Using HEC-WAT and HEC-RAS-Sediment to Evaluate the Effect of Hydrologic Uncertainty on Bed Evolution

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Introduction

Long term river aggradation or degradation can compromise flood risk management measures like levees, reservoirs, diversions, and conveyance channels. Deposition can reduce channel conveyance or reservoir capacity over time, reducing future project benefits. Channel incision and migration can affect levee fragility, increasing risk of failure. Therefore, project benefit calculations, in morphologically active systems, must account for deposition or erosion.

Additionally, sediment transport has a non-linear relationship to flow. Large flows carry a disproportionate fraction of the sediment load. This makes sediment impacts on flood risk management projects very sensitive to the projected future hydrology, including both the frequency and timing of peak flows. The Hydrologic Engineering Center (HEC) has developed new stochastic tools to investigate the impact of morphological responses to natural variability (i.e. uncertain future flows) on project benefits and future flood risk. This paper introduces two main sources of morphological uncertainty on flood risk (magnitude and timing) and demonstrates how the connection between HEC's stochastic hydrology and sediment transport modeling tools help quantify these uncertainties.

Morphological Flood Risk: Magnitude

Non-linear morphological processes amplify the effects of flow variability. Rivers commonly transport most of their sediment during a relatively limited time period, the 1 to 10% of the year with the highest flows. Rivers with significant year-to-year hydrologic variability can transport most of the system sediment in a few high flow years.

Morphological amplification of flow variability can complicate flood risk studies. For example, Figure 1 includes fifty, synthetic, 50-year time series, that sample of a hypothetical, non-linear depositional distribution. The final bed elevation depends on the frequency and magnitude of the largest flows. Because deposition reduces channel capacity and increases water surface elevations, each potential hydrologic future will not only expose a project to different hydrologic risks but will also degrade the level of protection at different rates. If this project began losing befits after 2.5 meters of deposition, project performance would vary dramatically over these different hydrologic futures. Additionally, the non-linearity of the flow-transport relationship can skew the bed change distribution (see the histogram summarizing the final bed change distribution in Figure 1), introducing some low probability-high deposition events.

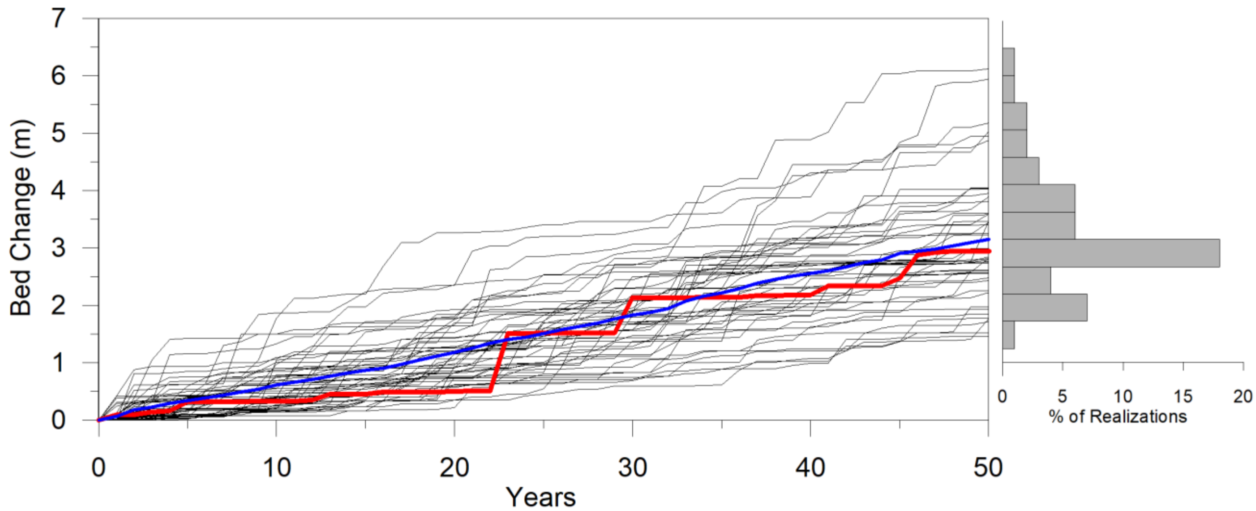

Figure 1. Fifty Realizations sampling a non-linear, annual, bed change distribution and a histogram of final bed change (right). The median final bed change realization is red and the mean is blue.

Morphological Flood Risk: Timing

Morphological, flood-risk impacts are not limited to the magnitude and frequency of large events. The non-linearity of sediment processes makes the flood risk benefits sensitive to the *timing* of these events. **Error! Reference source not found.** illustrates the importance of event timing on morphological benefit impacts.

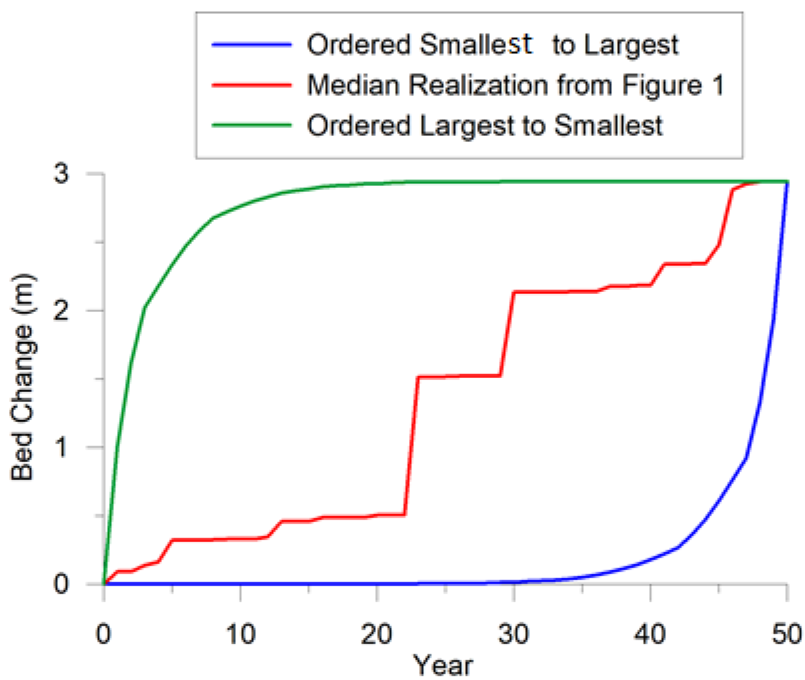

Figure 2. Median bed change time series from previous plot (red), reordered from max-to-min bed change (green) and min-to-max bed change (blue) to demonstrate the morphological impact of event timing on flood risks. If the larger events occur earlier project benefits are likely negatively impacted or project O&M expenses may be significantly increased.

Error! Reference source not found. includes the median, total, bed-change time series from Figure 1 (red curve). **Error! Reference source not found.** also re-orders these events in worst- and best-case-scenarios, front loading and back loading the large events respectively. Because the system deposits almost 70% of the total material in three events, the timing of these events affects the subsequent level of protection and the overall project benefits. Early deposition reduces benefits for most of the project life while hydrologic time series that backload the large flows retain benefits for most of the project life, for example the timing of large capital improvement costs (e.g. dredging, lowering water intakes that are necessary to accommodate degradation). USACE costs estimates of O&M during the project life may also be impacted by timing.

Even with just one future hydrologic realization, a hypothetical project that starts to lose benefits at 2.5 meters will perform better if the large events are later than if they are earlier or evenly distributed. For example, engineers sometimes assume constant deposition rates (e.g. historic bed change divided by years between surveys) when computing the benefits raising a levee in a depositional system. However, early events can reduce the level of protection and reduce the benefits throughout the project life. This makes morphologically active reaches sensitive to not only the magnitude and frequency of future events but also the timing.

Sediment feedbacks also affect the flow-stage relationship in a reach. Channel deposition in each event is not independent. Deposition tends to increase the slope of the reach and decrease subsequent deposition. So the magnitude, frequency, and timing of the morphologically significant events not only affects the project performance, but also the impact of future events on project performance. For example, **Error! Reference source not found.** simply re-orders depositional events without year-to-year feedbacks, yielding identical final conditions. In reality (and in a high quality model) the event order will also affect subsequent bed change, potentially driving divergent final conditions.

Continuous Simulation in HEC-WAT

Flood risk management benefits can be very sensitive to the magnitude, frequency and timing of future flows on morphologically dynamic reaches. Therefore, project teams must quantify the impact of natural variability on project performance in these systems. The Hydrologic Engineering Center's Watershed Analysis Tool (HEC-WAT) can quantify the impact of natural variability by sampling historic and synthetic flow records and run other HEC software with multiple, stochastic, future time series.

Previous versions of HEC-WAT combined flood risk computations by feeding the HEC's River Analysis System (HEC-RAS) multiple, independent, sampled, water years and compiling the results. Simulating independent, annual events is appropriate if the channel is static and the relationship between flow and river stage is stationary. However, HEC-WAT required a new approach to support serial impacts of continuously simulated events to account for morphological change.

HEC-RAS has a mobile-bed, sediment-transport model (Brunner and Gibson, 2006, Gibson et al., 2006, Gibson et al., 2017a) that can simulate deposition and erosion and the water surface response in morphologically dynamic systems (Shelley and Gibson, 2015, Gibson et al., 2017b). However, if the channel is dynamic, water-surface elevations in each year are contingent on the previous flood history. The assumption of year-to-year temporal independence breaks down.

Therefore, the HEC-WAT could no longer run independent water years through HEC-RAS and compile the results. Computing the morphological impacts on flood stage with HEC-RAS required a new, continuous-simulation module in the HEC-WAT. HEC added functionality to the Hydrologic Sampler plugin to generate continuous simulations. Through that plugin HEC-WAT can now generate long term, multi-year, stochastic time series. The study team then used this tool to investigate the impact of natural variability on HEC-RAS mobile bed results.

Simulating the Impact of Natural Variability on Reservoir Deposition with HEC-WAT and HEC-RAS

The study team applied the continuous-simulation plugin in HEC-WAT with the mobile-bed mode in HEC-RAS to investigate the role of natural variability on reservoir sedimentation. The study team used Gibson and Boyd's (2014) calibrated, unsteady, sediment transport model of the Lewis and Clark reservoir. The Lewis and Clark reservoir is the downstream pool of the Missouri Cascade, impounded by Gavins Point Dam (Boyd and Gibson, 2015). While the Missouri River delivers most of the flow in this system, the Missouri Reservoirs (including Fort Randall, just upstream) are an efficient sediment trap. Therefore, the Niobrara River - a mid-reservoir tributary – delivers most of the sediment load to this reservoir. The study team set up HEC-WAT to sample both the upstream Missouri flows out of Fort Randall and the Niobrara flows that deliver most of the sediment. HEC-RAS computed Niobrara sediment loads with a flow-load rating curve.

HEC-WAT ran 350, 50-year, mobile-bed, HEC-RAS, sediment transport simulations of this reservoir with sampled, future, hydrologies. Figure 3 includes time-series results of bed change for two cross sections. The final (50 year) longitudinal cumulative volume change profiles for all 300, 50-year realizations are plotted in Figure 4. The reservoir bed and volume change included more uncertainty in the reservoir pool and along the foreset bed of the delta (approximately downstream of river mile 830) than upstream, along the topset bed of the delta.

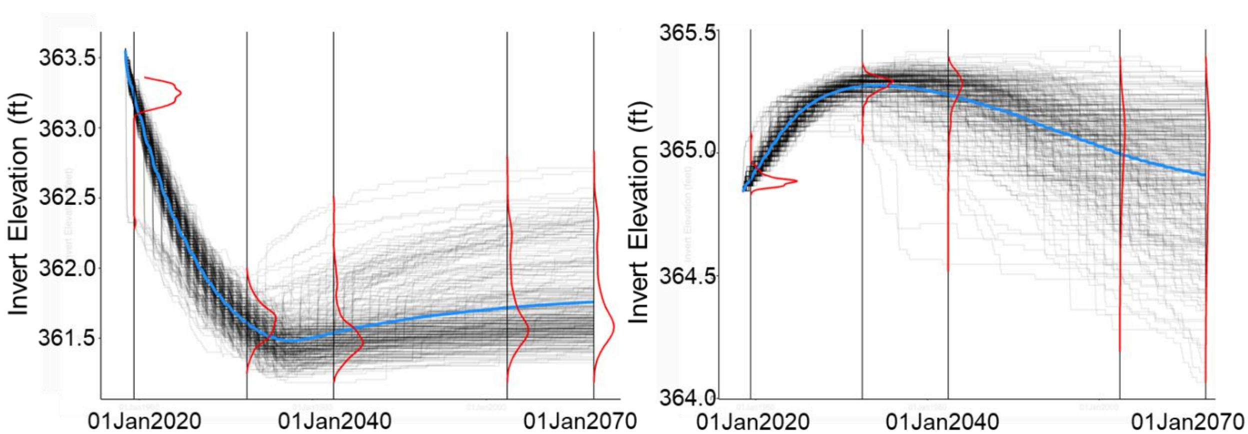

Figure 3. HEC-RAS bed change time series traces at two cross section on the Missouri River. Plots include 350 realizations based on stochastic 50-year future hydrologies provided by HEC-WAT. Blue line is mean and red lines are proportional distributions.

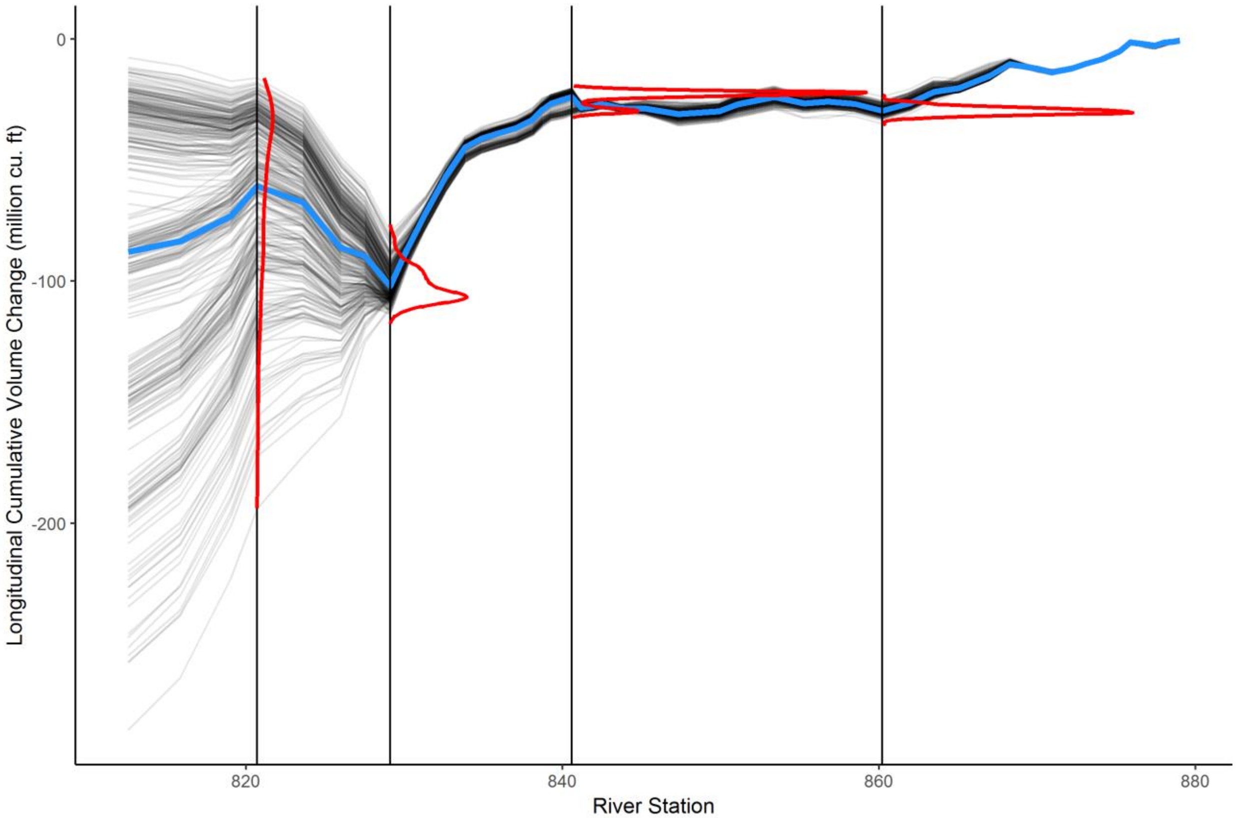

Figure 4. Longitudinal cumulative volume profile for 300, 50-year, mobile-bed, sediment-transport simulations with different hydrologic realizations from HEC-WAT. The blue line is the mean and the red lines are distributions at diffrent locations.

Limitations and Development

HEC-WAT generates continuous, future, flow series in HEC's Data Storage System (HEC-DSS) through the Hydrologic Sampler plugin. Therefore, an HEC-RAS project must use HEC-DSS flow boundary conditions to leverage the continuous, natural-variability features of HEC-WAT. In version 5.0.7, only unsteady sediment transport can use HEC-DSS flow boundary conditions. Therefore, in the 5.0.x versions of HEC-RAS, these features are available for unsteady sediment transport models, not the more common quasi-unsteady models. Developmental versions of HEC-RAS 5.1 now include quasi-unsteady, HEC-DSS boundary conditions, making these tools applicable for quasi-unsteady models in future releases. Additionally, sampled boundary conditions are sampled together (e.g. the upstream and tributary flows represent the same sampled year). Future versions should include options to sample these boundary conditions independently or with correlation assumptions.

Conclusion

Sediment processes are non-linear, and can amplify the uncertainty associated with natural hydrologic variability (future flows). The magnitude, frequency, and timing of future flows can introduce uncertainty in the future stage-flow curve and project benefits. HEC added continuous simulation capabilities to the HEC-WAT's Hydrologic Sampler plugin that feeds multi-year flow series to mobile-bed, sediment-transport simulations in HEC-RAS. This connection helps project-delivery teams quantify the influence of natural variability and future flow assumptions on future-with-project, flow-stage uncertainty. Quantifying this uncertainty is critical to understand risk to project benefits in morphologically active systems.

Acknowledgments

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