Sediment Modeling
Failure Modes and Best Practices

Stanford Gibson, PhD, Hydrologic Engineering Center, USACE, Davis, CA,
stanford.gibson@usace.army.mil
Gary Brown, ERDC - Coastal and Hydraulics Lab, Vicksburg, MS,
Gary.L.Brown@erdc.dren.mil.
Blair Greimann, Stantec, Denver, CO, blair.greimann@stantec.com.
Alex Sánchez, Hydrologic Engineering Center, USACE, Davis, CA,
Alejandro.Sanchez@usace.army.mil

Abstract

Sediment and morphological modeling can be challenging. These models have multiple uncertain inputs and sensitive parameters. Sediment modeling has several best-practices as well as tips and tricks that are not immediately obvious to fixed-bed/blue-water modelers making the transition to a mobile-bed, sediment-routing model. Many of the best practices and much of this guidance is independent of the modeling software selected. We have gathered four sediment model developers for this paper and panel discussion to collect our common lessons learned from developing, applying, and reviewing four different, 1D and 2D sediment transport models. These topics include pre-modeling practices, model evaluation practices, approaches to forecasting, and some common modeling error

Introduction

When morphological model developers get together, we find that we have had similar experiences. We often see our models applied in unexpected ways. Some of these applications are innovative, applying the model in unanticipated but appropriate directions. But more often, we see the model applications built on misunderstandings of the model assumptions and modeler decisions that are unlikely to generate useful results. Most morphological model developers are also morphological modelers. Our model development reflects modeling experiences, including recurring problems and the best practices we have developed over time.

The goal of this paper and panel discussion is to make some of the conversations we have had over the years public, to expand the circle of people who could benefit from them. The session gathers four morphological model developers to discuss the most common modeling failure modes we have seen in hundreds of sediment model applications and the best practices we have developed over the years, often independently. The panel includes 1D (HEC-RAS and SRH-1D) and 2D (ADH and HEC-RAS) sediment model developers. We will also release the panel conversation as a podcast.

Pre-Modeling Practices

Successful sediment transport models begin before modelers ever open modeling software…or even select a software package. Strong modeling practices begin with several pre-modeling practices.

Specify the Modeling Question

Pre-modeling practices begin with clarifying the modeling objective and the management question. Mangers, planners, and decision makers who request morphological models do not always have a clear morphological question at the outset. But a well-conceived sediment model will not just set out to simulate all the sediment processes in the system. Numerical models should be designed to answer a specific question, or small set of related questions. The modeling question will drive decisions like the model domain, the calibration metrics and approach, and additional data requirements. The modeling question will also distinguish between the processes the model should simulate in detail, those the model can approximate, and the low-sensitivity or low-consequence processes that can be ignored.

Stake holders often have a vague sense that they need a sediment model, without a clear understanding of where the model will meaningfully reduce their uncertainty and where it will not. Often, modelers must clarify their question before they decide on the scope of their simulation or data requirements. After the question(s) have been defined, the numerical modeler must determine if a numerical model can reduce the risk surrounding the design or morphological management decision with the data available, or if the question is more suited to qualitative, geomorphic, assessment, or physical modeling.

Develop Conceptual Model and Sediment Budget

After the team clearly identifies the modeling question, the modeler must collect and assess the available flow, sediment, and calibration data. Input data are important, but project success often depends on calibration data. The team should develop a rough sediment budget before modeling. When the sediment budget does not balance – because they rarely do – the study team must decide how to deal with the residuals prior to model development (e.g. adjust one-or-more of the sources or sinks computed from lower-reliability data, or apply residuals to unmeasured processes). If the sediment budget does not balance with the available data, the data will not magically balance in the model.

A numerical model does not replace careful application of the classic scientific method. Models should test clear, *a priori*, hypotheses. Models often subvert hypotheses and cause analysts to re-evaluate their assumptions about a river or interrogate their data, but the study team will get the most out of this learning cycle if they start modeling with a clear hypothesis about what the model will demonstrate.

Before the modeling team build a numerical model, they should develop a clear conceptual model of the system, including, the major sediment sources, sinks, and pathways, how sediment moves through the system (e.g. transport mechanisms of the grain classes), the important/trivial sediment processes, and how resistant/resilient the system is to disturbance. Then the study team should make a qualitative predication about how the system will respond in the future with and without the management alternatives, which they test with the model.

Select Appropriate Modeling Approach

With a clear modeling question, a complete understanding of the data available, and a rough sediment budget, the modeler should select their software and construct a model - with the end in mind from the beginning. The selected model should be able answer the specific modeling question, scale to the available data, and generate clear evaluation metrics that are easily compared to the available calibration measurements.

Before the modeling team tries to answer the "which" model question, they should tackle the "if" question. Some sediment management questions do not lend themselves to numerical simulations. The set of analyses considered should include no-model options as well as physical models or prototype experiments. Numerical models will not reduce uncertainty of some processes enough to justify their cost. In some cases, additional data-collection and semi-qualitative geomorphic assessments will improve decision making more than a numerical model. In other cases, where processes are too chaotic or consequences are too severe for numerical models, physical models or prototype experiments may be required to answer the question or, at least, to parameterize a numerical model.

The uncertainty reduction associated with each incremental increase in model complexity will vary for different modeling problems.

Finally, in the early days of morphological modeling, Dawdy and Vanoni (1986) argued that "…the choice of a modeler is probably more important than the choice of the model." This is still true. Several, excellent, sediment transport models are available. These models often include different approaches and algorithms, but skillful application of similar models usually provides comparable results. The modeler must decide the appropriate dimensionality and identify if there are any processes critical to their modeling question that are only available in a subset of the models. It may be more useful to identify which models would not perform well to address a specific modeling question (e.g. because they do not include necessary algorithms, do not have the dimensionality required to evaluate the process, or are too computationally expensive for the study resources). Because any sediment modeling package should be calibrated to prototype observations, calibrated models, skillfully constructed in different software packages should, generally, predict similar trends.

Model Calibration and Evaluation

Thomas and Cheng (2006) famously claimed that an uncalibrated, numerical, sediment simulation is not a "model." They asserted that uncalibrated sediment simulations can only aspire to be "computational analyses." Sediment data and algorithms include so much uncertainty, that an analyst has not really "modeled" a sediment system until they have demonstrated that their the reproduce historical system processes.

However, calibrating morphological models can be difficult; it can be more than half the scope of a sediment modeling study. Additionally, calibration can take many forms. Sediment data are often noisy or inconsistent. Sediment modelers can choose from several possible calibration targets to evaluate their model and sediment models have many uncertain variables/parameters modelers can "tune" to change their results. Variables calibrated over one time series (e.g. a low-to-moderate flow period) might not hold up over another time-window (e.g. a flood). Even the language surrounding sediment model evaluation (e.g. calibration, validation, verification, circumstantiation) is fraught and can be confusing.

Selecting Calibration Metrics

Sediment model calibration should begin with an independent hydraulic model calibration. Sediment equations and processes are very sensitive to hydraulic results. Many modelers spend a lot of time looking for problems in their sediment model that do not turn out to be issues with the sediment algorithms or data, but errors in the hydraulic model can propagate (and amplify) through the sediment simulation.

After a good hydraulic calibration, sediment models are most often evaluated with in-domain concentration observations or bed change data from repeated bathymetric measurements. Bed change data integrate processes over time while concentrations provide a temporal snapshot of sediment processes at a specific time. Because concentration data are discrete temporal measurements, study teams can collect them during a modeling study. It is usually useful to measure the grain-class components of the concentration data – at least the sand-silt split – to compare model results by grain class or transport mechanism (e.g. wash load/bed-material load). Concentration measurements also ignore bed load which can be a small percentage of the total load but a critical component of bed change. Calibrating to concentrations involves determining the appropriate portion of the sediment measurement and model flux result to compare.

A study team can only collect bed change data during a study if a good historic baseline already exists (e.g. range lines, repeatable cross sections with useful locations and spacing, or single-beam/multi-beam bathymetry/LiDAR with sufficient resolution to compare to a modern DEM). Therefore, it is useful to collect baseline bathymetric data on a potential study site several years before a modeling study.

Other calibration metrics can include bed gradation and specific gage results. It is always important to evaluate the model bed-gradation evolution to make sure the model maintains a reasonable bed gradation. But if the prototype bed gradation changes substantially over the calibration period, reproducing the bed fining (e.g. reservoir deposition) or coarsening (e.g. gravel augmentation) can be part of the model evaluation.

The calibration metrics should be selected to evaluate the uncertain sediment processes that affect the modeling question. For example, while dam removal models often have historic reservoir deposition data, calibrating to these data will not limit the uncertainty of the dam removal erosion algorithms very much.

When no calibration data are available, modelers should still evaluate their model with qualitative, historic, narratives. If the system includes historic erosion or deposition "hot spots" then the model should at least reproduce those. If the stake holders believe the system is in qusi-equilibrium, modelers can even evaluate their model with that information, rejecting parametrizations that generate long-term erosion or deposition. An uncalibrated sediment simulation will have much more uncertainty but can still be useful for "relative change" analyses.

Calibration Parameters

Even though sediment models are built on hydraulic models, sediment parameterization can be more like hydrology or groundwater modeling. Sediment models can have dozens of variables or free parameters. This makes them vulnerable to "overtuning," compensating errors, non-unique solutions, and equifinality traps (see section "Overcalibration and Equifinality").

Modelers should identify a small set (2-4) of variables or parameters to adjust during the calibration process. These should be the most-sensitive and least-certain model inputs (see section "Identify a Small Set of Sensitive and Uncertain Calibration Inputs"). Modelers should only adjust these variables and parameters within reasonable ranges, and, whenever possible, document a physical justification for selecting values based on field observations. If the calibration requires variables or parameters that fall outside the reasonable range of parametric uncertainty or natural variability, the modeler should consider what other model inputs can cause the model to trend in a similar direction and evaluate those variables.

Multiple Time-Series Evaluation

Classical modeling process include discrete, sequential, calibration and validation phases. In this framework modelers calibrate to one time series, and then evaluate their parameterization against another time series. But, in practice, calibration and validation inform each other. If the "validation" performs poorly, a practical modeling study must go back and update the calibration parameterization until the model performs reasonably well for both time-series or events.

Multiple-time-series evaluation will reduce the uncertainty of a sediment model. Sediment models that reproduce low-to-medium flows may simulate flood responses poorly, and visa vera. Whenever possible, evaluate the model against data (or even qualitative observations) that cover the range of possible flow and river conditions. Multiple time-series model evaluation helps modelers avoid over-calibration (see section "Overcalibration and Equifinality"). The agreement with observed data for each, individual, time-series evaluation will be worse, but the model will be more robust and reliable.

Because sediment processes unfold more gradually than hydraulic processes, long-term calibrations (months-to-years for multi-dimensional models, years-to-decades for 1D models) are preferable to event calibrations, unless the modeling question is event-based (e.g. reservoir flush).

Common Sediment Modeling Errors

Starting with a Mediocre Hydraulic Model

Hydraulic equations are relatively forgiving. They are self-correcting and can generate reasonable water-surface results even if the velocities or shear stresses are unrealistic. Building a sediment analysis on a mediocre hydraulic model, however, will reveal its liabilities. Project managers often believe that if a hydraulic model already exists, that adding sediment will be a trivial additional task. But this is usually a mistake for two reasons: sediment modeling is more difficult than hydraulic modeling and sediment models require better hydraulic models than most hydraulic modeling applications. A hydraulic model developed for a sediment analysis, must, generally be higher quality than most hydraulic models developed for flood risk or ecosystem analysis. When we troubleshoot sediment models, we often trace the problems back to the hydraulics, rather than the sediment equations or data.

Over-Calibration and Equifinality Traps

Equifinality traps and compensating errors are more familiar topics in hydrology and groundwater than hydraulics. Because most of the uncertainty in hydraulic models is lumped in a single, linear, parameter (bed roughness) hydraulic calibrations are not as vulnerable to these issues. But sediment models have many uncertain inputs and free parameters, making them more vulnerable to these issues. Equifinality poses possibilities of offsetting errors that generate the right answer for the wrong reasons, resulting in a calibrated model that is not general or predictive.

Equifinality traps, overfitting, and compensating error issues all revolve around the idea that modelers can get the same model response by adjusting multiple model inputs (Beven, 2006). For, example, a model that needs more deposition to match repeated surveys, can increase or coarsen the sediment load at boundary conditions, change the transport function, decrease the critical shear stress (or other incipient motion parameter), or decrease the adaptation parameter. Changing the bed gradation or bed roughness could even generate the desired deposition, though indirectly and in with potentially non-monotonic trends. Modelers who adjust all these parameters can deliver a model that produces the right answer for the wrong reasons, because one parameter is too low, and another is too high to compensate for it. Models with these kinds of compensating errors may not generalize well outside of the calibration window, when applied to a different starting bathymetry or flow series. The most sensitive model inputs in most models are flow and bathymetry, which are sometimes uncertain. Bathymetry, in particular, can miss important features that control sediment responses in the prototype. Changing global model parameters to compensate for fundamental geometry or flow data discrepancies many not perform well outside the calibration window.

Sediment Modeling Best Practices

Build a Strong, Calibrated, Hydraulic Model Before Adding Sediment

Because many sediment modeling problems can be traced back to issues in the hydraulic model, sediment modeling best practices begin with hydraulic modeling best practices. Sediment models are sensitive to the velocity and shear stress distributions, not just the water surface elevations. Therefore, they will be much more sensitive to floodplain roughness, break lines, mesh design, and low-quality bathymetry. One-dimensional models are very sensitive to any decisions that affect the cross-section flow distribution (e.g. ineffective flow areas, bank station location, overbank conveyance).

Most sediment modeling studies require modelers to return to their terrain, hydraulics, and mesh design after the sediment algorithms reveal issues with the hydraulic model. But the principle of "incremental model complexity" (see next section) suggests that analysts should spend time building the best hydraulic model possible, before they add sediment data.

The best way to develop a strong hydraulic model is to evaluate it against multiple calibration metrics. Water surface elevations (preferably multiple observations over space and time that cover a range of flows) can be very useful to evaluate the hydraulic model. But, if possible, velocity measurements will help calibrate the model to the data the sediment model will be sensitive to.

Identify a Small Set of Sensitive and Uncertain Calibration Inputs

Models with multiple uncertain inputs and free parameters require modelers to identify a small subset of those inputs to calibrate. The best way to avoid overfitting and equifinality is to identify the most sensitive and least certain model inputs to adjust during calibration. Low uncertainty or low sensitivity parameters should be fixed to the best estimate to avoid adjusting too many variables leading to compensating errors.

	Low Uncertainty	High Uncertainty
Low Sensitivity	Fixed	Fixed
High Sensitivity	Fixed	Adjust

Add Model Complexity Incrementally

When a modeling team has all the required data at the beginning of a study, it can be tempting to build the entire model and add all the expected complexity at the beginning, and then press "compute." But a model with all the intended (or possible) complexity will be very difficult to troubleshoot from the beginning and will skip valuable learning opportunities along the way.

It can be useful to start with the simplest possible model structure that has a chance to provide any insight into the modeling question. Then troubleshoot that simple model, learn the model sensitivities from those faster run times and smaller set of possible explanations. Then select the next, most likely, model refinement that is most likely to add value to the simplified model. Adding model complexity incrementally may sound more time consuming, as you are carefully evaluating each model component, but it will lead to a stronger model, a better understanding of the prototype, and often saves time, both in modeler analysis time and computation cost.

Evaluating a model in these incremental steps will help isolate the issues and prevent modelers from searching for a problem with their simple, steady-flow hydraulic parameterization in their complicated sediment data and algorithm set.

Avoid Unnecessary Detail

Many models invest too much modeler effort and run time in modeling details that do not affect the modeling question. Convergence analysis can help the study team decide on an appropriate resolution and time step. Convergence analysis begins with a very small cell/element size and a small time step to match (maintaining a reasonable Courant condition). Then increase the cell/element size and the corresponding time step until the model results start to change substantially, to find the maximum practical model resolution.

Model Pre-Conditioning and Warmup

Even in the best data environments, it is unlikely that the bed gradation, boundary load and gradation, bathymetry, and transport equations will all work together to represent prototype conditions from the first time step. Sediment models, particularly 2D models, usually need some time for these multiple, interacting, independent variables to adjust to each other to reach an internally-consistent, short-term equilibrium. Model adjustments to mismatches between bathymetry, bed material, boundary conditions and transport algorithms can drive simulation results and overwhelm the bed evaluation “signal” with initial conditions “noise.” For example, if the bed material includes too much fine sediment that is immediately transportable, the simulation can start with more, artificial, sediment flux and bed erosion than the rest of the simulation simulates.

Modelers should aspire to make their initial conditions as internally consistent as possible, by matching the transport equations to the sediment data; but most sediment models need time to finish the job. Most models include warmup or preconditioning options that will give the model time to equilibrate before the actual simulation. Other options include hotstarting the model (e.g. running a pre-conditioning simulation and using the final bathymetry and/or bed gradations as the initial conditions for the model) or starting the model with a sacrificial time series and evaluating model results after that period.

Forecasting with Sediment Models

The modeler should build the model domain and calibrate with forecast and alternatives in mind. Try early calibration runs *with* the alternatives to make sure the calibration domain can accommodate any model changes required. Model calibration can take most of the project timeline, and some modelers find they must re-calibrate because their model did not include the domain or components required for the alternatives.

One issue related to forecasting with morphologic models is quantifying the uncertainty in this prediction. Two basic forms of this uncertainty include epistemic (knowledge and measurement gaps) and aleatory (natural variability). The epistemic uncertainty includes limitations in the model formulations, uncertainty in model parameters, uncertainty in initial or boundary conditions, and errors introduced by the numerical method. Aleatory errors include such unknowns as the future hydrology or future sediment loading.

Future hydrology is one of the most important modeling decisions that well-calibrated sediment models face in the forecasting stage. Stationarity issues can also complicate the move from calibration (reproducing the past) to forecasting future processes. Therefore, sediment modeling results should be evaluated with multiple hydrologic futures and sediment studies should report the uncertainty that this hydrologic variability introduces into their forecasts. This can be as simple as running dry, average, and wet future hydrologies or stochastic approaches that run a suite of simulations with a range of random hydrologic series.

Epistemic uncertainty can be more constrained. While many sediment inputs are highly variable and uncertain, the calibration process constrains that cumulative uncertainty, especially if the calibration includes multiple, long-term time series. But modeling studies should still investigate and report uncertainties and the possible range of outcomes.

In this session, the current or former sediment transport leads for ADH, SRH-1D, and HEC-RAS 1D and 2D sediment development, will discuss how the develop their future-condition hydrology and sediment parameters.

Link to Panel Discussion

This paper is an overview of the topics the authors plan to discuss in the panel discussion, but we are likely to cover additional themes or add depth or nuance to those covered in this paper in the live event. The audio from the panel discussion will be released as a *River Mechanics Podcast*, and will be available at this site:

www.hec.usace.army.mil/confluence/rasdocs/rastraining/latest/rsm-river-mechanics-podcast

References

Beven, K. 2006. A manifesto for the equifinality thesis, Journal of Hydrology, 320(1-2), 18-36.

Dawdy, D.R. and Vanoni, V.A. 1986: Modeling alluvial channels. Water Resources Research 22, 71S-81S.

Thomas, W.A. and Cheng, H., 2006. Computational Modeling or Sedimentation Processes, *ASCE Manuals and Reports on Engineering Practice No. 110: Sedimentation Engineering Processes, Measurement, Modeling, and Practice,* Ed. M. Garcia, American Society of Civil Engineering, 649-680.