for anticipating future flood and channel migration hazards. This study illustrates the interacting influences of potential discharge regime change (due to climate or management) and management approaches such as levee setbacks or sediment augmentation/removal on channel morphodynamics and flood hazard. It utilizes the Morphodynamics and Sediment Tracers in 1-D (MAST-1D) model (Lauer et al., 2016) to illustrate the sensitivity of a 60-km long reach of a large gravel-bed river to hypothetical changes in discharge regime and floodplain management while accounting for spatially-varying tributary water and sediment supply.

MAST-1D computes size-specific sediment fluxes for sediment nodes representing relatively short (km-scale) sections of a channel reach. Computations are performed using a simplified cross section that includes a constant-elevation floodplain. A sediment budget computation at each node accounts for sediment storage in the channel bed and in an off-channel deposit representing the floodplain. Independent models for bank erosion, which depends on mobility of bank-toe material, and vegetation-moderated point bar formation allow channel width to adjust. A size-specific Exner equation applied to each sediment storage reservoir ensures that sediment liberated by any net channel widening or stored due to narrowing or floodplain deposition can be tracked through the model. The independent submodels for bank erosion and vegetation encroachment facilitate computations of overall lateral change rates as the channel shifts across the channel migration zone. Simulations based on daily discharge hydrographs illustrate how channel geometry adjustment in response to high flows affects subsequent flood hazard, as well as how channel widening can represent a dominant source of sediment during and well after a large flood. Management scenarios, including levee setback projects and sediment augmentation and removal scenarios, can also easily be represented in the model, supporting assessment of the resilience of these techniques in a changing climate. Python-based Jupyter Notebooks representing the simulations provide templates that can be modified to represent similar climate and management changes in other river systems.

Bank Erosion and Width Adjustment

In MAST-1D, in-channel sediment fluxes are computed using the Wilcock and Crowe (2003) transport equation, in which sediment transport depends on the ratio between the shear stress felt by sediment particles, τ', and a size-specific reference shear stress, τ_{ri}, that depends on the grain size structure of the bed surface. Following DeRego et al. (2020), this model was extended to represent lateral bank erosion by assuming that the bank erosion rate E is proportional to the ratio of τ' to a reference shear, $\tau_{r,toe}$, computed for a characteristic fraction (e.g., D_{65} or D_{84}) of a mixture of bed- and bank- material representing material protecting the bank toe,

$$E = \begin{cases} MF_M\left(\frac{\tau'}{\tau_{r,toe}} - E_t\right) & \frac{\tau'}{\tau_{r,toe}} > E_t \\ 0 & \frac{\tau'}{\tau_{r,toe}} \leq E_t \end{cases} \quad (1)$$

In the model, M is a global mobility rate (m/day), F_M is the fraction of banks in a given MAST-1D note that are erodible (i.e., the fraction of banks not affected by bedrock, revetments, or erosion-resistant deposits), and E_t is a threshold transport stage below which erosion is assumed negligible.

Channel narrowing occurs at a rate that is proportional to the difference between the channel's width and a hypothetical minimum width. The volume flux of material associated with narrowing is equal to a characteristic point bar height, H_{pb}, times the narrowing rate and channel length. Point bar material originates from the node's active layer and has a size distribution equal to a weighted mixture of the channel's load and the active layer's size distribution.

MAST-1D Computations

At each node, MAST-1D performs mass conservation computations for the channel's active layer, for a floodplain deposit adjacent to the channel, and for an arbitrary number of substrate reservoirs below the channel or floodplain. For each node, the hydraulics are computed using a steady uniform flow approximation that partitions flow between channel and floodplain zones. Channel discharge and τ' depend primarily on the thickness of the floodplain reservoir, the channel slope, and the hydraulic roughness computed from the active layer grain size distribution.

Bed material transported into a node from upstream, produced by bank erosion, or supplied by tributaries is considered as input to the node's active layer. Export from the active layer to the next downstream node occurs at rates computed from the size-specific transport equation, and export to the floodplain is computed using the narrowing function and an overbank deposition function (see Lauer et al., 2016). Within each node, overall channel bed elevation and texture adjustment are computed for each timestep according to a size-specific Exner equation applied to the active layer. In this way, any sediment brought into any node is either stored within the node or transferred downstream.

Sediment enters the floodplain reservoir through the narrowing and overbank deposition processes or by transfer from the substrate. It leaves the floodplain reservoir through bank erosion or transfer to a substrate reservoir. A net difference between erosion and deposition results in a change in overall floodplain thickness. Floodplain thickness (and thus also channel capacity) also changes if bed aggradation raises the bed or if channel incision lowers it. Together, the dependence of erosion fluxes on floodplain thickness and the dependence of narrowing rate on deviations from the channel's minimum width represent stabilizing feedbacks that push the system towards a steady-state bankfull capacity.

Simulations

A 60-km reach of a large gravel bed river was considered in a set of MAST-1D simulations representing approximately 35 years. The simulations occurred at a daily timestep, with shorter steps when flow was above a threshold discharge. The channel geometry, bed slope, and size distributions for each node were based loosely on field measurements but have been simplified significantly. Several tributaries were included in the reach, so discharge timeseries varied slightly from upstream to downstream. Two hydrologic scenarios were considered, one representing existing conditions hydrology and one representing an extremely simplified (and completely ad-hoc) modified hydrologic regime in which all daily discharges are increased by 5 percent. Our simplifications mean that these scenarios do not represent any specific river system and are included here only to illustrate the relative magnitude of change that can be simulated in MAST-1D. Simulations were performed for 1) no bank erosion, unmodified (lower) discharge, 2) bank erosion allowed, unmodified (lower) discharge, 3) no bank erosion, modified (higher) discharge, and 4) bank erosion allowed, modified (higher) discharge.

For all cases, MAST-1D is used to track overall channel width at a node located roughly mid-reach. Because MAST-1D tracks sediment load for each timestep, it can also be used to compute various measures of discharge effectiveness. Output was used to compute the discharge above which X percent of the overall sediment flux moves, Q_{sX} (cf. Vogel et al., 2003; Hassan et al., 2014). The computation was performed by sorting the record of discharge and sediment fluxes by discharge from low to high, creating a cumulative sum of sediment flux (representing the total movement of sediment below the each discharge), then identifying the discharge associated with a given percent of the total flux. The computation was repeated for several sediment size classes for the unmodified discharge simulations.

Results and Discussion

Timeseries of width at up-channel coordinate 40 km for the two scenarios considering bank erosion (Figure 1) indicate that both simulations converge towards a dynamically stable width characterized by similar amounts of widening and narrowing. Widening is consistently greater in the higher discharge scenario, resulting in the final width being about ten meters greater in the higher discharge scenario. Cumulative channel widening and cumulative channel narrowing at the end of the simulation are plotted against along-channel coordinate in Figure 2 for both the lower and higher discharge scenarios. Widening and narrowing vary somewhat from location to location, most likely because of tributary inputs and/or variability in floodplain size distributions. However, at a given node, widening and narrowing are similar within a given simulation, indicating that channel capacity achieved a dynamically stable value that remains relatively constant throughout the reach.

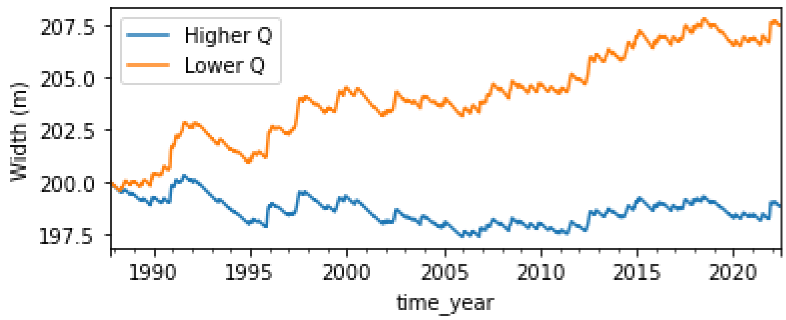

Figure 1. Simulated channel width at mid-reach node (at upstream coordinate 40 km).

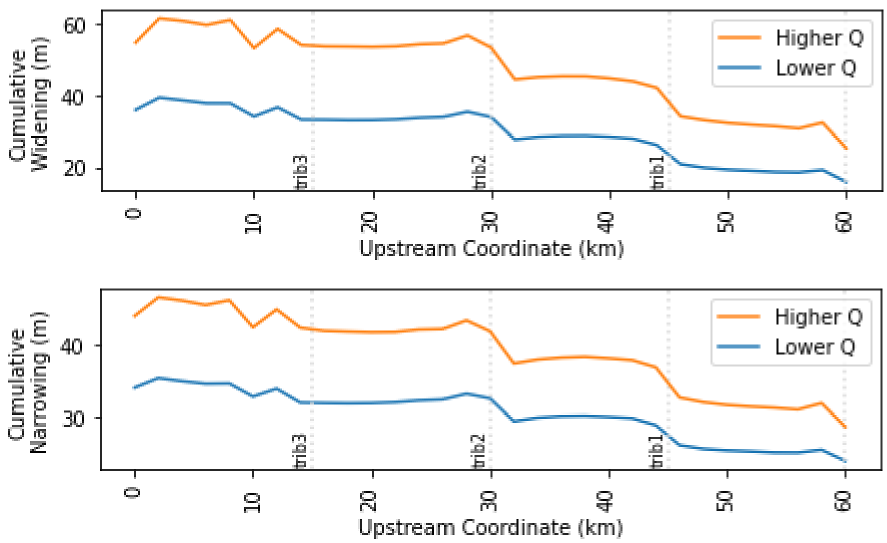

Figure 2. Cumulative widening and cumulative narrowing over the course of the simulation for base hydrology (denoted Lower Q) and invigorated hydrology 20% larger than base (denoted Higher Q). Tributary confluences are show with the vertical dotted lines.

Figure 3 presents the estimates of Q_{sX} computed at up-channel coordinate 40 km. In all size classes, the discharge above which a given percentage X of bed material moves is lower for the runs that include bank erosion than for those that do not. Evidently, mobilization of bank toe material in the simulations occurs earlier and at lower discharge than does full mobilization of the bed, despite rather aggressive adjustment of τ' in the in-channel transport computation to increase active layer mobility. The effect is most apparent for the coarsest sediment size classes, highlighting the increasing importance of bank sediment as a sediment source relative to the bed as sediment size increases. Together, the results emphasize the importance of considering storage and mobilization of near-channel bank and bar deposits when evaluating channel stability, evaluating sediment budgets, or simulating long-term channel change on gravel-bed rivers.

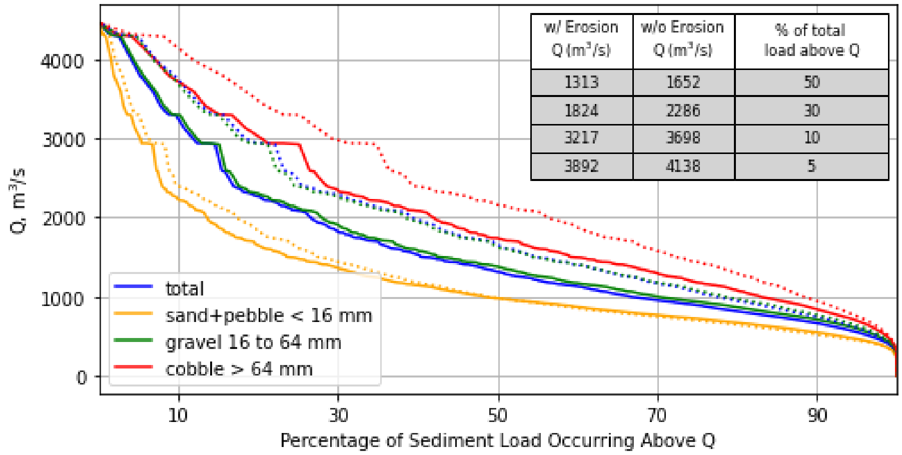

Figure 3. Dependence of cumulative sediment load on discharge for node at upstream coordinate 40 km. Solid lines denote simulation that includes bank erosion. Dotted lines denote simulation that does not include bank erosion.

References

De Rego, K., Lauer, J.W., Eaton, B., Hassan, M. 2020. "A decadal-scale numerical model for wandering, cobble-bedded rivers subject to disturbance," Earth Surface Processes and Landforms 45, pp 912–927.

Hassan, M., Brayshaw,D. Alila, Y., Andrews, E. 2014. "Effective discharge in small formerly glaciated mountain streams of British Columbia: Limitations and implications." Water Resources Research. https://doi.org/10.1002/2013WR014529.

Lauer, JW, Viparelli E, Piégay H. 2016. "Morphodynamics and sediment tracers in 1-D (MAST-1D): 1-D sediment transport that includes exchange with an off-channel sediment reservoir." Advances in Water Resources 93: pp 135–149.

Vogel, R.M., Stedinger, J.R., Hooper, R.P. 2003. "Discharge indices for water quality loads," Water Resources Research 39(10), 1273: pp. 1-9.

Wilcock, P.R., Crowe, J.C., 2003. "Surface-based transport model for mixed-size sediment," Journal of Hydraulic Engineering 129: pp 120-128.