Practical evaluation of USACE sediment models on the Lower White River in Washington State- Case Study of the Countyline Levee Setback project

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Abstract

This paper is focused on summarizing recent sediment models developed by the U.S Army Corps of Engineers (USACE/Corps) to better understand the dynamic, coarse-bedded alluvial fan formed by the Lower White River in Washington State. The paper illustrates practical uses of the Adaptive Hydraulics (AdH) and 1D and 2D HEC-RAS sediment transport models to look at issues related to channel capacity and setback levee design. The modeling is focused on hindcasting observed changes resulting from the recently constructed Countyline levee setback project. All models performed reasonably well at matching depositional trends. The 2D AdH and 2D HEC-RAS exhibited highly dynamic behavior consistent with observed changes namely channel establishment, bar building, braiding, and channel abandonment relevant for feature design (levee breach configuration, macro scale roughness elements). The AdH model had the greatest fidelity to observed changes but required one week on a supercomputer to simulate 4 years. The HEC-RAS 2D model was practical to set up on a desktop PC but struggled with long run times and had a harder time reproducing smaller scale changes in the floodplain and channel. The branching 1D model was able to reproduce reach scale trends in the main channel and reconnected floodplain and was used to efficiently forecast near-term (5-year) changes in channel capacity relevant for emergency management. Both 1D and 2D models should be considered for dynamic reaches – with 1D models used to quickly analyze reach scale phenomena and to constrain and inform 2D models that are focused on understanding complex changes in shorter time horizons/spatial domains. While all models show immense promise for more reliably managing flood risks in dynamic rivers, further improvements in hardware and software are needed before these types of investigations become routine. This talk is a companion to the Comport et al. paper.

Introduction

The channelized alluvial fan reach of the Lower White River in Washington State (Figure 1a) has been subjugated to over a century of large-scale river engineering “improvement” projects in response to a catastrophic avulsion of floodwaters into the Puyallup Basin via the Stuck River, from the Green River Basin that occurred in 1906 (Figure 2). The Countyline reach, which is the focus of this paper, spans the portion of the former Stuck River/ current White River that crosses the King County/Pierce County line and transits the communities of Auburn, Pacific and Sumner. The Lower White River and project reach have been intensively manipulated over the last century in response to flood damages, sediment buildup and woody debris (Figure 1b, 2d).

As shown in Figure 2, interventions in this reach include complete channelization with multiple cutoffs (Figure 2a), decades of repeated dredging events (Figure 2c, ceased by the 1990s), installation of a permanent diversion dam (Figure 2f), installation of a valley spanning debris barrier (Figure 2d, failed about a decade after installation) and installation of a myriad of levees and revetments along most of the length of the river (Figure 2a, b).

Flooding continued along the Lower White/Stuck River until the Corps completed Mud Mountain Dam in 1948 (for the purpose of flood damage reduction for the Puyallup mainstem). Mud Mountain dam is unique in that it drains the glaciers of the northeast flank Mt. Rainier which generate a high annual sediment load (~500,000 tonnes including wash-load, USGS 2012b) necessitating installation of a low level outlet to pass most sediment stored during flood operations. Because of the canyon setting this results in continued passage of sediment through the dam but altered capacity to transport it downstream. Despite decades of interventions in this reach, the geologic constraints of the lower valley continue to amplify depositional processes that reduce the capacity for flood flows and increase flood risks over time for adjacent properties. Up until the 1990s this risk was managed by repeated and costly dredging.

Development in the 1980s and 1990s along the riverbanks was fostered by soon to be outdated FEMA flood maps that did not reflect the changing risk along this dynamic river. Severe flooding in the towns of Pacific and Sumner occurred in January 2009 in response to a buildup of bed material upstream of the 8th Street bridge during what was then less than a 10-year recurrence interval flood discharge from the Mud Mountain Dam reservoir. The flooding resulted in renewed efforts by the communities and the Federal Government to address the local flood issue including comprehensive studies of sedimentation and channel capacity (Czuba et al. 2010), initiation of the Puyallup Basin general investigation study (USACE 2017), construction of temporary floodwalls, and recent construction of a large setback levee by King County on the left bank of the river (King County, 2020).

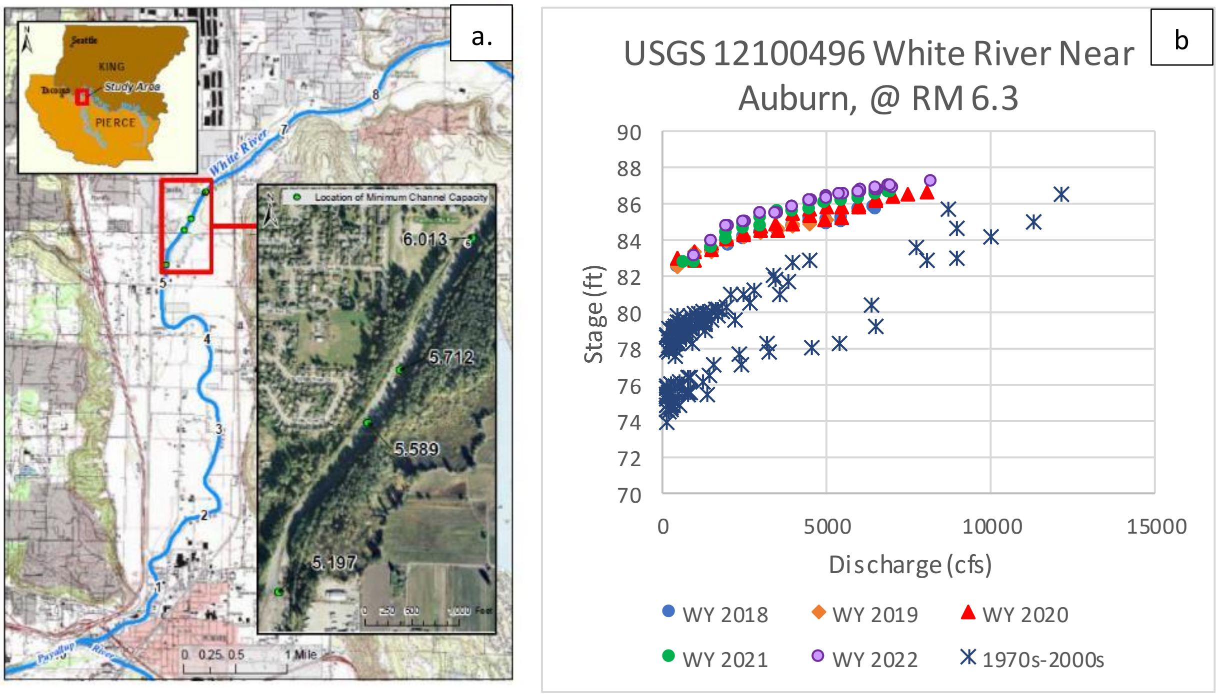


Figure 1. Countyline Reach site map (a.) and rating curve changes (b.) over time attributed to sediment buildup / channel capacity loss

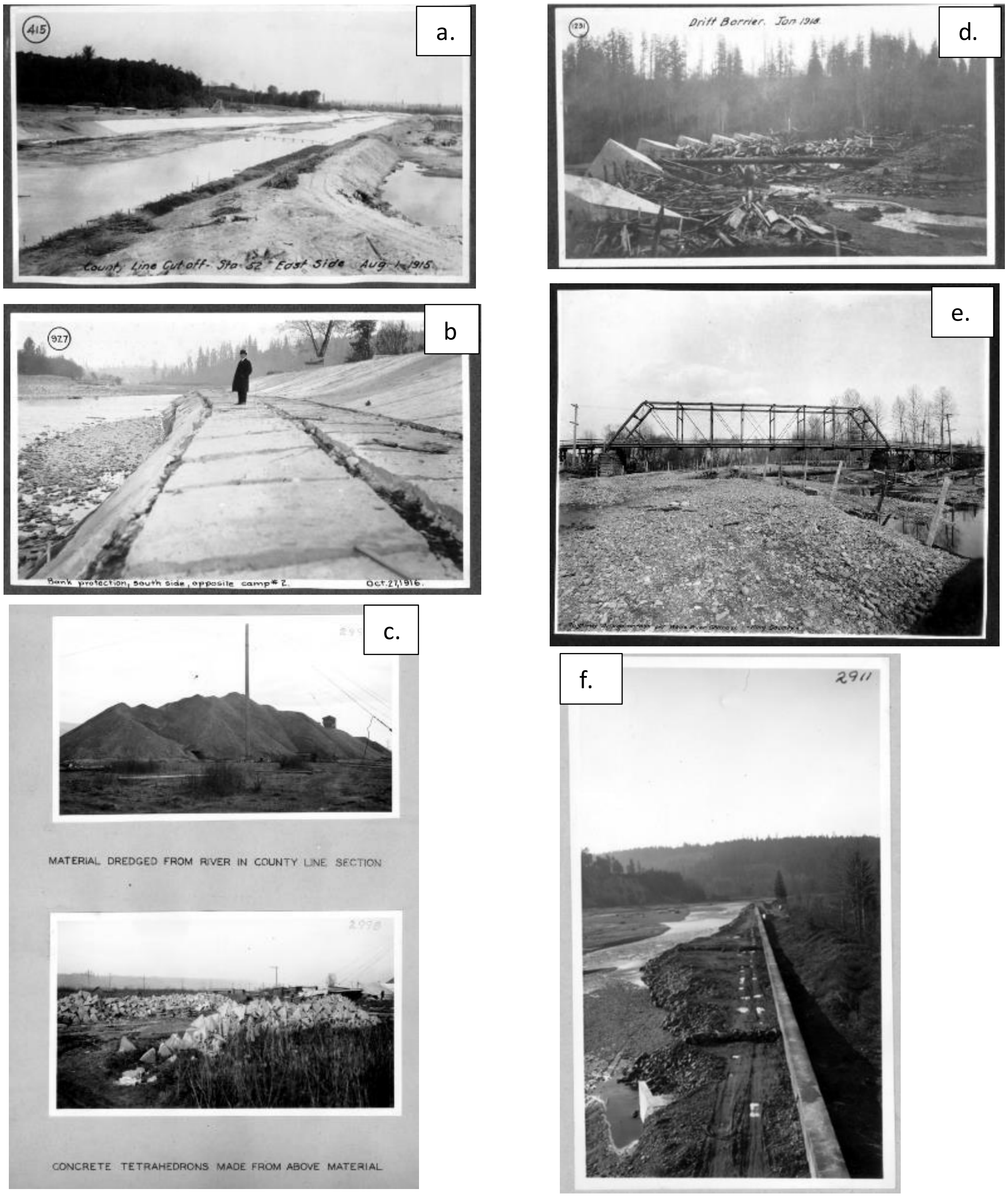


Figure 2. Examples of Lower White River historical channel modifications influencing river conditions (a) Countyline channelization (b) concrete revetments along right bank (c) repeated dredging of gravel (d) debris trap and debris removal, (e) 1906 flood avulsion from Green River to Puyallup River basin and (f) Auburn Wall that maintained the avulsion. All images from King County ICRIC files.

The Corps has conducted several sediment transport model investigations that began in the late 2000s building on the work by the USGS. This work included recalibration of the Lower White River model using the measured streamflow and documented dredge history (Gibson et al. 2017, USACE 2017). This reach has the benefit of repeat channel surveys by King County and a reliable

USGS rating curve with measured sediment loads. In anticipation of the pending construction of the Countyline project the Corps modified the single thread hydraulic model to include the effects of the Countyline setback which reconnected 120 acres of wetland to the river via strategic levee breaches. Due to channel aggradation and levees, portions of the floodplain were more than 10 feet below the channel thalweg elevation. The project designers included several bioengineered revetments and logjams to add large scale roughness to manage flow into the site and reduce likelihood of a full avulsion. This included adding extensive pile based woody revetments along the toe of the levee and several engineered logjams in the main path of the expected overflow.

Several years have elapsed since completion of the Countyline project in October 2017 allowing for post-project validation of the original models, recalibration of updated models to observed conditions, and forecasts of future conditions (channel capacity trends) relevant for real-time reservoir operations and emergency management. The previous models reproduced some of the observed changes that followed levee breaching but these models did not have observed change data to aid in calibration so had higher uncertainties. This work is significantly aided by a commitment by King County to monitor river conditions that includes repeated aerial photos, lidar and bathymetric surveys since 2016. Conditions from July 2021 are shown below in Figure 3 downstream of the upstream connection with the White River. Because of the investments by King County in repeat monitoring, post-project elevation change data are available to assist with model calibration. Consistent with the predictions of the previous AdH modeling work by Jones et al. (2018) sedimentation has been focused in the vicinity of the upstream connection between the mainstem and the restored site.

DEMs of difference (Figure 3) for the 2016/2017 to 2018 period and the 2018 to 2021 period indicate that the bulk of the deposition (~150,000 cubic yards (cy)) occurred in the first year post-completion, after which the site continued to accumulate material but at a much slower rate (9% of the first-year rate). Erosion also occurred within the site, primarily at the downstream end. The deposited material consists of a mix of sands to large cobble. Large concentrations of woody material are found at the heads of bars and three engineered logjams installed to prevent a full avulsion of the mainstem into the site. This woody material unpredictably accumulates and disperses, influencing channel formation and evolution and is a potential explanatory variable for model departure from observation.

This paper is focused on summarizing recent sediment models developed by the U.S Army Corps of Engineers (USACE/Corps) on the Lower White River and illustrating the practical use of AdH and HEC-RAS to look at issues related to channel capacity and feature design. The Lower White River was originally modeled by the USGS in the late 1980s (Prych 1988, Sikonia 1990). This modeling was comprehensively updated in the late-2000's (Czuba et al. 2010) by the USGS who re-surveyed the reach and incorporated sediment transport data from previous studies. This work was followed by project specific updates by the Corps (Gibson et al. 2017) which led to a detailed one-dimensional (1D) and two-dimensional (2D) sediment transport model investigation (Jones et al. 2018) of the large-scale King County designed and constructed Countyline levee setback project (King County, 2020).

Lower White River Sediment Model Overview

In 2015 the Coastal and Hydraulics Laboratory at ERDC began a series of investigations to document setback levee projects (Smith et al. 2017) that led to modeling of the proposed Countyline setback project using the Corps 1-dimensional (1D) HEC-RAS and 2-dimanesional (2D) Adaptive Hydraulics (AdH) numerical modeling software (Jones et al. 2018).

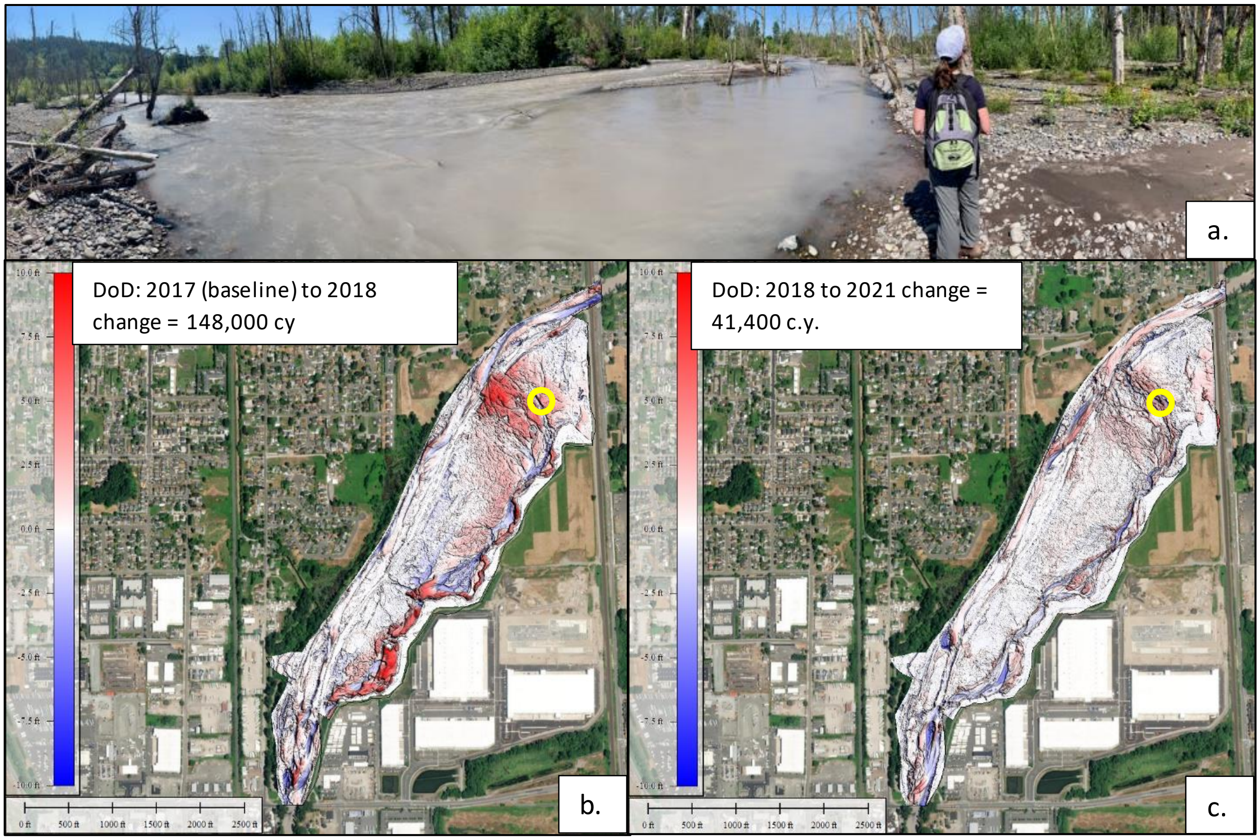


Figure 3. (a) Countyline levee setback project site conditions near upstream connection with White River – summer 2021. Flow into site from mainstem is from right to left. Observed elevation change in Countyline setback reach, 2016/2017-2018 (b) and 2018-2021 (c). Location of panorama photo shown in yellow circle.

The Jones et al. modeling used assumed future conditions hydrology and the latest bathymetry and sediment data from the Puyallup General Investigations study model (USACE 2017, Gibson et al. 2017). This modeling is the basis for much of the work presented in this paper and was used to hindcast the response of the river to the levee setback. The main difference between the previous effort and this effort is that this modeling uses observed instead of assumed flows to hindcast the 1-year and 4-year response from the point of levee breach and compares modeled response to observed response (volumetric, elevation, grain size). This allowed for recalibration of the sediment models and for more accurate forecasts of future bed elevations (2021 to 2026) important for understanding changes in flood risk. This paper presents the setup and results of the 1D hindcast analysis, and compares the results and setup to two computationally distinct USACE 2D morpho-dynamic models. All models use the same underlying terrain dataset which was developed previously as part of a levee setback investigation (Jones et al. 2018). The model setup is discussed below and summarized in Table 1.

Model Setup

1D HEC-RAS: Two one-dimensional (1D) models were developed. The first model was an update and recalibration of the Jones et al. (2018) 1D model (modified from single thread to branching, roughness values adjusted) to match as best possible observed aggradation in the main channel and restored side channel area. The model extends from the Puyallup River to river mile 8.5, just above the "Auburn Wall" built in the 1910s to divert the White River into the Stuck River permanently. The model was run for the 4-year period of 1-Jan. 2017 to 1- Jan.2021. The geometry, transport parameters, grain size data and roughness data were used in a new model cut from 2021 channel data to forecast potential changes in channel capacity. This model was run for 5 recent years of lower than average flows and 5 recent years of higher than average flows to provide a prediction of near-term future bed elevations. This data was then merged with an existing 1D/2D channel capacity model to understand the flood risk implications of future aggradation. This work is described in more detail in the practical use case section of this paper. The 1D model uses the Laursen-Copeland total load transport function due to the high silt/sand load and high gravel/cobble load.

2D Adaptive Hydraulics (AdH): The AdH model from Jones et al. (2018) was updated to include increased resolution and adjusted roughness values through the setback area and simulated observed flows from 2017 to 2021. The updated AdH model is used as reference for 2D RAS model and basis for comparison. The refined model mesh was developed in the Surface Water Modeling System (SMS) and is composed of 36,751 nodes and 73,045 elements. The model uses version 4.6 of AdH and is run on the ERDC high performance computer (HPC) "Jim". The model run dedicated use of 216 processors to simulate 4 years using observed flows requiring 7 days to complete. The transport function is Wright-Parker for suspended sediment and Meyer Peter-Muller with Wong Parker Correction for bedload. Non displacement materials and six bed layers were used to achieve a stable solution. Refer to other model details in Jones et al. (2018).

2D HEC-RAS: The HEC-RAS 2D model grid was created in HEC-RAS Mapper with 5-ft to 100-ft square cells, aligned with flow. Meshed to result in similar cell dimensions and computational nodes as AdH. The underlying terrain data originated from the AdH mesh. Sediment was input to the model with a rating curve and equilibrium load method. Equilibrium load was ultimately selected as it was more stable. The terrain at the upstream end of the model had to be lowered to create a pool so that deposition at the boundary did not create instabilities. Inflow boundary effects (erosion) extended over a mile downstream before equilibrium conditions established near R street bridge. Use of a gradation hot start would likely ameliorate these effects. An upstream flow and downstream normal depth boundary for inflow/outflow was used. The bed sediment data uses the same range of grain classes as AdH, and same roughness values. To improve run times bed materials were distributed in three layers – a top layer composed of 50% medium sand, 50% very coarse sand, a coarse base layer composed of 50% medium gravel, and 50% large cobble. The bottom layer was set as non-erodible. Transport functions and parameters: Wu transport function, active layer sorting method, Wu and Wang fall velocity method, Wu et al. hiding function with default exponents. Active layer thickness set to d90 with a minimum thickness of 0.01 feet which was found to improve convergence and thus reduce simulation time. The base-bed slope coefficient was disabled as it was causing model instabilities. Avalanching was turned on with default values as it appeared to improve stability. Avalanching occurs when the slope of the bed is steeper than the angle of repose of the bed material, causing a slide. The transport model advection diffusion parameters enabled the total load correction factor (Van Rijn-Wu bed-load factor, no correction for suspended load). The weighted suspended and bedload total load diffusion method was used, the suspended and bedload diffusion methods were disabled. The total length method was selected for the adaption coefficient. A length about 2 times the average grid cell dimension (25 feet) was selected.

The HEC-RAS model uses the unsteady flow engine with the shallow water equations Eulerian-Langrangian method (SWE-ELM) equation set, conservative turbulence model, 0.3/0.1/0.05 longitudinal/transverse/Smagorinsky coefficients. 0.3 to 20 second adaptive time step. 60x morphologic acceleration used with a reduced inflow hydrograph time step by 1/60 (1 hour real time = 1 minute accelerated), PARADISO sediment matrix solver, Exponential advection scheme, default outer loop convergence, computational sediment layer and subgrid parameters.

Table 1. Hydraulic model setup summary

Sediment Transport Model	Geometry	Bathy/topo Data	Simulated period	Run-time, Processor	Transport Function, Sediment boundary	Notes
HEC-RAS 1D (v. 6.2)	100 cross sections, 4 reaches; RM 0 to RM 8.4	2012-2016 (per Jones et al. 2018)	January 2017-January 2021	18 minutes, Intel(R) Xeon(R) CPU E3-1535M v6 @ 3.10GHz 3.10 GHz	Laursen (Copeland) (total load), flow-load curve	Calibrated. 2-year warmup of grain size distributions.
HEC-RAS 2D (v. 6.3.1)	20,000 cells, RM 8.5 to RM 3.75	2012-2016 (per Jones et al. 2018)	January 2017-January 2021	18 hours, Intel(R) Xeon(R) CPU E3-1535M v6 @ 3.10GHz 3.10 GHz	Wu (total load), 4 grain classes, equilibrium total load, Wu et al. hiding	Uncalibrated. 60x Morpho-dynamic acceleration, 1/60 reduction inflow hydrograph time step.
AdH (v. 4.6)	73,050 elements, 36,750 nodes; RM 8.5 to RM 3.75	2012-2016 (per Jones et al. 2018)	January 2017-January 2021	7 days. High Performance Computer "Jim" with 216 processors	Wright-Parker (suspended) & MPM w/W&P correction (bedload), flow-load time series (suspended), equilibrium (bedload)	Calibrated (2-yr). 60 day high-flow warmup of grain size distributions.

Results

This purpose of this paper is to provide real world examples of how Corps enterprise models performed relative to observed changes not to rank models relative to observed changes and to each other. Model performance for this investigation is limited to volumetric changes – how does the model compare to observed changes and fidelity to observed geomorphic behavior – do grain sizes generally match trends in reach (downstream fining, coarse bed materials at entrance to side channel), are major channel changes captured (side channel establishment and braiding)? Is the side channel flow split maintained? Are the locations and patterns of sediment buildup within the site captured by the models? Table 2 and 3 summarize the model behavior for two time periods: the first year (Jan. 2017-Jan 2018) and the period from 2017-2021 for the 1D HEC-RAS and 2D AdH model as the 4-year simulation 2D HEC-RAS model was incomplete at time of submission.

Table 2. Model results summary, 2016/2017 - 2018

Sediment Transport Model	Modeled vs. Observed Depositional Change (2017-2018)	Flow Split Established and Maintained?	Grain Glass Spatial Distribution replicated?	Bars, Channel Braiding, Pools replicated?
HEC-RAS 1D	-46%	Yes	Yes**	No
HEC-RAS 2D*	+ 168%	Yes	No	Yes
AdH	-42%	Yes	Yes	Yes

The similarity in the 1-year and 4-year volumetric change between the 1D HEC-RAS and 2D AdH model is attributed to the diligence on the part of the modelers to calibrate to the observed data. The similarity of the predictions is pure coincidence and was checked multiple times.

Table 3. Model results summary, 2016/2017 – 2021

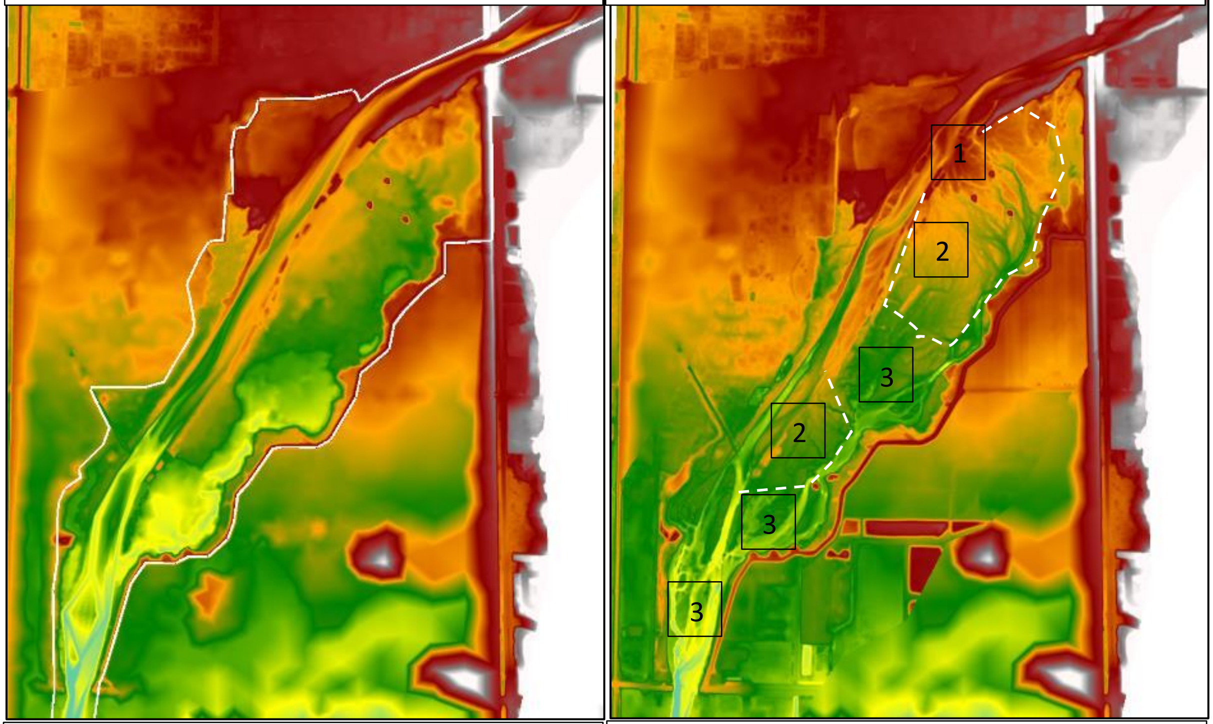
Sediment Transport Model	Modeled vs. Observed Depositional Change (2017-2021)	Flow Split Established and Maintained?	Grain Glass Spatial Distribution replicated?	Bars, Channel Braiding, Pools replicated?
HEC-RAS 1D	-13.1%	Partially	Yes**	No
AdH	-13.2%	Partially	Yes	Yes

** Longitudinal, not lateral

Figure 4 provides output for bed elevations after 1 year of simulation for the two 2D models compared with observed changes. In Figure 4a the initial condition is shown for the two 2D models. This terrain is a simplified version of site data available in 2016/2017. In figure 4b the conditions for the 2018 topo-bathy lidar survey are shown, with the abrupt deposition at the entrance of the restored area clearly evident, along with formation of several braided channels through the site. Two lobes of deposited sediment are visible (outlined by dotted white dash line), the larger of the two is located at the upstream end of the site, and the smaller of the two is located at the downstream end of the site where inflowing sediment met deeper slower backwater. The sediment is clearly built up in the vicinity of three engineered logjams installed as part of the setback project. Interfingered bars and channels are a result of rapid deposition of incoming bedload during high flows and subsequent reworking of these deposits by moderate flows that have less incoming sediment. In figure 4c the HEC-RAS model reproduces the large lobe and sediment mound at the upstream flow split into the site, as does the AdH model (4d). Both the AdH model and RAS1D, and RAS 2D models reproduced the initial downcutting of the sill at the entrance to the site and maintained some flow into the site through the duration of the simulation. Both the RAS 1D and AdH models showed significant decreases in the percent of the total flow entering the side channel by the end of the 4th year. Aerial photos of the site show a distinct widening of the active channel (unvegetated alluvial surfaces) after reconnection and a steady narrowing of the active channel since.

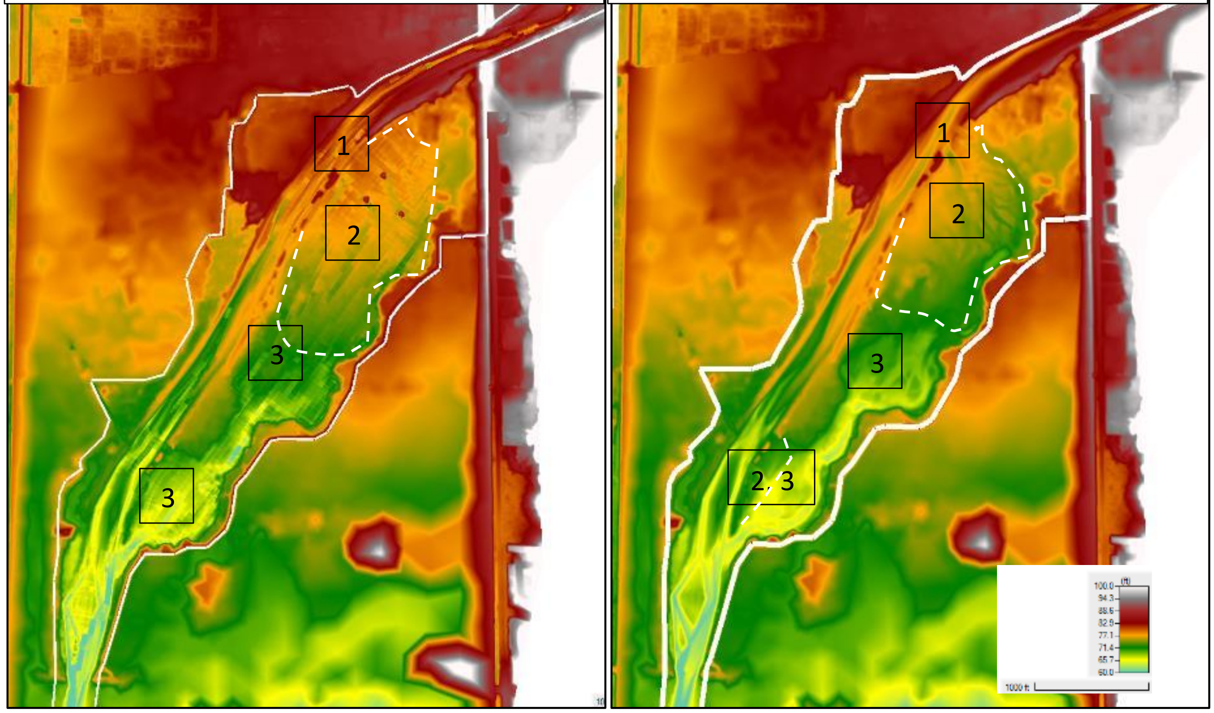
The major difference between AdH and RAS 2D is apparent in the end state bed elevation grids. The RAS model which uses a grid/sub-grid technique for computation efficiency results in a lumpy surface and less distinct channels. The AdH model which uses a mesh refinement scheme maintains a tighter smoother surface with more intricate channels and bars. Note that an earlier version of the AdH model with larger cell sizes failed to reproduce these fine details and under-predicted overall deposition. Smaller mesh size RAS models did a much better job of capturing these features, but long run times prevented presenting these results here.

In most design applications 2D sediment transport models are avoided due to high cost and run times. To better understand potential uses of the RAS 2D sediment transport model as a design tool a version of the model that overpredicts sediment transport (to reduce overall simulation time) was used to provide insights on macro scale geomorphic influence of the three logjams added by the project designers at the Countyline site. This analysis is described in the practical use case section.



a. Jan. 2017 (baseline)

b. Jan. 2018 observed (topo-bathy Lidar)



c. Jan. 2018 modeled (HEC-RAS coarse grid 60 x M.A.)

d. Jan. 2018 modeled (AdH fine grid)

Key: Solid white outline = model extents; 1. Setback notch breaching, channel establishment, followed bar by building; 2. Depositional fan formation and braiding (white dashed line); 3. Channel and bar development

Figure 4. Observed versus modeled bed elevations and major geomorphic changes after 1 year of simulation

Primary findings

The Corps' AdH and HEC-RAS 2D models presented in this paper are most informative for predicting geomorphic responses relevant to design of mainstem diversions into restored floodplains (capturing the spatial distribution of scour and deposition and bed material size variation as well as side channel, bar and pool evolution). The AdH model geomorphic evolution (fine scale braiding and side channel evolution) more closely tracks with the observed changes than does the RAS 2D model, likely due to the RAS model using a courser grid and not taking advantage of the subgrid routines. The HEC-RAS 1D model was efficient and accurate once calibrated for analysis of long term sediment budgets and trends but was highly sensitive to small input variations and parameter adjustments; The closeness of the 1D and 2D AdH volume changes between 2017 and 2021 is coincidental, and indicates both models are well calibrated. The Corps' AdH 2D sediment model is robust and able to capture fine scale physical response of the river to the setback with reasonable runtimes due to the HPC capability; RAS 2D sediment engine (beta) shows promise due to stability, ease of use/setup, and ability to capture spatial sedimentation patterns, but long compute times limit its use to shorter time windows (at present). All post-project validation models were partially confounded by several factors which are presently outside the ability of numerical models to capture including vegetation recruitment and colonization, large wood recruitment and jam formation which dictates channel evolution, and resultant influence on depositional and erosional processes and rates.

Table 3. USACE sediment transport model practical usage recommendations in similar settings based on White River modeling

Model/ Use case	Reach Scale trends	Long Reaches/Large River systems	Decadal scale simulations	Steep, coarse bed, high sediment load	Flow Splits, levee setbacks	Bed changes near structures	Complex geomorphic phenomena (side channel formation braiding, bars, pools)
HEC-RAS 1D	Yes	Yes	Yes	Yes	Yes	No	No
HEC-RAS 2D	Yes	Depends on desired accuracy and reach length	No	Yes	Yes	Yes	Yes
AdH	Yes	Yes (w HPC)	No	Yes	Yes	Yes	Yes

Calibration and sensitivity analyses with both 1D and 2D models confirms that model results tend to be highly sensitive to small changes in underlying data (terrain, grid size), parameters (transport function, hiding, gradations), and computational settings (duration of simulation, acceleration factors, computational tolerances) and that achieving good results will always require comparison with physical data and a solid understanding of transport analyses and river mechanics because the non-linearities inherent with the transport functions create unintuitive feedback loops that magnify as the simulation time window increases. Use of multiple calibration and validation metrics (mass change, vertical elevation change trends, side channel connection, grain class changes) was necessary to gain confidence in the final results. In the case of the 1D model, it was common for a model iteration to match one metric well at the expense of others. Trial-and-error was needed to gain sufficient understanding of model sensitivity and guide parameter and computational setting adjustment. Most of the study effort was dedicated to this process. Model calibration benefited from high quality geomorphic change data but in the case of the 2D analyses was hindered by long run times (despite multi-threading and supercomputers) highlighting needs for continued improvements in software and hardware. A 10-fold improvement in run-times will likely be needed before 2D morpho-dynamic analysis reaches its full potential. Software advancement (GPU computing) or shift to "cloud" supercomputing may also help.

Practical Use Cases

Practical use case 1: Channel discharge capacity investigations

HEC-RAS 1D inherited the routines of HEC-6 in version 3. The model has been continuously updated over the ensuing years and has been proven capable of evaluating reach scale sedimentation problems in nearly any setting. Because the problems of the Lower White River are related to decadal scale deposition in a channelized reach the 1D version of RAS is very well suited for analysis of the problems, however because of the complex overbank topography, simultaneous analysis of out of bank inundation concurrent with sediment modeling requires use of the unsteady flow engine, which can require very short time steps and is not commonly done unless there are no other practical ways to address the problem. A workaround was developed to couple the predictive power of the calibrated 1D sediment model with a calibrated 1D/2D fixed bed/clear water channel capacity model. The calibrated model was modified to update the bathymetry to the current conditions. Maintaining all other calibrated parameters, then run for 5 consecutive lower than average flow years, and five higher than average flow years to establish a near-term range of channel bed elevations in the primary reach of concern. The sediment transport end state cross sections were exported to a new geometry which was then converted to bathymetric DEM which allowed for rapid updates to the 1D/2D model cross sections and lateral structures affected by sedimentation. This fixed bed model was then run with an aggraded channel for range of potential floods to establish changes in channel discharge capacity. The modeling indicates that risks in this reach are greater than current fixed bed models suggest, and that channel discharge capacity should continue to decrease in the near future despite provision of the setback levee. The sediment modeling thus provides and early warning system to give emergency managers more response time and places to focus attention. Note that the end state of the 2D models could also be exported to support a similar analysis. Refer to Comport et al. (2023) for details of this analysis.

Practical use case 2: Feature design

A second version of the HEC-RAS 2D sediment transport model described above was created as a post-hoc experiment to test what could have happened if the three logjams that were added downstream of the main Countyline levee breach by the project designers to manage avulsion risks were not added to begin with. This model has higher fine sediment inflows and greater tendency to deposit in the project reach. In this experiment the jams were removed from the terrain and the model was rerun and compared to the "existing conditions" model. No other changes were made other than the simulation period was shortened to the first 96 days when three successive high flow events connected the river to the side channel area. From inspection of the modeled bed change plots for the with jams and without jams runs (Figure 5), removal of the three jams appears to have had significant influence on reach scale sedimentation. More flow and sediment enter the site initially, and it deposits in a larger fan than the model run with the jams present, however because the sediment buildup on the fan and channel entrance, the amount of flow decreases by the end of the simulation. Presuming the effects of the model limitations on the results are self-cancelling these differences appear to indicate that inclusion of the jams contributed to maintenance of defined low flow channels, which routed more sediment into the site. The presence of these channels around the jams appears is also associate with reduced deposition at the entrance to the site and significant reduction in main channel deposition upstream of the project.

The velocity field around these structure and morphodynamic changes are surprisingly consistent with observed changes, however because of the overloading of sediment in the model and morphologic acceleration factor of 60 these changes occur after 3 moderate flood events instead of over 4 years. Note that the behavior of both models is consistent with the AdH model which suggested sediment buildup over time would shift flow from the side channel back to the main channel. The RAS 2D model with the jams presents appears better able to capture the present day channel network than the model without jams indicating these are important to include in restoration project modeling. Side channels are found in the locations visible in photos despite the original topographic surface in the model being quite coarse. Similarly the mid channel islands and bars are located in the same locations. The areas that have experienced significant deposition are the same areas that experience this in the model (near the main flow split, in the wide area about halfway between the upper and lower connection to the river). The coupling of the hydraulics with the bed change provides as viewed on velocity inundation maps over time provides an insightful picture of the channel network evolving and moving over time. The shading of the velocities provides indications of flow intensity which is helpful for understanding morphologic evolution depicted in bed change or grain size results in a distinctive braided pattern for both model runs with the no jams run being more braided, which makes sense because there are fewer topographic features for the river to concentrate against, resulting in shallow sediment laden flows that are prone to deposition.

Given that this model is uncalibrated some of these features are likely to be a result of numerical diffusion and should be treated with skepticism until validated with observation. Note that RAS-2D model can be run with transport capacity turned on (i.e. no displacement or grain size changes) to provide insights on likely deposition and erosion areas at a fraction of the computational time of a full sediment transport analysis. Thus morpho-dynamic modeling informed design of channel modification projects should arguably become an important step in hydraulic analysis.

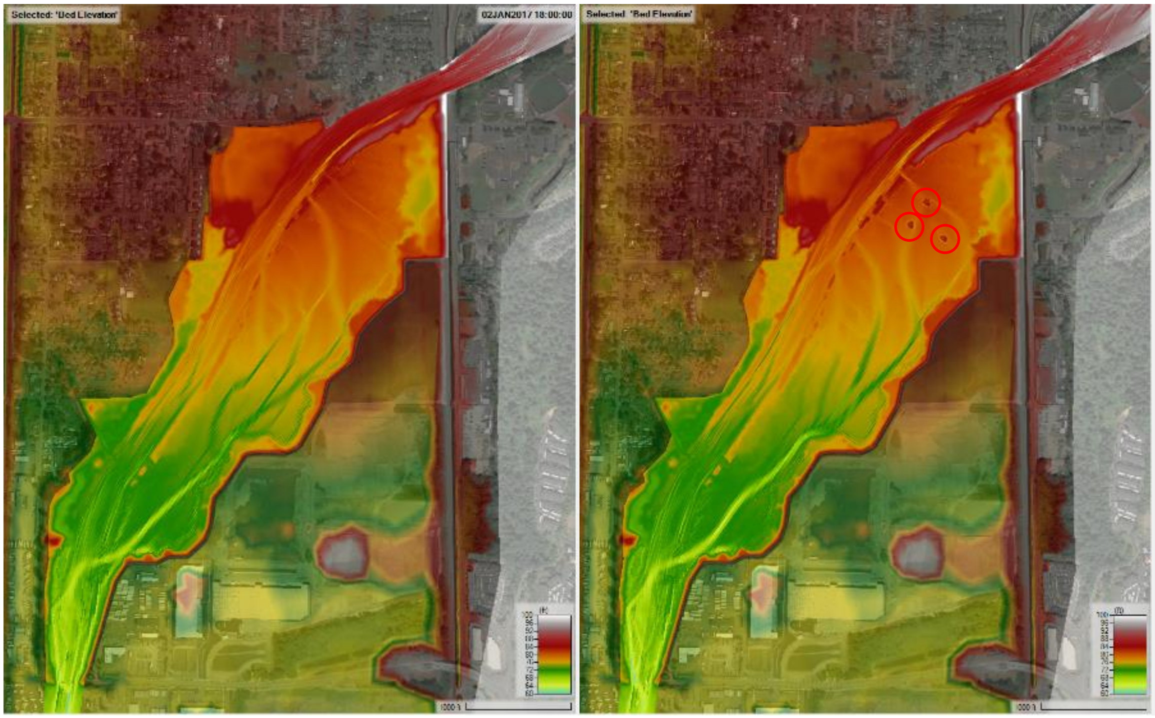


Figure 5. Feature design use case 2: Evaluation of the effects on sedimentation and channel pattern from excluding 3 engineered logjams from the Countyline project

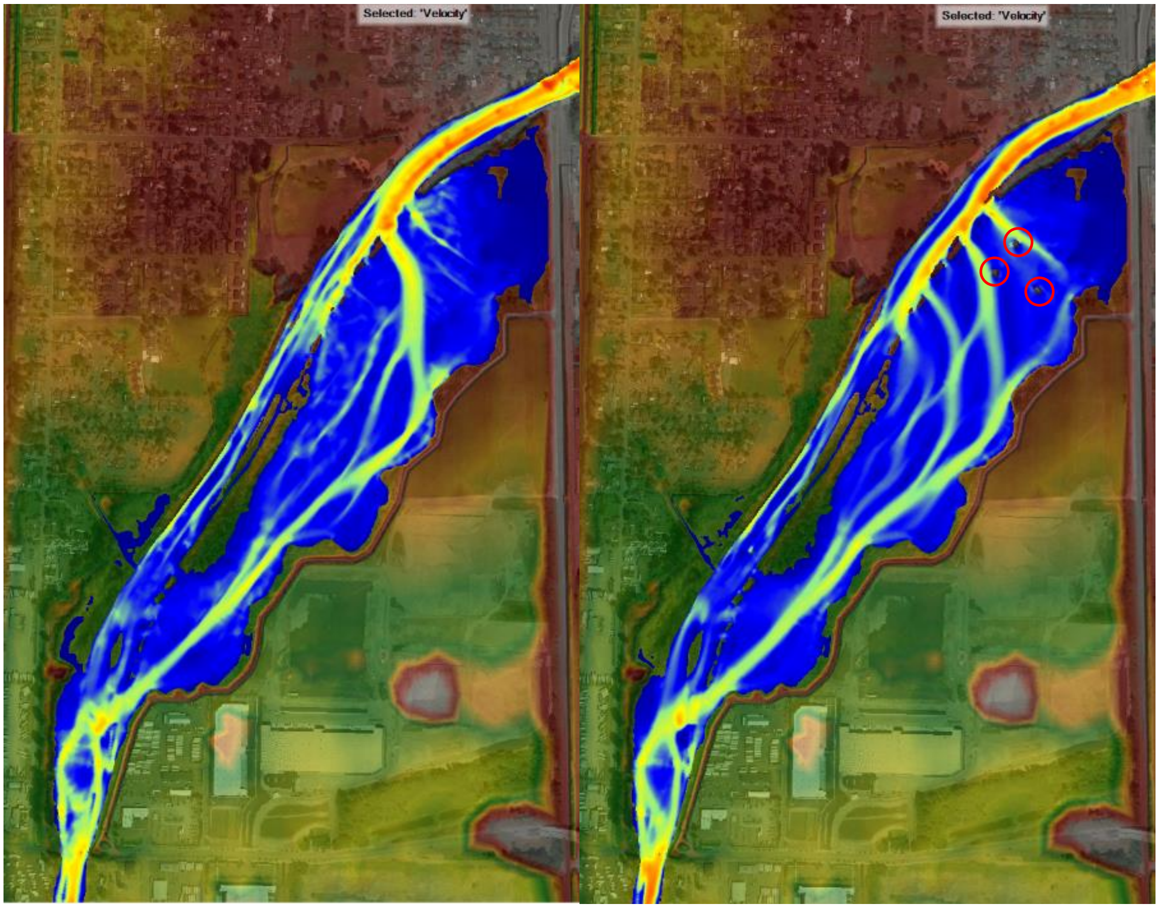


Figure 6. Feature design use case 2: Evaluation of the effects on the resultant velocity field from excluding 3 engineered logjams from the Countyline project

Discussion

Dynamic rivers require dynamic models

The Lower White River has challenged and continues to challenge both the people that live along its banks and those that attempt to manage its waters. One of the fundamental challenges of this river is its sediment load, both abundant and coarse. Once viewed as a foe to be conquered this sediment and the cold glacial waters fed by Mt Rainier are now recognized as a valuable ecological resource for both people and threatened and endangered fish resulting in a dramatic slowdown in the pace of interventions to tame the river. Despite this shift in management philosophy real risks to people and property persist, often as a direct result of static hydraulic models and resulting flood risk mapping.

In the 1980s using what was then state of the art hydraulic models engineers drew static maps of a dynamic river, inadvertently hiding flood risks of the effects of the Mountain and its sediment load. These engineers surely recognized what they were doing had limitations and would by all means have included the effects of the sediment if they had that authorization to do so. This simplification of our rivers and floodplains to static, theoretical, statistical points in time is due to the inherent difficulty of accurately portraying a moving river. The limitations of the FEMA models were laid bare in 2009 when the White River unpredictably flooded hundreds of homes and dozens of businesses during what was then a routine reservoir release. Had the models and survey data collection techniques we use today been available a few years prior that flood, it is likely emergency actions could have been taken to reduce flood damages during that event. It is becoming clear that we can now use best available data and models to predict pending changes and intervene *in advance of* rather than in response to a disaster.

Emerging opportunities and challenges of dynamic models

The authors have combined sediment modeling experience that closes in on a century and are continuously humbled by the curve balls thrown by mother nature. This appreciation is in part due to the effort required to calibrate sediment models and the insights gained from seeing small changes in input manifest in large differences in response given enough simulation time.

The longstanding computer hardware and software limitations that have posed major hindrances to sediment transport and morpho-dynamic modeling have begun to fall away. We are entering a new era where seeing a river move its boundaries during simulation of months to years will become commonplace. Similar to the issues associated with AI deepfakes we will soon need to grapple with the benefits and risks posed by the visual fidelity of simulated results to observed phenomena. The ubiquity of fast PCs, free, powerful software and opensource land use, terrain and streamflow data, and 2D codes that visually and intuitively reveal intricacies of fluvial processes that beforehand required seasoned experts to interpret imply that anyone with a computer and an internet connection could start experimenting with morpho-dynamic modeling. Within the Corps of Engineers, the availability of these tools should justify the increased use on projects where sediment modeling would previously have been avoided. Because good sediment data needed for calibration are still costly and difficult to collect many of these models will lack sufficient calibration and validation datasets. As a community we need to ask ourselves if uncalibrated and unvalidated morpho-dynamic modeling helps us or not before we routinely embrace it. As modelers we need to remember the adage that “all models are wrong and some are useful” when a model is calibrated, as all models include simplifications of physical processes that limit our understanding.

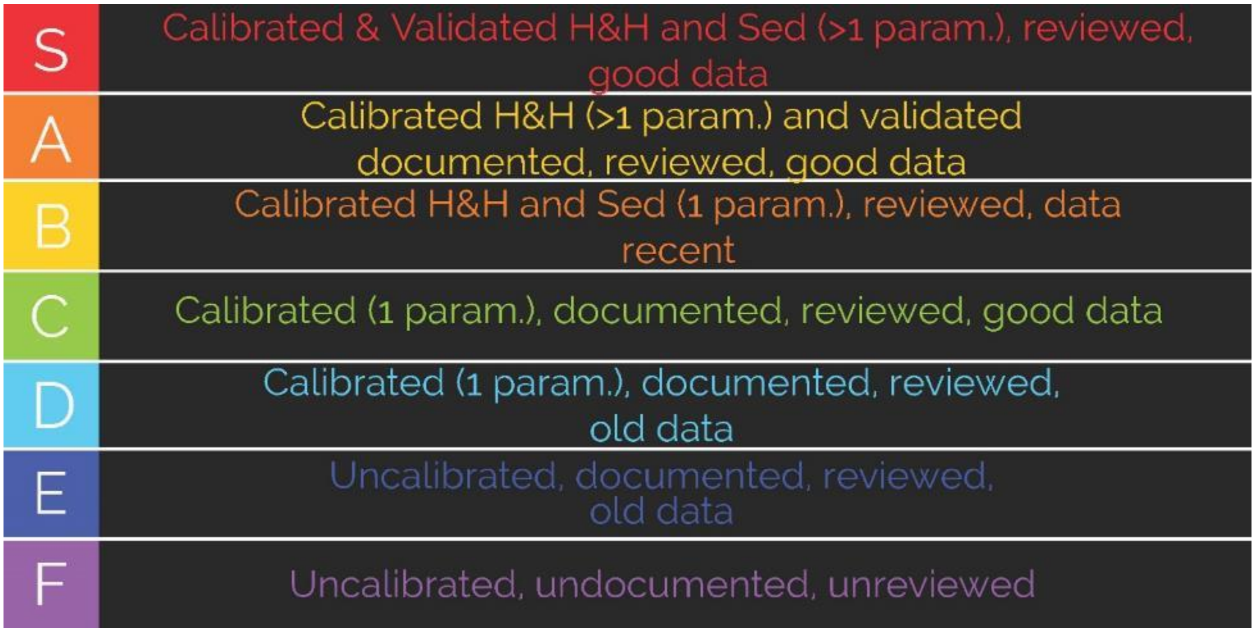
These new capabilities will pose both opportunities and challenges for users and model developers alike. In terms of opportunities – model users can offer new services to project partners and develop new insights on fluvial processes and develop designs that are more sustainable. In terms of challenges – the high complexity of these models is initially hidden from the user. This could result in many modelers getting in over their heads or putting forth results they or their customers have little ability to scrutinize or validate, or creating a false sense of confidence, or overwhelming with too much data, clouding or delaying sound decision making.

Recommendations

1. Single thread and branching 1D models are sufficient to provide reach scale insights on morphologic trends important for sediment budgets and channel capacity investigations. Studies that are attempting to understand changes over decadal time scales will continue to rely on 1D methods. The significantly shorter 1D run times mean that a modeler can put more effort into calibration or longer simulations than into a 2D model for the same reach and study budget. Thus, the scope of modeling efforts should balance the need for accuracy to reach scale trends vs. localized morphologic change.
2. Good calibration will be hindered by long run times. At the enterprise level USACE should increase investments in model development so that these tools can reach their full potential. While organic processor speed increases will improve the situation, software advancements that allow for running HEC-RAS on an HPC, or use of high-speed GPUs would accelerate this transition.

3. As a practical tool, 2D sediment transport models available today provide the ability to explore and predict near term (single event, several months to few years) channel responses in dynamic reaches that will aid in design of side channel connections, levees, training dikes, revetments, levee setbacks, gravel nourishment, grade control, and major channel modifications. Habitat suitability studies (depth, velocity, substrate) for ecosystem restoration are also facilitated. Study scopes should be updated to include these methods when risks posed by sediment are high enough to warrant 1D studies or where morphologic response is a significant design variable. 2D methods will be most useful for design of complex features and most beneficial when informed by calibrated 1D sediment models (so that reach scale trends important for project design are identified and included). When relative differences between plans in terms of erosion or deposition response is of importance 2D methods can be streamlined to significantly improve run times while providing insights on responses that cannot be gleaned from hydraulics alone.
4. Hydraulic engineers with sufficient experience should be able to embrace these new tools as they have many practical benefits that should scale as the community of practice becomes more adept in their use. All hydraulic engineers should be encouraged to get basic training related to these advanced features even if they will not be running them routinely. Knowledgeable peer review is essential to good modeling. Newer engineers without specialized education and training will likely need a combination of focused work under an experienced mentor in addition to PROSPECT level training to reach their full potential. Mentorship is likely infeasible in some Districts so developing virtual mentorship opportunities should be considered.
5. Bootstrapping and experimentation will lead to further discovery, deeper insights, and more innovation. This positive feedback loop can be accelerated by providing a sample set of “gold standard” models and documents to serve as project templates so that new modelers can see how a good model runs and behaves. Models should match physics as best possible, but the tradeoffs for run time may prevent that. Knowing when to increase or decrease dimensions is as important as knowing how to run the model (USACE 2020). Updating USACE modeling guidance to reflect current capabilities is essential.
6. To safeguard the public in terms of model quality it should be incumbent upon modelers to be transparent about the quality of their model calibration and validation whenever it is presented to others or used as part of larger studies or design efforts. A simple, visual, “Tier List” (similar to Table 4 below) could be developed that reflects a common understanding from the USACE Hydraulics, Hydrology and Coastal community of practice regarding model quality. Uncalibrated, undocumented, and unreviewed models would have the lowest tier (F) and essentially be unusable on most projects. Models that are calibrated and validated using good datasets for both flow and sediment, have undergone review and are well documented would be top tier (S). Models would then be tiered along a continuum between these extremes based on their level of development, documentation, and review. This tier list could be developed to follow the work by Sutherland et al. (2004) to statistically rate a model’s skill in capturing observed morpho-dynamic change.

Table 4. Potential “Tier List” to rank hydraulic and morpho-dynamic model quality



S	Calibrated & Validated H&H and Sed (>1 param.), reviewed, good data
A	Calibrated H&H (>1 param.) and validated documented, reviewed, good data
B	Calibrated H&H and Sed (1 param.), reviewed, data recent
C	Calibrated (1 param.), documented, reviewed, good data
D	Calibrated (1 param.), documented, reviewed, old data
E	Uncalibrated, documented, reviewed, old data
F	Uncalibrated, undocumented, unreviewed

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