o

US Army Corps
of Engineers
Hydrologic Engineering Center

HEC-RAS
Sediment Transport

User's Manual

Version 6.0
September 2020

CPD-68c

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to the Department of Defense, Executive Services and Communications Directorate (0704-0188). Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ORGANIZATION.

1. REPORT DATE *(DD-MM-YYYY)*
September 2020

2. REPORT TYPE
Computer Program Documentation

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
HEC-RAS
Sediment Transport User's Manual
Version 6.0

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Stanford Gibson PhD, CEIWR-HEC
Alejandro Sánchez PhD, CEIWR-HEC

5d. PROJECT NUMBER

5e. TASK NUMBER

5F. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
US Army Corps of Engineers
Institute for Water Resources
Hydrologic Engineering Center (HEC)
609 Second Street
Davis, CA 95616-4687

8. PERFORMING ORGANIZATION REPORT NUMBER
CPD-68

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/ MONITOR'S ACRONYM(S)

11. SPONSOR/ MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The Hydrologic Engineering Center's (HEC) River Analysis System (HEC-RAS) software allows you to perform one-dimensional steady and 1D and 2D unsteady flow river hydraulics calculations. HEC-RAS is an integrated system of software, designed for interactive use in a multi-tasking, multi-user network environment. The system is comprised of a graphical user interface (GUI), separate hydraulic analysis components, data storage and management capabilities, graphics and reporting facilities.

The HEC-RAS system contains four hydraulic analysis components for: (1) steady flow water surface profile computations; (2) One and two-dimensional unsteady flow simulations; (3) movable boundary sediment transport computations; and (4) water temperature and constituent transport modeling. A key element is that all four components use a common geometric data representation and common geometric and hydraulic computations routines. In addition to the four hydraulic analysis components, the system contains several hydraulic design features that can be invoked once the basic water surface profiles are computed.

The current version of HEC-RAS supports Steady and Unsteady flow water surface profile calculations, sediment transport computations, and water quality analyses. The software also contains tools for performing inundation mapping directly inside the software. New features and additional capabilities will be added in future releases.

15. SUBJECT TERMS
water surface profiles, river hydraulics, steady flow, unsteady flow, software, HEC-RAS, HEC, one-dimensional, hydraulic, analysis, two-dimensional hydraulic analyses, computations, sediment transport, water quality; calculations, integrated system, graphical user interface

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			
U	U	U	UU	962	**19b. TELEPHONE NUMBER**

HEC-RAS
Sediment Transport

User's Manual

September 2020

US Army Corps of Engineers
Institute for Water Resources
Hydrologic Engineering Center
609 Second Street
Davis, CA 95616

(530) 756-1104
(530) 756-8250 FAX
www.hec.usace.army.mil

CPD-68c

River Analysis System, HEC-RAS, User's Manual

HEC cannot provide technical support for this software to non-Corps users. See our software vendors list (on our web page) to locate organizations that provide the program, documentation, and support services for a fee. However, we will respond to all documented instances of program errors. Documented errors are bugs in the software due to programming mistakes not model problems due to user-entered data.

Terms and Conditions of Use:

Use of the software described by this document is controlled by certain terms and conditions. The user must acknowledge and agree to be bound by the terms and conditions of usage before the software can be installed or used. The software described by this document can be downloaded for free from our internet site (www.hec.usace.army.mil).

The United States Government, US Army Corps of Engineers, Hydrologic Engineering Center ("HEC") grants to the user the rights to install the HEC River Analysis System (HEC-RAS) "the Software" (either from a disk copy obtained from HEC, a distributor or another user or by downloading it from a network) and to use, copy and/or distribute copies of the Software to other users, subject to the following Terms and Conditions for Use:

All copies of the Software received or reproduced by or for user pursuant to the authority of this Terms and Conditions for Use will be and remain the property of HEC.

User may reproduce and distribute the Software provided that the recipient agrees to the Terms and Conditions for Use noted herein.

HEC is solely responsible for the content of the Software. The Software may not be modified, abridged, decompiled, disassembled, unobfuscated or reverse engineered. The user is solely responsible for the content, interactions, and effects of any and all amendments, if present, whether they be extension modules, language resource bundles, scripts or any other amendment.

The name "HEC-RAS" must not be used to endorse or promote products derived from the Software. Products derived from the Software may not be called "HEC- RAS " nor may any part of the "HEC- RAS " name appear within the name of derived products.

No part of this Terms and Conditions for Use may be modified, deleted or obliterated from the Software.

No part of the Software may be exported or re-exported in contravention of U.S. export laws or regulations.

Waiver of Warranty:

THE UNITED STATES GOVERNMENT AND ITS AGENCIES, OFFICIALS, REPRESENTATIVES, AND EMPLOYEES, INCLUDING ITS CONTRACTORS AND SUPPLIERS PROVIDE HEC-WAT \"AS IS,\" WITHOUT ANY WARRANTY OR CONDITION, EXPRESS, IMPLIED OR STATUTORY, AND SPECIFICALLY DISCLAIM ANY IMPLIED WARRANTIES OF TITLE, MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE AND NON-INFRINGEMENT. Depending on state law, the foregoing disclaimer may not apply to you, and you may also have other legal rights that vary from state to state.

Limitation of Liability:

IN NO EVENT SHALL THE UNITED STATES GOVERNMENT AND ITS AGENCIES, OFFICIALS, REPRESENTATIVES, AND EMPLOYEES, INCLUDING ITS CONTRACTORS AND SUPPLIERS, BE LIABLE FOR LOST PROFITS OR ANY SPECIAL, INCIDENTAL OR CONSEQUENTIAL DAMAGES ARISING OUT OF OR IN CONNECTION WITH USE OF HEC-WAT REGARDLESS OF CAUSE, INCLUDING NEGLIGENCE.

THE UNITED STATES GOVERNMENT'S LIABILITY, AND THE LIABILITY OF ITS AGENCIES, OFFICIALS, REPRESENTATIVES, AND EMPLOYEES, INCLUDING ITS CONTRACTORS AND SUPPLIERS, TO YOU OR ANY THIRD PARTIES IN ANY CIRCUMSTANCE IS LIMITED TO THE REPLACEMENT OF CERTIFIED COPIES OF HEC-RAS WITH IDENTIFIED ERRORS CORRECTED. Depending on state law, the above limitation or exclusion may not apply to you.

Indemnity:

As a voluntary user of HEC- RAS you agree to indemnify and hold the United States Government, and its agencies, officials, representatives, and employees, including its contractors and suppliers, harmless from any claim or demand, including reasonable attorneys' fees, made by any third party due to or arising out of your use of HEC- RAS or breach of this Agreement or your violation of any law or the rights of a third party.

Assent:

By using this program you voluntarily accept these terms and conditions. If you do not agree to these terms and conditions, uninstall the program and return any program materials to HEC (if you downloaded the program and do not have disk media, please delete all copies, and cease using the program.)

Cover sketch adapted from: Flood Plain Management Program, Handbook for Public Officials, State of California, Department of Water Resources, August 1986

Table of Contents

CHAPTER 3 BSTEM: USDA-ARS BANK STABILITY AND TOE EROSION MODEL – TECHNICAL REFERNCE MANUAL CXI

CHAPTER 1 1D SEDIMENT TRANSPORT – USER MANUAL

This chapter describes the HEC-RAS mobile bed, sediment transport model. An HEC-RAS sediment model requires a geometry file, a flow file (quasi-unsteady or unsteady), a sediment data file, and a sediment analysis plan file. Instructions on creating a geometry file can be found in the HEC-RAS User's Manual, and the editors for creating unsteady flow files are the Unsteady Flow chapters of that document. The following chapter describes the sediment-specific RAS editors, including the editors for creating quasi-unsteady flow files, sediment data files, and sediment plans.

Flow Data and Event Conditions

The current version of HEC-RAS includes two hydrodynamic approaches to Sediment Transport Analysis:

- Quasi-Unsteady Flow and
- Unsteady Flow.

HEC-RAS allows users to run Quasi-unsteady flow simulations without sediment transport (e.g. for riparian vegetation analysis) but sediment transport models are the most common application of the quasi-unsteady flow method. The quasi-unsteady hydrodynamic model simulates the flow series with a sequence of steady flow computations (Figure 1-1a). Hydrodynamic parameters for the sediment model are computed with the HEC-RAS steady flow engine, then applied over specified time windows to compute sediment transport temporally.

Unsteady sediment transport capabilities are new in HEC-RAS version 5.0 (Figure 1-1b). HEC-RAS can run unsteady flow simulations without sediment. Setting up unsteady flow files and troubleshooting unsteady flow models are covered in detail in Chapter 8 (Performing and Unsteady Flow Analysis). Constructing an accurate, calibrated, stable unsteady hydraulic model is the first step in unsteady sediment modeling.

Selecting the appropriate hydrodynamic model for an HEC-RAS sediment transport analysis involves classic trade-offs between precision and effort (Gibson 2013). Quasi-unsteady modeling tends to be easier, but because it does not conserve flow, it can introduce unacceptable errors, particularly in systems with significant storage.

Unsteady flow modeling requires careful and skillful practice because the solution can be unstable with a fixed bed. Moving unsteady model cross sections can make model stability problems worse, because bed change can introduce instabilities. Making an unsteady flow model robust is not trivial. However, unsteady flow conserves mass and accounts explicitly for volume change, making it particularly applicable for reservoir modeling (Gibson and Boyd, 2014), models with lateral structure flows, reverse flows, or engineering problems where hydrograph timing is critical.

Table 1-1 summarizes the costs and benefits of the two approaches and Figure 1-2 outlines the file structure of both approaches.

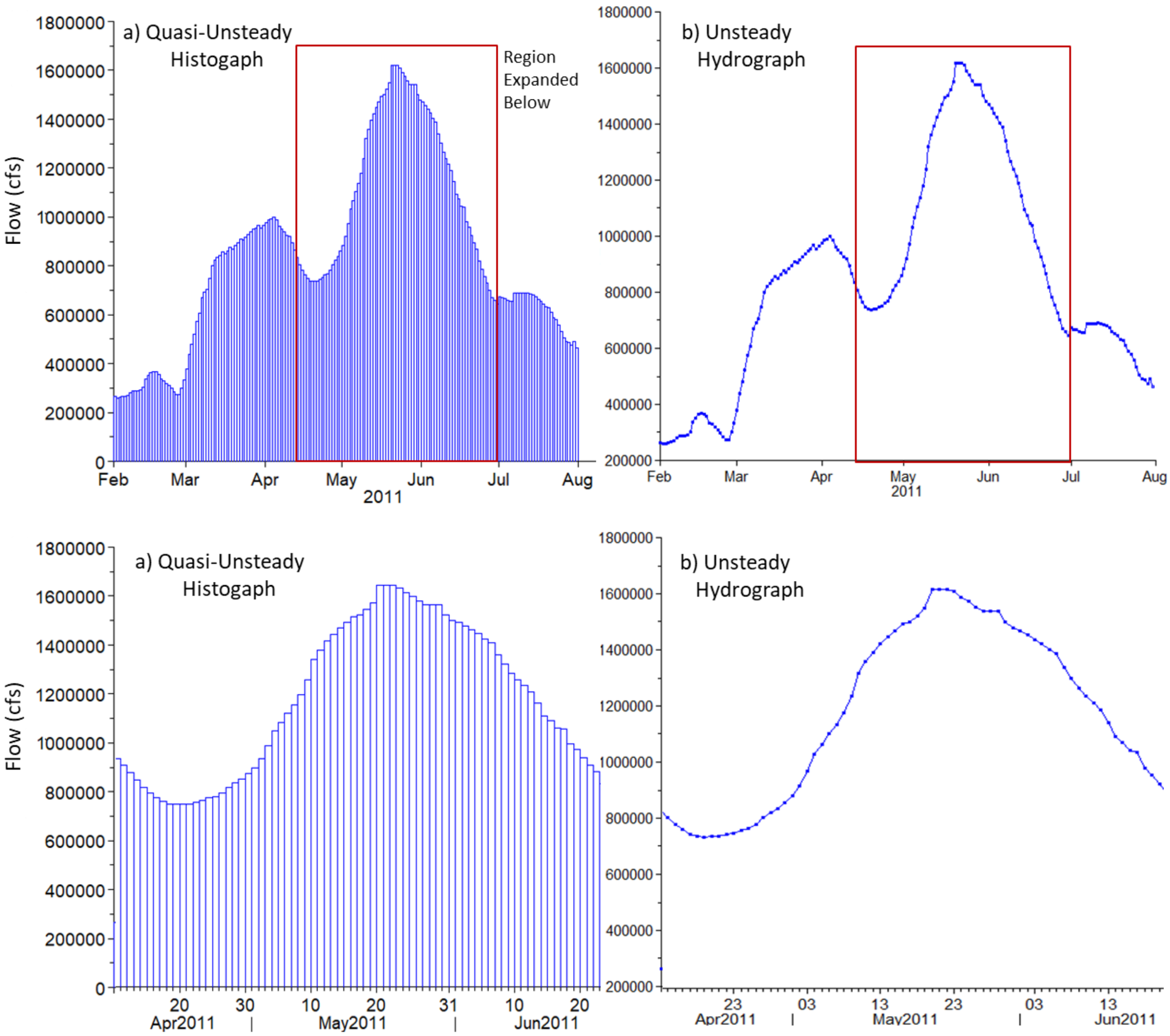


Figure 1-1: Hydrographs modeled with (a) the quasi-unsteady flow model (a series of steady flows or 'histograph') and (b) the unsteady flow model.

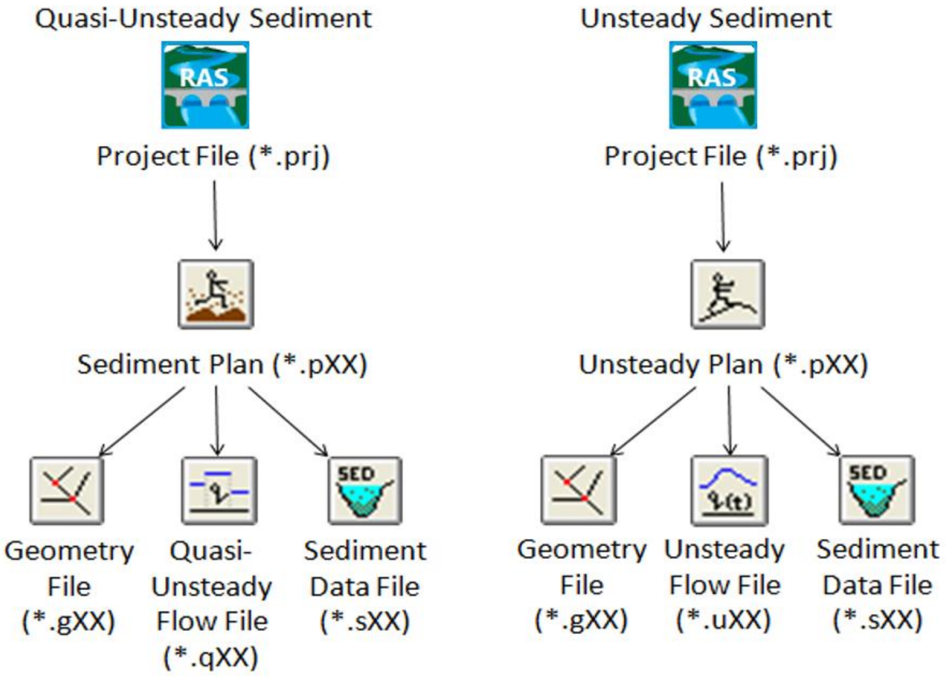


Figure 1-2: File structure for quasi-unsteady and unsteady sediment transport models.

Table 1-1: Decision Criteria for Selecting Unsteady or Quasi-Unsteady Sediment Simulations.

Quasi-Unsteady	**Unsteady**
Solves the steady flow backwater equations for a series of flows with associated times (a histograph).	Solves the Saint-Venant equation implicitly.
Does not conserve flow or account for storage.	Conserves flow and accounts for reservoir storage.
More stable.	Less stable. Bed change can exacerbate the unsteady model instabilities, common to the Saint-Venant solution.
Individual time steps take longer, but the variable time step feature usually translates into shorter model runs.	The unsteady flow engine is faster than steady flow, so each unsteady computation is faster. But the unsteady hydraulics usually require a smaller time step for stability, which makes run times longer.*
Limited to steady flow options.	Complex flow boundary conditions available including groundwater interflow, rules, lateral structures, internal boundary gate controls, pumps and others.

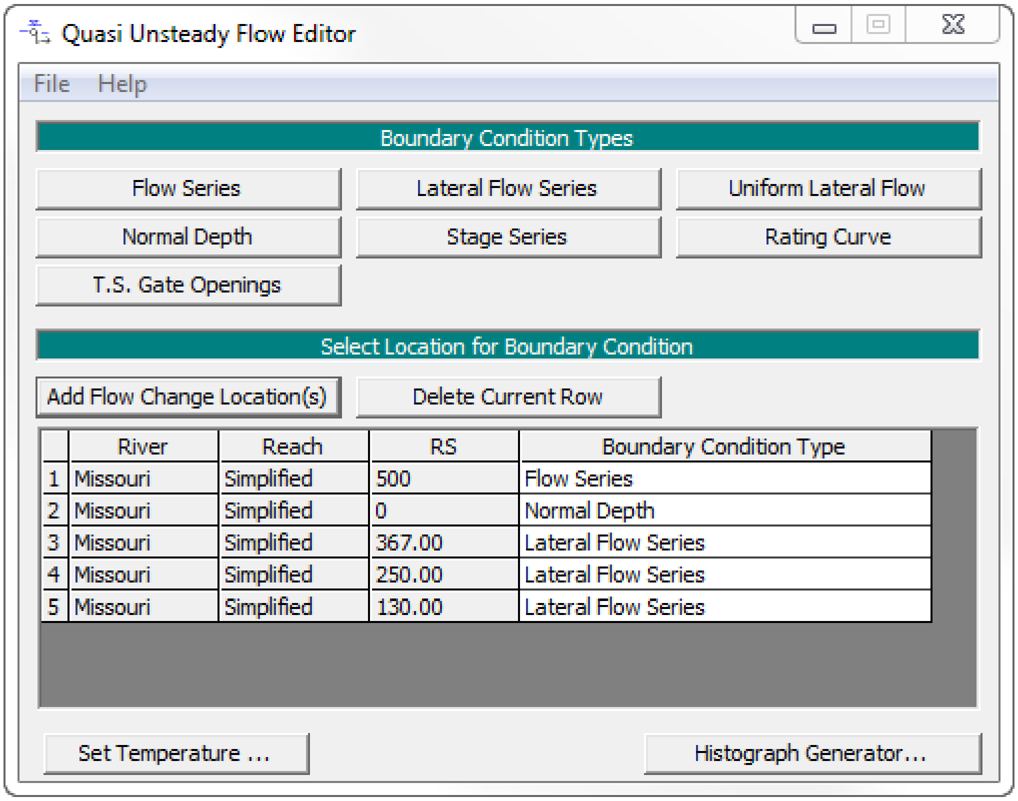
*Version 5.0 and later include variable time steps in unsteady simulations and 6.0 decoupled the flow and sediment time steps, giving users some flexibility with these time steps. But unsteady flow runs are still, generally, more computationally expensive.

Entering and Editing Quasi-Unsteady Flow Data

Entering and editing unsteady flow data are covered in the main HEC-RAS user manual. Because quasi-unsteady hydraulics only apply to sediment transport modeling, they are included in this chapter. The quasi-unsteady approach approximates a flow hydrograph by a series of steady flow profiles associated with corresponding flow durations. This analysis requires different information than steady or unsteady flow: a separate quasi-unsteady flow dialog (Figure 1-3) is available by selecting **Quasi-Unsteady Flow** under the **Edit** menu of the main HEC-RAS dialog or by pressing the Quasi-Unsteady Flow shortcut button.

Boundary Conditions

HEC-RAS includes several quasi-unsteady boundary conditions, but only one upstream quasi-unsteady boundary type. Each upstream boundary (the upstream cross section of an open-ended upstream reach) requires a Flow Series boundary. Quasi-unsteady flow models must be dendritic, which means they will have one and only one downstream boundary. HEC-RAS includes three options for setting quasi-unsteady downstream boundary conditions: Stage Time Series, Rating Curve, or Normal Depth. Optional internal boundaries include Lateral Flow Series, Uniform Lateral Flow Series, and Time Series Gate Operations.



	River	Reach	RS	Boundary Condition Type
1	Missouri	Simplified	500	Flow Series
2	Missouri	Simplified	0	Normal Depth
3	Missouri	Simplified	367.00	Lateral Flow Series
4	Missouri	Simplified	250.00	Lateral Flow Series
5	Missouri	Simplified	130.00	Lateral Flow Series

Figure 1-3. Quasi-Unsteady flow dialog.

Upstream Boundary Conditions

HEC-RAS requires external (upstream and downstream) boundary conditions to run sediment analyses. The **Quasi-Unsteady Flow** editor automatically includes entries for external boundary cross sections, requiring boundary conditions. Select a **Flow Series** for each upstream boundary. Click the blank **Boundary Condition Type** field associated with the upstream node and then press the **Flow Series** button to open the **Flow Series** editor.

Flow Series

Define upstream boundary flow in the **Flow Series** editor, depicted in Figure 1-4. The **Quasi-Unsteady Flow** series editor shares the look and feel of the **Unsteady Flow** series editor (Figure 8-2), with a few important differences. The time reference conventions are the same as unsteady flow (DDMMMYYYY). Most sediment models tie the flow series to a **Fixed Start Time** reference. This feature ties historical records or synthetic future records to a fixed start date, allowing simulation windows that include all or any part of the record. For example, in Figure 1-4 the historical record starts at 01May1955 2400 but the simulation starts on 15Oct1957 2400. The shaded dates in Figure 1-4 indicate that those flows are outside the simulation window (defined in the plan editor described below).

during low flow-transport regimes and fine time steps during large flows that transport most of the sediment and move the bed. Therefore, each flow has two time steps: a **Flow Duration** and a **Computational Increment**.

Flow Duration:

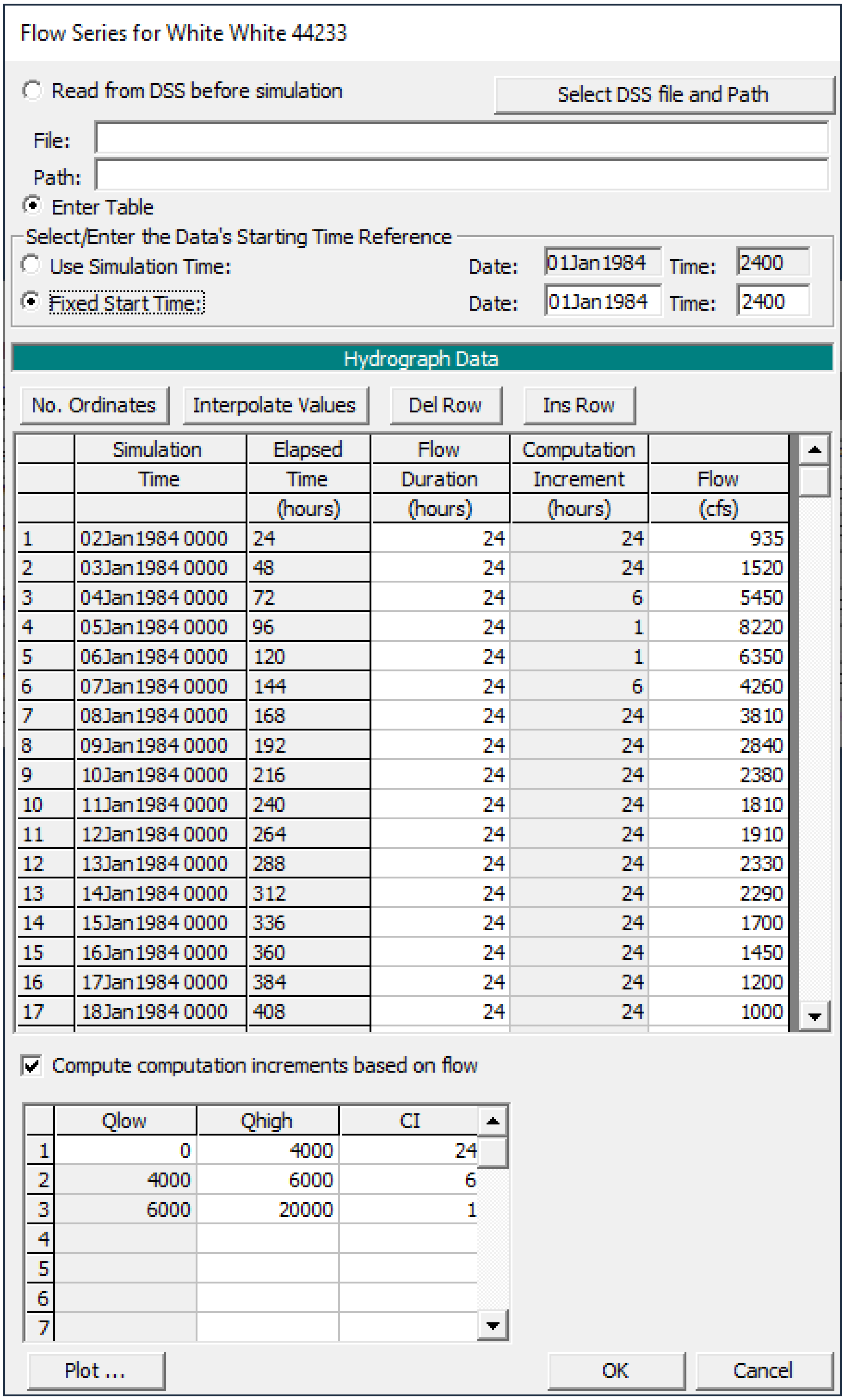
The flow duration is a constant flow input increment. It does not control the model time step (i.e. computational increment). For example, if the data are from a daily USGS flow gage, the durations would be 24 hours, regardless of the computational time step applied to the sediment model. However, the time step cannot be larger than the flow duration. In order to use coarse time steps often used during low flow, low transport seasons, flow duration should be large enough to span the entire time step (e.g. if daily USGS data are used but weekly times steps are targeted for summer flows with very little morphological change, then those flow duration – and computational increment – should be 168 hours).

Specify Flow Durations in the first column of the flow editor (in hours). Values can be copied from Excel and pasted into the Flow Series Editor with the *Ctrl+C* and *Ctrl+V* commands, but all of the destinations cells must be selected. (Note: all destination cells can be selected by clicking on the heading. Users can also populate the table (particularly if all the durations are the same) by dragging a value (hover over the bottom right corner of the cell to get cross hairs to drag values) or populating the first and last value and pressing the **Interpolate Values** button.

Quasi-unsteady flow can handle irregular (varying) time steps, allowing coarse time steps

Flow durations for different boundary conditions do not need to match. If boundary conditions have different time steps (flow durations or computational increments) HEC-RAS will compute and use the smallest time step common to all.

The **Flow Series** editor defaults to 100 rows. Almost all sediment studies require more flow records. Press the **No. Ordinates** (number of ordinates) button to customize the Flow Series length up to about 40,000 flows. If the model requires more than 40,000 flows, either combine low flows into longer durations (possibly using the Histograph Generator tool) or consider running the model in two phases, hotstarting (see Hotstart section below) the geometry and bed gradation.



Flow Series for White White 44233

○ Read from DSS before simulation

File:

Path:

● Enter Table

Select/Enter the Data's Starting Time Reference

○ Use Simulation Time: Date: 01Jan1984 Time: 2400

● Fixed Start Time: Date: 01Jan1984 Time: 2400

	Simulation Time	Elapsed Time (hours)	Flow Duration (hours)	Computation Increment (hours)	Flow (cfs)
1	02Jan1984 0000	24	24	24	935
2	03Jan1984 0000	48	24	24	1520
3	04Jan1984 0000	72	24	6	5450
4	05Jan1984 0000	96	24	1	8220
5	06Jan1984 0000	120	24	1	6350
6	07Jan1984 0000	144	24	6	4260
7	08Jan1984 0000	168	24	24	3810
8	09Jan1984 0000	192	24	24	2840
9	10Jan1984 0000	216	24	24	2380
10	11Jan1984 0000	240	24	24	1810
11	12Jan1984 0000	264	24	24	1910
12	13Jan1984 0000	288	24	24	2330
13	14Jan1984 0000	312	24	24	2290
14	15Jan1984 0000	336	24	24	1700
15	16Jan1984 0000	360	24	24	1450
16	17Jan1984 0000	384	24	24	1200
17	18Jan1984 0000	408	24	24	1000

☑ Compute computation increments based on flow

	Qlow	Qhigh	CI
1	0	4000	24
2	4000	6000	6
3	6000	20000	1
4			
5			
6			
7			

Figure 1-4. Flow series editor.

Computational Increment:

The Computational Increment subdivides the Flow Duration. The quasi-unsteady model computes new steady flow profiles at each computational increment, applying the hydraulic parameters over this time step. This approach assumes bed geometry does not change enough between computational increments to alter hydrodynamics appreciably.

Sediment transport is highly non-liner. Most transport and bed change is concentrated in relatively brief periods of high flow, and flood events are often highly dynamic. Large quasi-unsteady time steps (e.g. 24 hours or more) are often sufficient for low flow periods with little bed change. However, moderate to high flows can change channel geometry quickly, undermining the assumption that the hydrodynamics are the same throughout a large time step. Therefore, moderate to high flows require smaller computational increments.

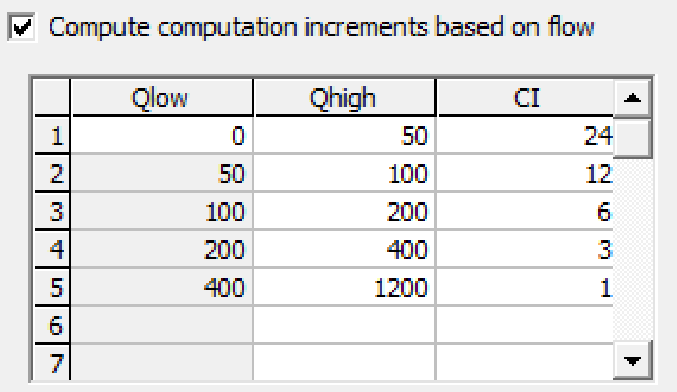
Model stability is very sensitive to computational increment. If the simulation window reports "Model fills with sediment" when the model fails, the computational increment associated with that flow duration is probably too large. If channel geometry is updated too infrequently (i.e. if the computational increment is too large), too much material could be eroded or deposited in a time step, causing the model to over correct in the next time step, generating oscillations and model instabilities.

For example, the first two flow records in Figure 1-4 (02 and 03 January) are daily flow records with 24 hour computational increments. Therefore, HEC-RAS will only compute hydraulic parameters once over these days. However, the third- and fourth-time steps (ending 04Jan and 05Jan) have daily flow durations but are subdivided into multiple steps. HEC-RAS will update the hydraulics four times during the third flow record (every 6 hours, based on the 6 hour computational increment) and will update hydraulics 24 times (every hour, for the fourth and fifth flows), at the beginning of each 1-hour computation increment.

Modeling Note – Computational Increments Drive Run Times and Model Stability: While smaller computation increments will increase run time, re-computing geometry and hydraulics too infrequently (e.g. computation increments that are too large) is the most common source of model instability.

Automate Computational Increments (Optional)

It is often useful to apply a consistent flow-computational increment (CI) relationship to the entire flow series, particularly when trying to optimize the increment for a long flow series. HEC-RAS will automatically populate computational increments with user specified flow ranges. Click the Compute Computation Increment Based on Flow check box (Figure 1-5). This will open an editor to associate consecutive, non-overlapping flow ranges with computational increments. The feature also grays out the computational increment column, because it populates automatically. The computational increments persist and become editable if the user turns the Compute computation increments based on flow off (i.e. uncheck the check box), but the tool will overwrite any existing computational increments if it is turned on.



☑ Compute computation increments based on flow

	Qlow	Qhigh	CI
1	0	50	24
2	50	100	12
3	100	200	6
4	200	400	3
5	400	1200	1
6			
7			

Figure 1-5: Computational increment editor that automatically populates computational increments as a function of flow.

Modeling Note - Automated Increment Range: If your flow time series includes flows lower than the smallest flow of higher than the largest flow in your automated computational increment, HEC-RAS will automatically use the Computational increment associated with the lowest or highest range respectively. (Note: this is new in version 6.0. Previous versions returned an error)

Fixed or Simulation Start Time?

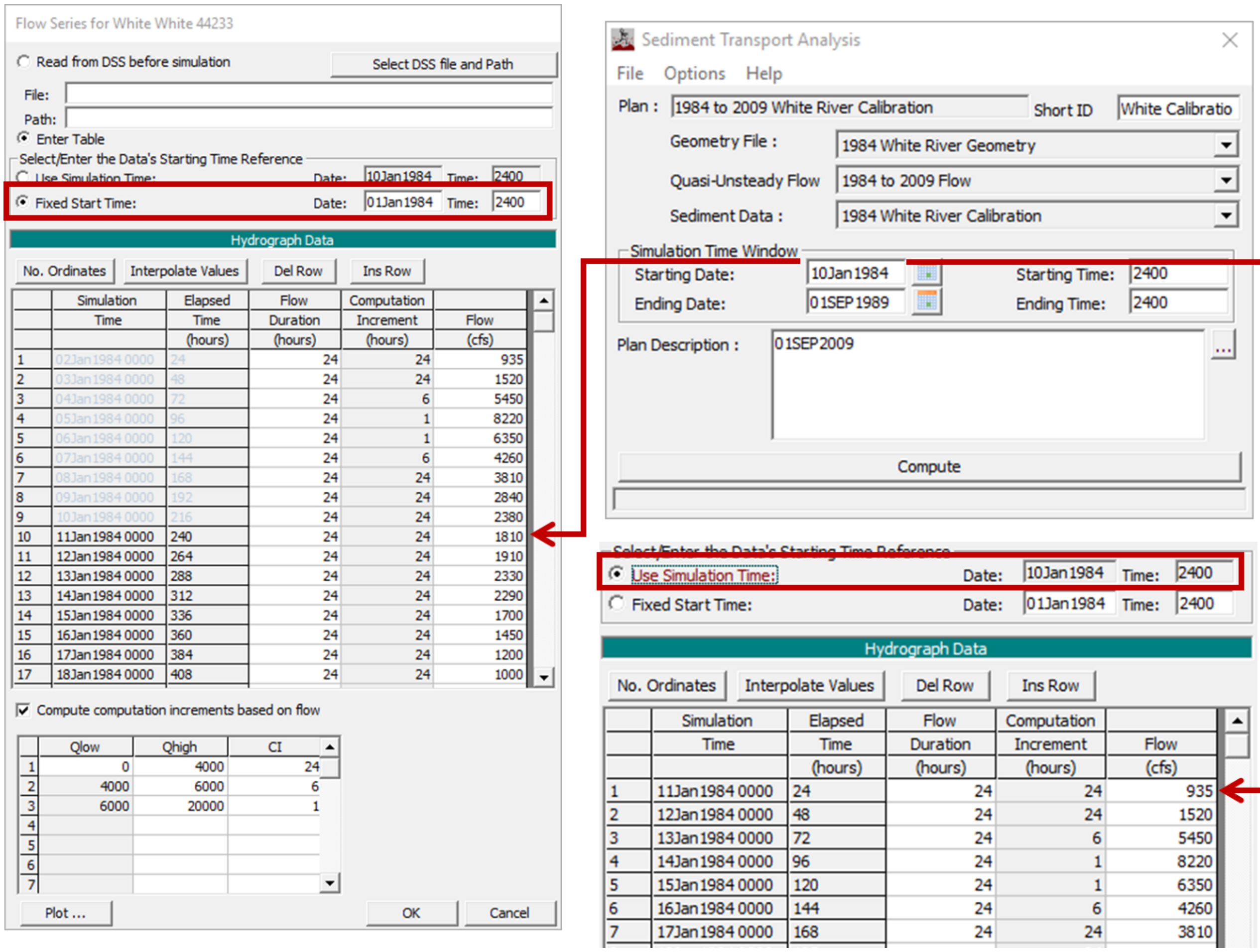
Most HEC-RAS time series editors aske users to **Select/Enter the Data's Starting Time Reference**. This is one of the places in HEC-RAS where the default is usually not the best practice. **Use Simulation** Time is the default. In this method, the time series is always relative in time. The first record will always adopt the starting time in the **Simulation** time window. So in the figure below, the simulation starts on 10Jan1984, so the default time reference (bottom right of the figure) automatically assigns that time stamp to the first flow (the Simulation Time in quasi-unsteady marks the end of the time step, so it shows 11Jan).

However, apart from experimental studies with set start times or synthetic hydrographs, flow data are almost always temporally fixed. The example on the left in the figure above shows a F**ixed Start Time** that begins on 01Jan. Now the simulation that starts on 10Jan starts on the 10th daily record. The **Fixed Start Time** has two main advantages:

1. First, using fixed start times allows users to simply enter their complete data time series for different boundary conditions without trimming them all to the same start time.

2. Second, Fixed Start Times give modelers a lot of flexibility in the simulations. By fixing time series, modelers can shift the simulation time window to simulate a wet-r-dry decade, a three-day flood, a full period of record that is longer than the project window, multiple calibration periods, or other sensitivity/calibration/credibility tests without editing the flow file.

Therefore, the **Fixed Start Time** is the appropriate data format for most sediment models, whether the data are historical or synthetic future.



Select/Enter the Data's Starting Time Reference
○ Use Simulation Time: Date: 10Jan1984 Time: 2400
● Fixed Start Time: Date: 01Jan1984 Time: 2400

	Simulation Time	Elapsed Time (hours)	Flow Duration (hours)	Computation Increment (hours)	Flow (cfs)
1	02Jan1984 0000	24	24	24	935
2	03Jan1984 0000	48	24	24	1520
3	04Jan1984 0000	72	24	6	5450
4	05Jan1984 0000	96	24	1	8220
5	06Jan1984 0000	120	24	1	6350
6	07Jan1984 0000	144	24	6	4260
7	08Jan1984 0000	168	24	24	3810
8	09Jan1984 0000	192	24	24	2840
9	10Jan1984 0000	216	24	24	2380
10	11Jan1984 0000	240	24	24	1810
11	12Jan1984 0000	264	24	24	1910
12	13Jan1984 0000	288	24	24	2330
13	14Jan1984 0000	312	24	24	2290
14	15Jan1984 0000	336	24	24	1700
15	16Jan1984 0000	360	24	24	1450
16	17Jan1984 0000	384	24	24	1200
17	18Jan1984 0000	408	24	24	1000

☑ Compute computation increments based on flow

	Qlow	Qhigh	CI
1	0	4000	24
2	4000	6000	6
3	6000	20000	1
4			
5			
6			
7			

Plan : 1984 to 2009 White River Calibration Short ID White Calibratio
Geometry File : 1984 White River Geometry
Quasi-Unsteady Flow 1984 to 2009 Flow
Sediment Data : 1984 White River Calibration
Simulation Time Window
Starting Date: 10Jan1984 Starting Time: 2400
Ending Date: 01SEP1989 Ending Time: 2400
Plan Description : 01SEP2009

Select/Enter the Data's Starting Time Reference
● Use Simulation Time: Date: 10Jan1984 Time: 2400
○ Fixed Start Time: Date: 01Jan1984 Time: 2400

	Simulation Time	Elapsed Time (hours)	Flow Duration (hours)	Computation Increment (hours)	Flow (cfs)
1	11Jan1984 0000	24	24	24	935
2	12Jan1984 0000	48	24	24	1520
3	13Jan1984 0000	72	24	6	5450
4	14Jan1984 0000	96	24	1	8220
5	15Jan1984 0000	120	24	1	6350
6	16Jan1984 0000	144	24	6	4260
7	17Jan1984 0000	168	24	24	3810

*Figure 1-6: Examples of how the **Fixed** and **Simulation Start Times** work in the quasi-unsteady editor..*

Warning: A common error in HEC-RAS modeling involves setting a fixed start time but forgetting to select it with the radio button. This can be a problem in models with many boundary conditions. After adding all the flow boundary conditions, go in to each one and make sure the **Fixed Start Time** is not only specified, but also selected.

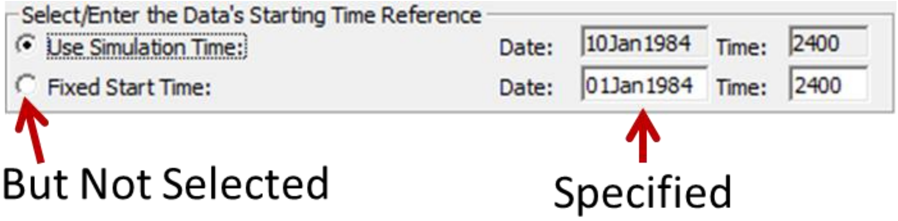

Select/Enter the Data's Starting Time Reference
● Use Simulation Time: Date: 10Jan1984 Time: 2400
○ Fixed Start Time: Date: 01Jan1984 Time: 2400

Figure 1-7: A common error in the flow boundary condition involves specifying a fixed start time but failing to select it.

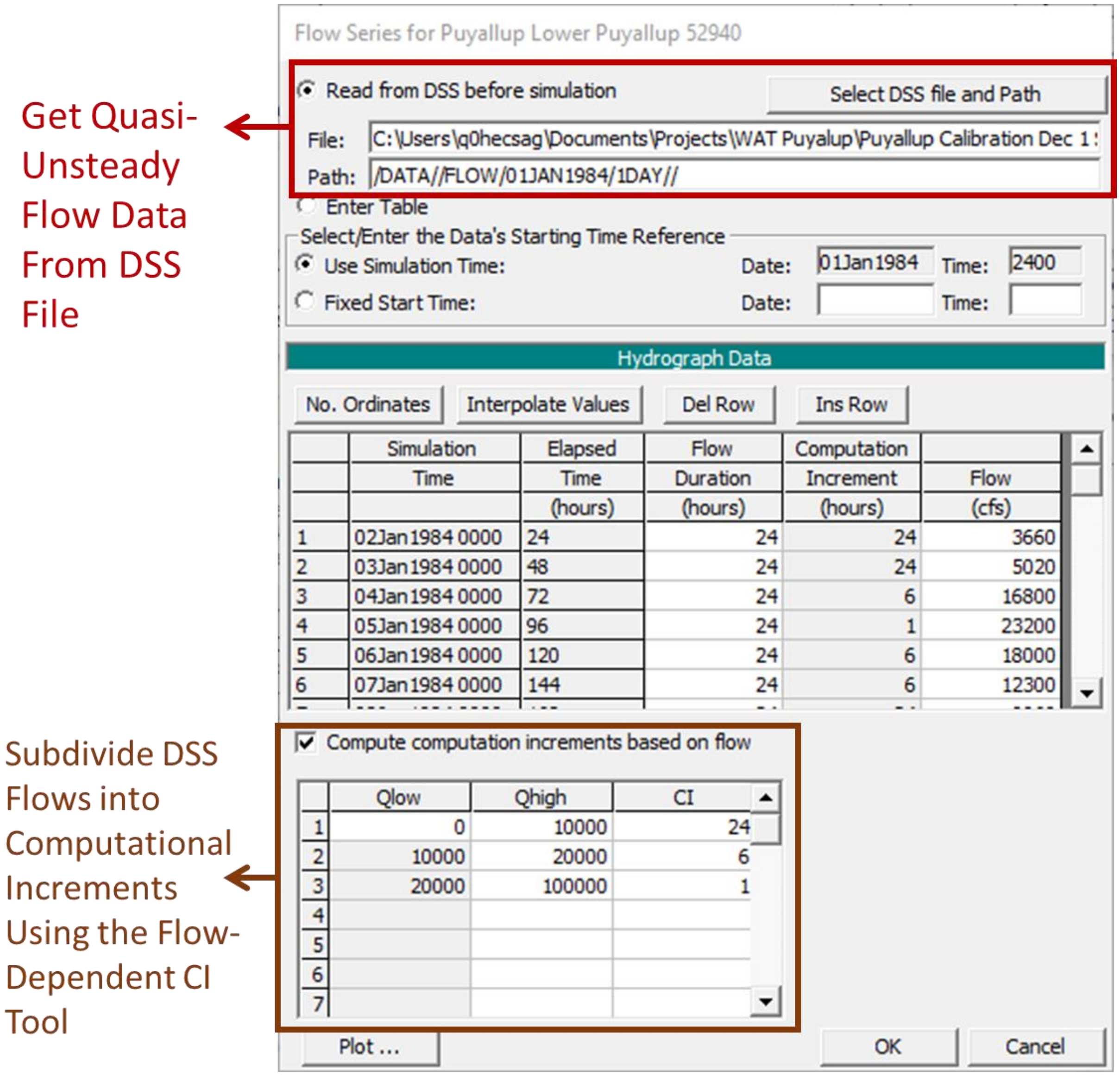
Using DSS Flow Data for a Quasi-Unsteady Simulation

Previous versions (before 6.0) of HEC-RAS could not use DSS files to define quasi-unsteady flow boundaries. Current versions can define quasi-unsteady flows with a regular time-step DSS flow record. Defining flows with a DSS record helps coordinate the sediment transport model with other HEC software, flow data bases, and allows HEC's stochastic engine (HEC-

WAT) to sample hydrologic realizations and automate stochastic simulations that evaluate the role of hydrologic uncertainty on quasi-unsteady sediment transport.

However, irregular time steps are important in long term sediment transport models. Daily flow time steps are often too coarse for floods, requiring modelers to subdivide daily flows into smaller computational increments for high flows. Therefore, the **Compute Computation Increments Based on Flow** feature works with regular time-step DSS flows, assigning irregular computational increments to each flow, based on its magnitude. This gives users control over an irregular computational time step even if they import a regular time step DSS record.

Users can also use the histography generator to convert a regular time-step DSS file into an irregular time step quasi-unsteady flow file based on equal sediment mass flux.



Get Quasi-Unsteady Flow Data From DSS File

Subdivide DSS Flows into Computational Increments Using the Flow-Dependent CI Tool

Flow Series for Puyallup Lower Puyallup 52940

● Read from DSS before simulation

File: C:\Users\q0hecsag\Documents\Projects\WAT Puyalup\Puyallup Calibration Dec 1

Path: /DATA//FLOW/01JAN1984/1DAY//

○ Enter Table

Select/Enter the Data's Starting Time Reference

● Use Simulation Time: Date: 01Jan1984 Time: 2400

○ Fixed Start Time: Date: Time:

Hydrograph Data

	Simulation Time	Elapsed Time (hours)	Flow Duration (hours)	Computation Increment (hours)	Flow (cfs)
1	02Jan1984 0000	24	24	24	3660
2	03Jan1984 0000	48	24	24	5020
3	04Jan1984 0000	72	24	6	16800
4	05Jan1984 0000	96	24	1	23200
5	06Jan1984 0000	120	24	6	18000
6	07Jan1984 0000	144	24	6	12300

☑ Compute computation increments based on flow

	Qlow	Qhigh	CI
1	0	10000	24
2	10000	20000	6
3	20000	100000	1
4			
5			
6			
7			

Figure 1-8: Define a DSS flow file at a quasi-unsteady boundary condition and define flow-dependent computational increments to subdivide regular time steps.

Downstream Boundary Conditions

The downstream cross section is a mandatory hydraulic model boundary location, so the Quasi-Unsteady flow editor automatically populates a row for the downstream cross section. HEC-RAS has three quasi-unsteady, downstream boundary conditions.

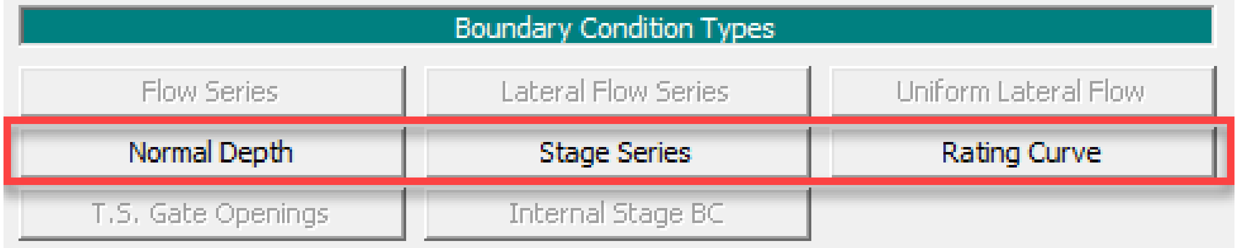
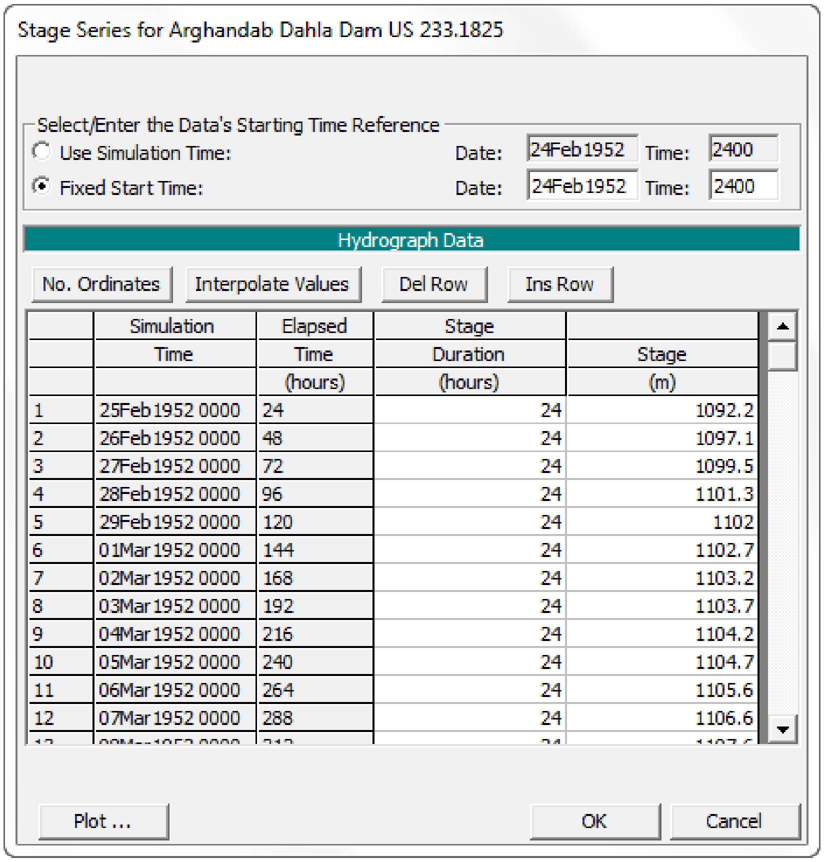


Figure 1-9: The three valid downstream boundary conditions for Quasi-Unsteady flow.

Stage Time Series

Quasi-unsteady flow has three downstream boundary conditions, all specifying downstream stages for each steady flow backwater computation. If stage data are available or projected for the simulation period, the **Stage Time Series** can set the downstream boundary (Figure 1-10). This editor follows the standard irregular time series format of a duration associated with a stage. No computation increment is required for a **Stage Time Series**.



Select/Enter the Data's Starting Time Reference

○ Use Simulation Time: Date: 24Feb1952 Time: 2400

● Fixed Start Time: Date: 24Feb1952 Time: 2400

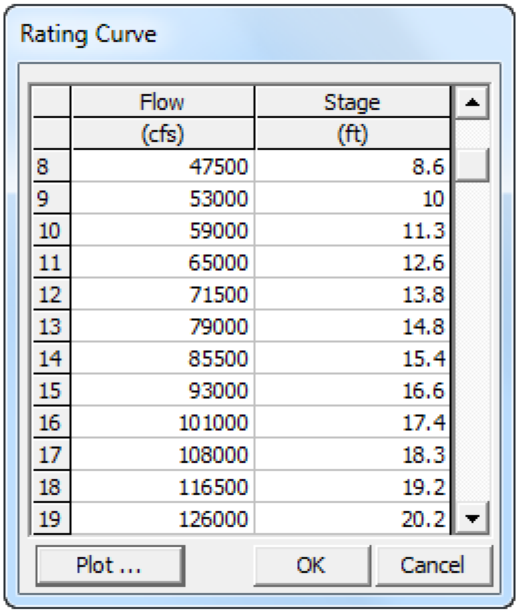
	Simulation Time	Elapsed Time (hours)	Stage Duration (hours)	Stage (m)
1	25Feb1952 0000	24	24	1092.2
2	26Feb1952 0000	48	24	1097.1
3	27Feb1952 0000	72	24	1099.5
4	28Feb1952 0000	96	24	1101.3
5	29Feb1952 0000	120	24	1102
6	01Mar1952 0000	144	24	1102.7
7	02Mar1952 0000	168	24	1103.2
8	03Mar1952 0000	192	24	1103.7
9	04Mar1952 0000	216	24	1104.2
10	05Mar1952 0000	240	24	1104.7
11	06Mar1952 0000	264	24	1105.6
12	07Mar1952 0000	288	24	1106.6

Figure 1-10: Specifying stage with a stage time series.

The stage time series is usually the best option for historical analysis. When using this feature for to predict future time series, however, be careful to set it at a reach in morphological quasi-equilibrium (e.g. a reach that is not actively aggrading or degrading on the decadal time scale).

Rating Curve

In the absence of time series data, a rating curve can define a downstream relationship between stage and flow, computing downstream boundary stages in response to the simulation flow series. The **Rating Curve** button launches a dialogue where users can enter a flow-stage rating curve for the downstream cross section (Figure 1-11). Be careful to place flow and stage in the correct columns (they are inverted from other editors). HEC-RAS will interpolate a boundary stage from the rating curve for each time step based on the flow. Like the stage time series, applying a rating curve boundary condition to predictive analyses assumes the downstream boundary condition is essentially in morphological quasi-equilibrium (i.e. not expecting long term deposition or erosion trends).



	Flow (cfs)	Stage (ft)
8	47500	8.6
9	53000	10
10	59000	11.3
11	65000	12.6
12	71500	13.8
13	79000	14.8
14	85500	15.4
15	93000	16.6
16	101000	17.4
17	108000	18.3
18	116500	19.2
19	126000	20.2

Figure 1-11: Rating curve editor for downstream boundary condition.

Normal Depth

The final downstream boundary option is Normal depth. The **Normal Depth** button launches a simple window requesting a single parameter: the Friction Slope. The friction slope (S_f in Manning's equation) is the slope of the energy grade line and can be estimated *a prior* by measuring the slope of the bed (press the *Alt* key in the HEC-RAS Water Surface Profile output view to get a tool that will measure the slope). With the friction slope, the flow, the n-value and the cross-section shape specified, HEC-RAS can back-calculate stage from Manning's Equation.

Modeling Note – Downstream Boundary Condition – Depth vs. Stage: **Normal Depth** is a popular boundary condition in steady and unsteady flow because it requires so little data. However, it also introduces more uncertainty than the stage series or the rating curve options. It is also popular in quasi-unsteady sediment analysis, for the same reasons. However **Normal Depth** can introduce troubling numerical feedback in the sediment model in addition to hydraulic uncertainties and should be used with *caution*.

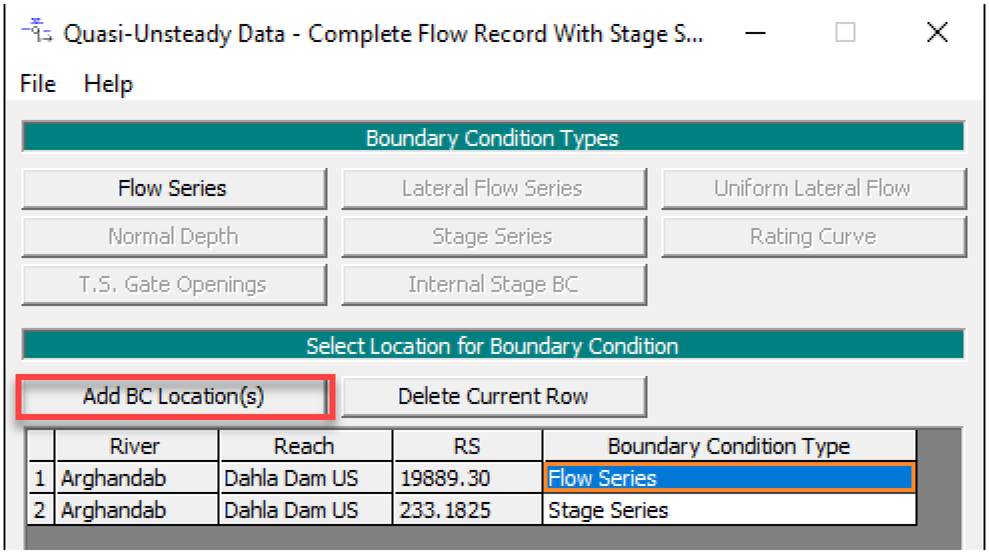
Setting a downstream *depth* rather than *stage*, makes the water surface elevation independent of the computed channel elevation. There is no feedback between bed change and water surface elevation. For stage boundary conditions, if the bed aggrades, shear will increase, and the rate of aggradation will drop until the cross-section approaches equilibrium. Erosion will introduce the opposite feedback, settling similarly on an equilibrium geometry. Therefore, stage boundary conditions should be specified in quasi-equilibrium reaches.

A depth boundary condition will continue to aggrade or degrade without water surface feedbacks. The next time step will simply compute a new depth on the new cross section shape. This can introduce numerical artifacts, where normal depth boundary conditions aggrade or degrade unrealistically over the simulation. Therefore, while convenient, normal depth is often a poorly posed boundary condition for sediment transport models, unless the downstream cross section is in equilibrium. The user can force equilibrium by setting the downstream boundary condition as a **Pass Through Node**, however, this sometimes just pushes the numerical problem one cross section upstream.

Internal Boundary Conditions

Users can also define boundary conditions at internal cross sections. Internal cross sections are mostly optional (except for Gate Openings; if an inline structure has gates HEC-RAS will add it to the boundary condition editor for gate opening information).

To add an internal boundary condition press the Add BC Location(s) button Add BC Location(s) and specify the cross section to add.



	River	Reach	RS	Boundary Condition Type
1	Arghandab	Dahla Dam US	19889.30	Flow Series
2	Arghandab	Dahla Dam US	233.1825	Stage Series

Figure 1-12: Add an optional internal boundary condition.

Lateral Flow Series

A lateral flow series can also be associated with any internal cross section in a project. This feature usually accounts for flows from un-modeled tributaries. The user must add an internal cross section to the **Quasi-Unsteady Flow** dialog before assigning it a quasi-unsteady boundary condition.

Add a flow change location with the **Add Flow Change Location(s)** button on the **Quasi Unsteady Flow** dialog. This will open the **Select River Station Locations** dialog (used elsewhere in the program e.g. Figure 1-51). Select one or more river stations by double clicking them or selecting them and pressing the arrow button. Pressing OK will create a boundary condition location for each selected station in the **Quasi-Unsteady Flow Editor**. The Lateral Flow Series editor is identical to the flow series editor in Figure 1-4.

Location of Lateral Flows and Sediment Loads

Steady and Unsteady flow bring “lateral flows” (a lateral boundary condition in unsteady and a flow change location) upstream and downstream of the specified cross section respectively (Figure 1-13). Steady flow changes show up at the specified cross section (conceptually entering the model upstream) and unsteady lateral flow boundaries show up at the cross section downstream of the defined cross section (conceptually entering the model downstream of the control volume).

Quasi unsteady follows the unsteady flow convention[1] (despite being a series of steady flows). A Quasi-unsteady flow model will bring flow into the model downstream of the specified cross section. If a sediment rating curve is assigned to one of these lateral flow series boundary conditions, it will come in at the same location as the flow, downstream of the specified cross section (Figure 1-13).

Modeling Note – Locating a Tributary: Because both quasi- and unsteady flow models bring tributary flows into the model downstream of the specified cross section, define the tributary flow and load at the cross section upstream of the point where it enters the system. Conceptually, the Tributary enters the model at the transition between the two control volumes. Therefore, a model that lays out the cross sections so a tributary (modeled as a lateral flow series) enters between the cross sections will work well.

---

[1] Quasi-unsteady only follows the unsteady convention in more recent versions of HEC-RAS. In earlier versions, quasi-unsteady followed the steady flow convention, entering the model upstream of the specified cross sections.

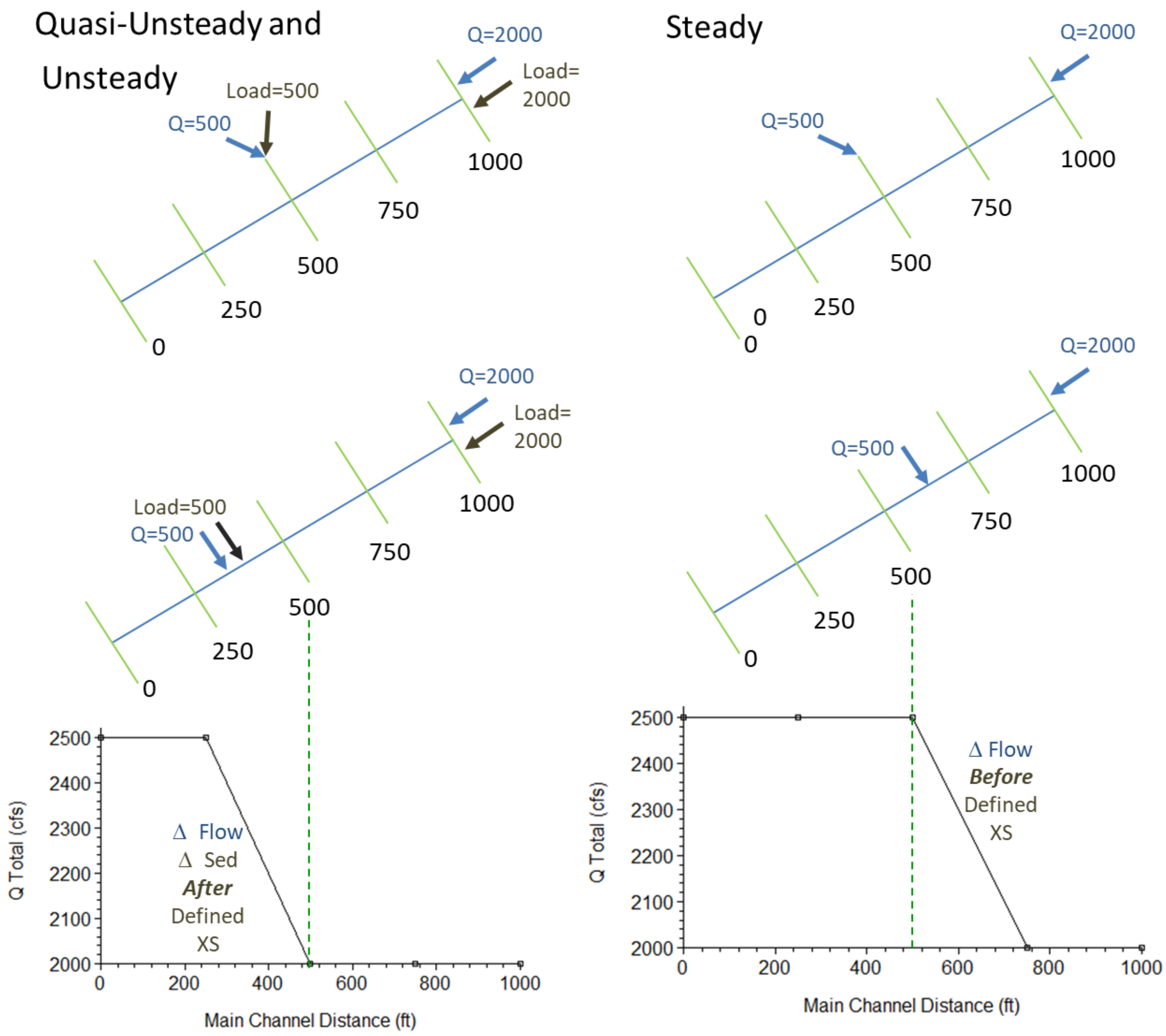


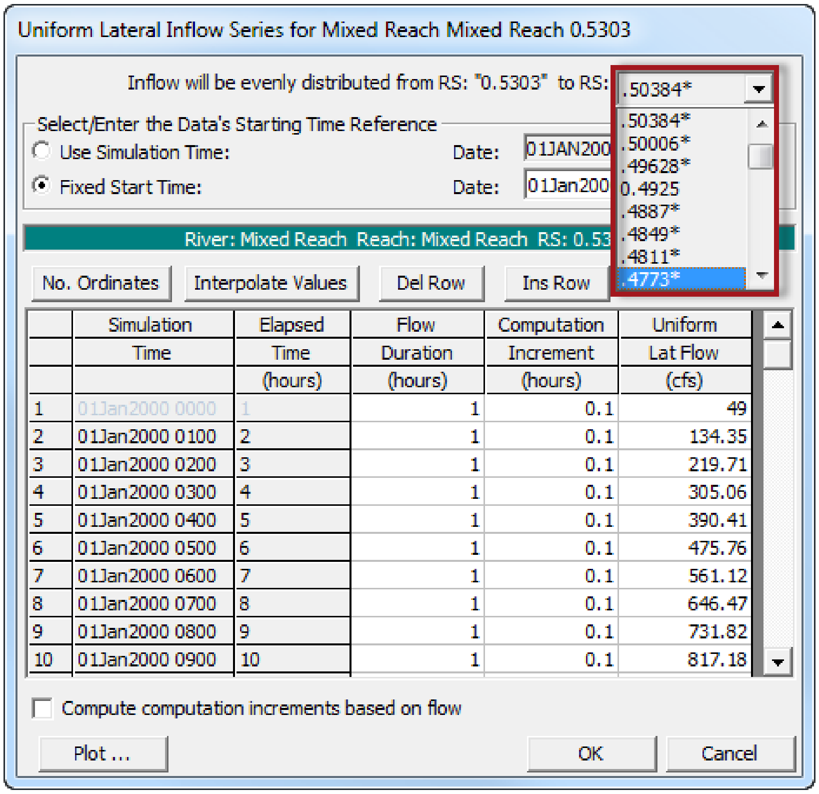
Figure 1-13: Schematic of flow change location associated with a lateral flow (and associated sediment) for the three flow models. This example increases flow from 2000 to 2500 at XS 500. The DQ shows up downstream of the cross section (at the next one) in quasi- and unsteady, and upstream of the XS (at the specified XS) for steady.

Uniform Lateral Flow

HEC-RAS can also distribute a lateral flow series over several cross sections. This feature often distributes overland watershed runoff, computed from a hydrologic model, along the hydraulic reach instead of concentrating it at one point.

Defining a uniform lateral flow follows the same steps as the lateral flow series (above). Add a lateral boundary location with the **Add Flow Change Location(s)** button at the cross section upstream of those HEC-RAS will distribute the flow over. Select the **Uniform Lateral Flow** button. The **Uniform Lateral Flow** button opens the editor shown in Figure 1-14. This dialog is similar to the other flow series dialogs (Figure 1-4) with one addition, a drop down list of downstream cross sections at the top.

HEC-RAS will distribute the flow by reach weighted averages, apportioning more flow to cross sections with longer downstream channel reach lengths. Uniform lateral flows cannot be specified across stream junctions, bridges, inline or lateral structures.


Uniform Lateral Inflow Series for Mixed Reach Mixed Reach 0.5303

Inflow will be evenly distributed from RS: "0.5303" to RS: .50384*

Select/Enter the Data's Starting Time Reference

○ Use Simulation Time: Date: 01JAN200

● Fixed Start Time: Date: 01Jan200

River: Mixed Reach Reach: Mixed Reach RS: 0.53

	Simulation Time	Elapsed Time (hours)	Flow Duration (hours)	Computation Increment (hours)	Uniform Lat Flow (cfs)
1	01Jan2000 0000	1	1	0.1	49
2	01Jan2000 0100	2	1	0.1	134.35
3	01Jan2000 0200	3	1	0.1	219.71
4	01Jan2000 0300	4	1	0.1	305.06
5	01Jan2000 0400	5	1	0.1	390.41
6	01Jan2000 0500	6	1	0.1	475.76
7	01Jan2000 0600	7	1	0.1	561.12
8	01Jan2000 0700	8	1	0.1	646.47
9	01Jan2000 0800	9	1	0.1	731.82
10	01Jan2000 0900	10	1	0.1	817.18

☐ Compute computation increments based on flow

Figure 1-14: Uniform lateral flow series dialog.

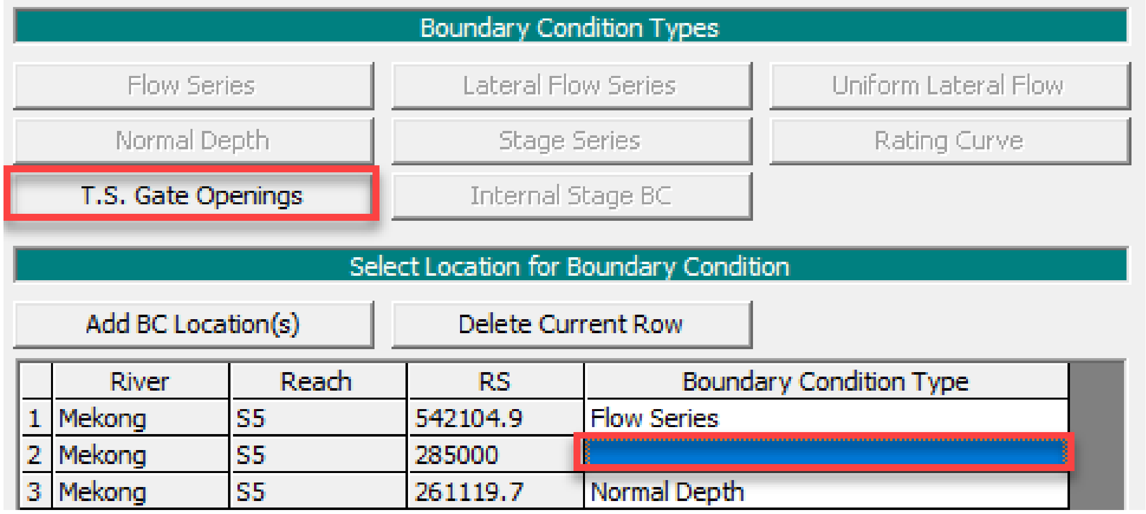
Gate Time Series

Inline structures with gates can be included in a quasi-unsteady sediment model. However, gate and reservoir operations are ill posed in a quasi-unsteady model. Since the quasi-unsteady approach uses a series of steady flows, it will compute a reservoir elevation based on the head required to reach steady state equilibrium, to 'push' the reach flow through the gates. This can lead to dramatic fluctuations in reservoir stage from time step to time step and does not conserve mass.

To replicate historic reservoir stages with gates in quasi-unsteady flow, a modeler could use the orifice equation to back calculate the orifice opening that will produce the historic head for the historic flow. But recent versions of HEC-RAS include an Internal Stage Boundary Condition

Unsteady sediment transport and in HEC-RAS version 5.0 should make quasi-unsteady gate operation mostly obsolete (with the exception of flushing studies, see section below on Interaction Between Internal Stage and BC Gates), which is why the quasi-unsteady gates have only one boundary condition while there are four different ways to operate gates in an unsteady flow simulation.

However, if an inline structure has gates, HEC-RAS requires gate openings (even if the model does not use them – see the section on Interaction Between Internal Stage BC and Gates) and the quasi-unsteady editor will generate a mandatory internal boundary condition for the structure (Figure 1-15). If the user does include gated inline structures in a quasi-unsteady model, however, the **T.S. Gate Openings** boundary condition in the Quasi-Unsteady Flow editor will control them. The **T.S. Gate Openings** boundary condition is required. Therefore, if the project includes an inline with gates the structure will show up in the **Quasi-Unsteady Flow Editor**.



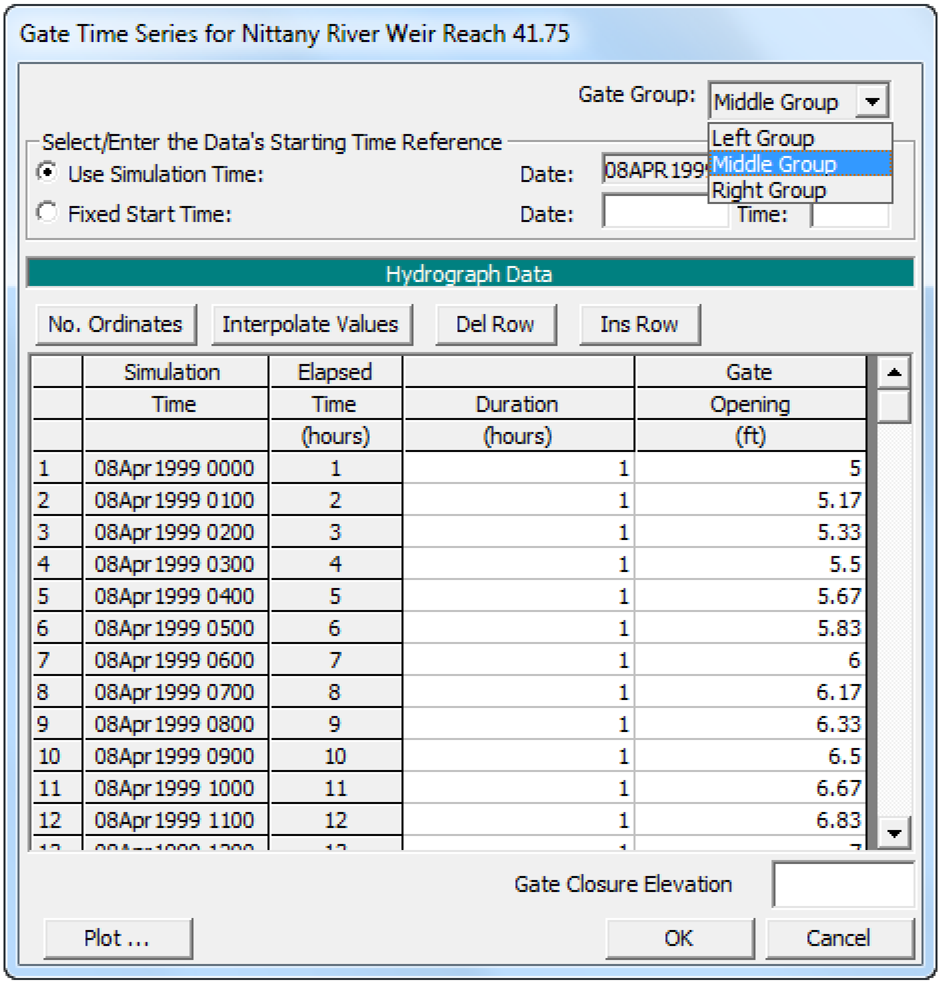
	River	Reach	RS	Boundary Condition Type
1	Mekong	S5	542104.9	Flow Series
2	Mekong	S5	285000	
3	Mekong	S5	261119.7	Normal Depth

Figure 1-15: Inline Structure with gates requires a boundary condition and populates in the quasi unsteady flow editor automatically.

If the model includes multiple gate groups, the boundary condition will require gate openings to cover the entire simulation time for *each* gate group. A drop-down menu in the upper right-hand corner allows users to specify gates for each gate group in a structure.

Modeling Note – Specify Openings for *ALL* Gate Groups: A common error involves only specifying gates for the gate group that is active when the editor opens, and not realizing there are others that need gates.

Warning: Quasi-Unsteady flow does not route flow through reservoirs or gates. Instead it simply computes the backwater stage for each time step based on the flow through the gates, leading to unrealistic reservoir stage fluctuations. Quasi-unsteady gate operations are **NOT RECOMMENDED** for most applications. Consider running reservoir models in unsteady flow or use one of the quasi-unsteady reservoir approaches described in the reservoir modeling video series like the Internal Stage Boundary Condition (next heading).



Gate Group: Middle Group

Select/Enter the Data's Starting Time Reference

● Use Simulation Time: Date: 08APR199

○ Fixed Start Time: Date: Time:

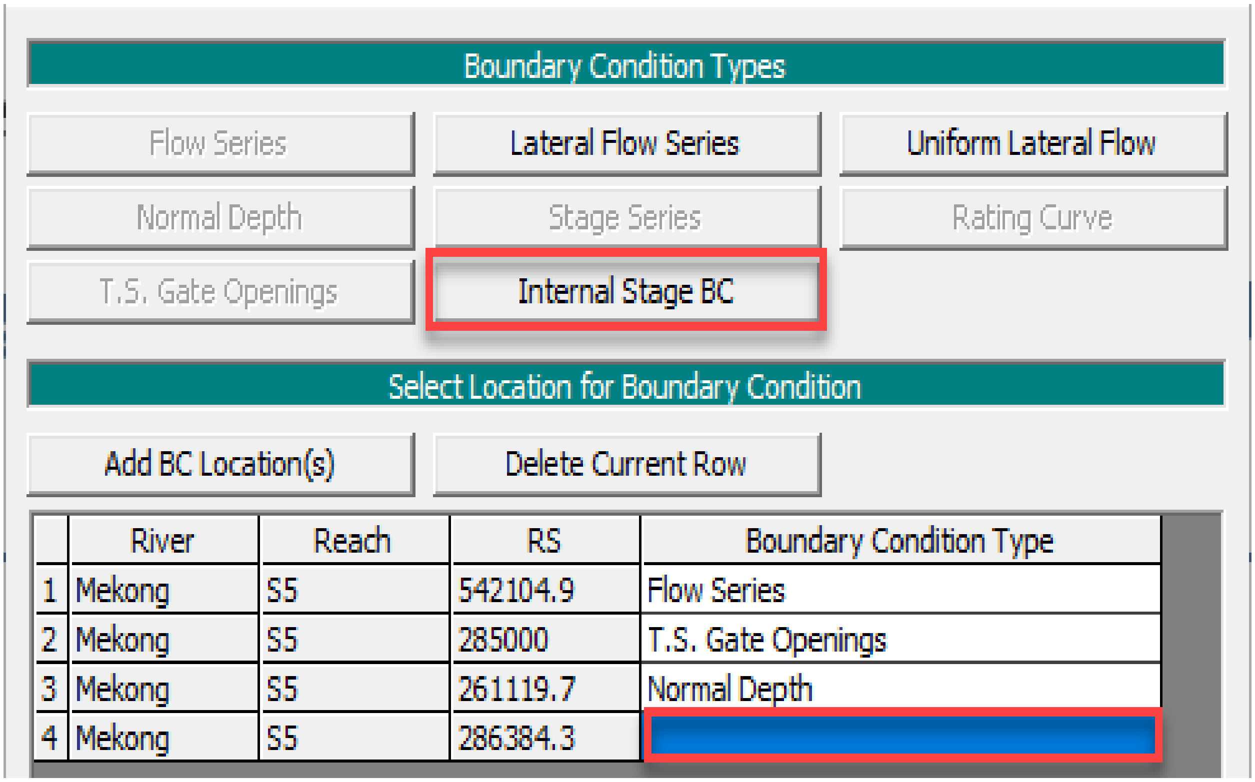
	Simulation Time	Elapsed Time (hours)	Duration (hours)	Gate Opening (ft)
1	08Apr1999 0000	1	1	5
2	08Apr1999 0100	2	1	5.17
3	08Apr1999 0200	3	1	5.33
4	08Apr1999 0300	4	1	5.5
5	08Apr1999 0400	5	1	5.67
6	08Apr1999 0500	6	1	5.83
7	08Apr1999 0600	7	1	6
8	08Apr1999 0700	8	1	6.17
9	08Apr1999 0800	9	1	6.33
10	08Apr1999 0900	10	1	6.5
11	08Apr1999 1000	11	1	6.67
12	08Apr1999 1100	12	1	6.83

Gate Closure Elevation

Figure 1-16: Time series gate editor

Internal Stage BC

Recent versions of HEC-RAS include an internal stage time series boundary condition Internal Stage BC that can control stage within the model. The most common use for this is to control reservoir stages. By defining a stage series at the cross section just upstream of the inline structure representing a dam, modelers can control reservoir stages directly throughout the duration of the model. This allows modelers to use the Quasi-Unsteady mode to simulate reservoir operation without routing the flows (if they know the reservoir stage for the entire simulation).

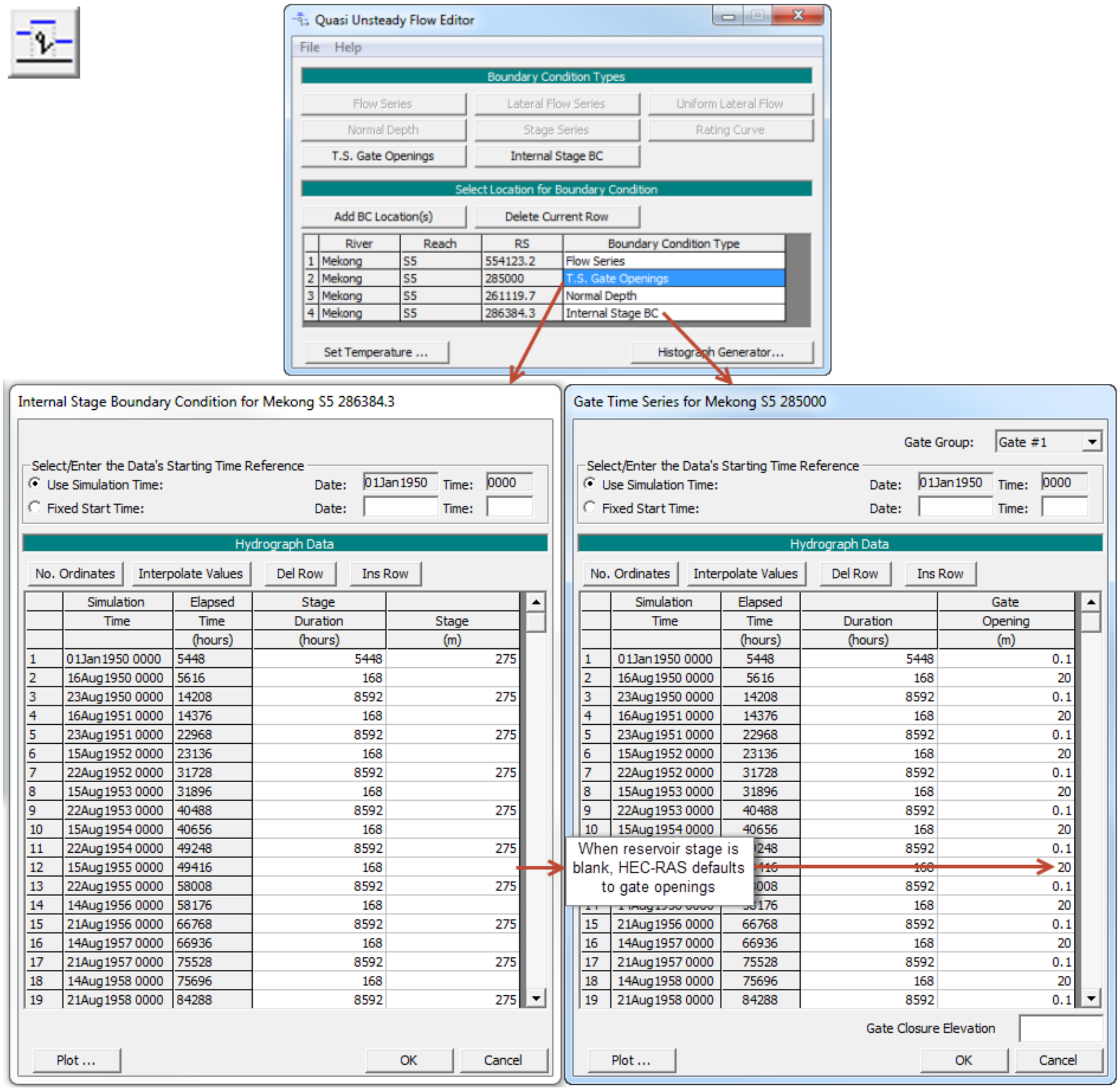


	River	Reach	RS	Boundary Condition Type
1	Mekong	S5	542104.9	Flow Series
2	Mekong	S5	285000	T.S. Gate Openings
3	Mekong	S5	261119.7	Normal Depth
4	Mekong	S5	286384.3	

Figure 1-17: Boundary Condition types

The model will still require Gate Openings if the inline structure has gates. However, the quasi-unsteady model does not use the gates to compute flow through the structure (it is a backwater calculation, so the flow is specified), only the reservoir stage. Therefore, if the user specifies the stage upstream of the dam, HEC-RAS does not end up using these Gate Openings and the modeler can fill them with place-holder values.

Modeling Note – Transition Between Stage and Gate Control: Sometimes it can be useful to switch between stage control and gate control in a reservoir model. The most common application of this is for a periodic reservoir flush. Figure 1-18 shows a simplified, quasi-unsteady approach to simulating an annual flush over an extended, period of record, simulation. The Internal Stage Boundary Condition holds the reservoir stage for most of the year (8567 hours is 51 weeks). But then, for 1 week per year (168 hours) the stage field is blank. When HEC-RAS encounters a blank stage in the Internal Stage Series, it reverts to the backwater computation. In this example, the blank internal stages correspond to fully opening the gates (20m). This does not gradually drain the reservoir. A modeler would have to gradually decrease the internal stages to simulate a gradual drawdown. But it does switch the reservoir between a specified pool and a run-of-river flush.



	River	Reach	RS	Boundary Condition Type
1	Mekong	S5	554123.2	Flow Series
2	Mekong	S5	285000	T.S. Gate Openings
3	Mekong	S5	261119.7	Normal Depth
4	Mekong	S5	286384.3	Internal Stage BC

Internal Stage Boundary Condition for Mekong S5 286384.3

Select/Enter the Data's Starting Time Reference
● Use Simulation Time: Date: 01Jan1950 Time: 0000
○ Fixed Start Time: Date: Time:

	Simulation Time	Elapsed Time (hours)	Stage Duration (hours)	Stage (m)
1	01Jan1950 0000	5448	5448	275
2	16Aug1950 0000	5616	168	
3	23Aug1950 0000	14208	8592	275
4	16Aug1951 0000	14376	168	
5	23Aug1951 0000	22968	8592	275
6	15Aug1952 0000	23136	168	
7	22Aug1952 0000	31728	8592	275
8	15Aug1953 0000	31896	168	
9	22Aug1953 0000	40488	8592	275
10	15Aug1954 0000	40656	168	
11	22Aug1954 0000	49248	8592	275
12	15Aug1955 0000	49416	168	
13	22Aug1955 0000	58008	8592	275
14	14Aug1956 0000	58176	168	
15	21Aug1956 0000	66768	8592	275
16	14Aug1957 0000	66936	168	
17	21Aug1957 0000	75528	8592	275
18	14Aug1958 0000	75696	168	
19	21Aug1958 0000	84288	8592	275

Gate Time Series for Mekong S5 285000

Gate Group: Gate #1

Select/Enter the Data's Starting Time Reference
● Use Simulation Time: Date: 01Jan1950 Time: 0000
○ Fixed Start Time: Date: Time:

	Simulation Time	Elapsed Time (hours)	Duration (hours)	Gate Opening (m)
1	01Jan1950 0000	5448	5448	0.1
2	16Aug1950 0000	5616	168	20
3	23Aug1950 0000	14208	8592	0.1
4	16Aug1951 0000	14376	168	20
5	23Aug1951 0000	22968	8592	0.1
6	15Aug1952 0000	23136	168	20
7	22Aug1952 0000	31728	8592	0.1
8	15Aug1953 0000	31896	168	20
9	22Aug1953 0000	40488	8592	0.1
10	15Aug1954 0000	40656	168	20
[illegible]	[illegible]	248	8592	0.1
[illegible]	[illegible]	416	168	20
[illegible]	[illegible]	008	8592	0.1
[illegible]	[illegible]	176	168	20
15	21Aug1956 0000	66768	8592	0.1
16	14Aug1957 0000	66936	168	20
17	21Aug1957 0000	75528	8592	0.1
18	14Aug1958 0000	75696	168	20
19	21Aug1958 0000	84288	8592	0.1

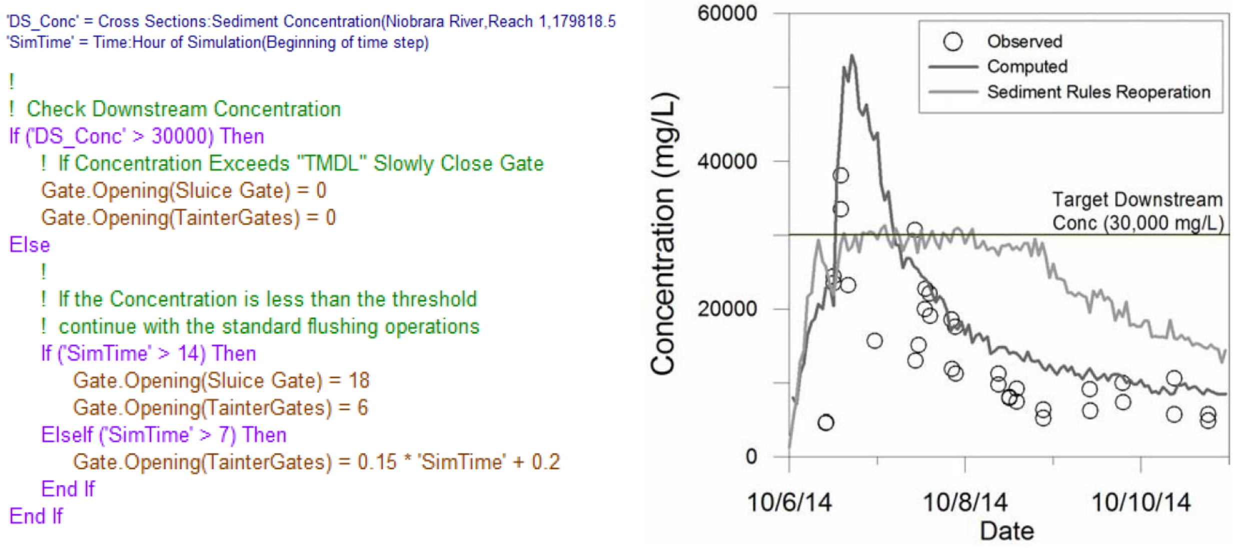
Gate Closure Elevation

When reservoir stage is blank, HEC-RAS defaults to gate openings

Figure 1-18: A weekly reservoir flush simulated in HEC-RAS quasi-unsteady mode by leaving the fixed stage blank during the annual, 1-week, flush and opening the gates to run-of-river flow.

Modeling Reservoirs with Unsteady Sediment

Reservoir modeling is the most common application of Unsteady Sediment Transport. In addition to routing and conserving flow, unsteady flow has a range of tools that make reservoir modeling easier and more powerful. In particular, the Operational Rules feature in the unsteady flow editor is an exceptionally powerful tool to model reservoir sediment management. The operational rules include concentration and bed elevation triggers, so users can write simple, but powerful, rules to operate their reservoir based on sediment output. For example, Gibson and Boyd (2016) used the very simple concentration rules in to re-operate a reservoir flushing event to maintain a proposed TMDL (result in the right pane of Figure 1-19).



```
'DS_Conc' = Cross Sections:Sediment Concentration(Niobrara River,Reach 1,179818.5
'SimTime' = Time:Hour of Simulation(Beginning of time step)

!
! Check Downstream Concentration
If ('DS_Conc' > 30000) Then
    ! If Concentration Exceeds "TMDL" Slowly Close Gate
    Gate.Opening(Sluice Gate) = 0
    Gate.Opening(TainterGates) = 0
Else
    !
    ! If the Concentration is less than the threshold
    ! continue with the standard flushing operations
    If ('SimTime' > 14) Then
        Gate.Opening(Sluice Gate) = 18
        Gate.Opening(TainterGates) = 6
    ElseIf ('SimTime' > 7) Then
        Gate.Opening(TainterGates) = 0.15 * 'SimTime' + 0.2
    End If
End If
```

Figure 1-19: HEC-RAS operational rules (left) that controlled simulated reservoir operations (right) to maintain a maximum downstream concentration of 30,000 mg/L.

There are several published examples (with sample code) of simulating reservoir management alternatives with operational rules in HEC-RAS sediment simulations, including:

Gibson, S. and Boyd, P. (2016) "Designing Reservoir Sediment Management Alternatives with Automated Concentration Constraints in a 1D Sediment Model," River Sedimentation: Proceedings of the 13th International Symposium onon River Sedimentation, ed edited by S. Wieprecht, *et al*.

Gibson, S. and Crain, J. (2019) Modeling Sediment Concentrations during a Drawdown Reservoir Flush: Simulating the Fall Creek Operations with HEC-RAS, RSM Tech Note ERDC/TN RSM-19-7. Vicksburg, MS: U.S. Army Engineer Research and Development Center. http://dx.doi.org/10.21079/11681/33884

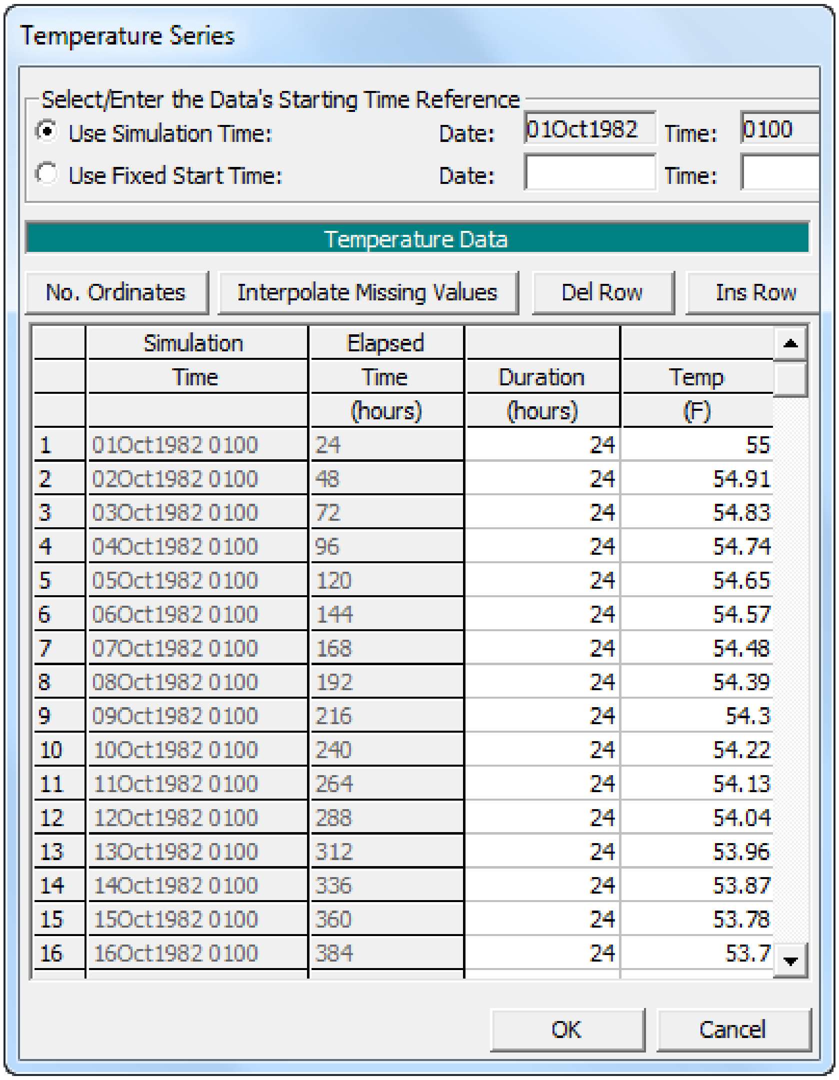
Gibson, S. and Boyd, P. (2014) "Modeling Long Term Alternatives for Sustainable Sediment Management Using Operational Sediment Transport Rules," *Reservoir Sedimentation* –Scheiss et al. (eds), 229-236.

Temperature Data

Quasi-Unsteady Temperature

Fall velocity and some sediment transport equations are sensitive to water viscosity, which is a function of water temperature. Therefore, sediment transport analyses require temperature data. Finer systems (systems with finer sediment) are more sensitive to temperature. Currently, users can only specify one temperature per time step for the entire model.

To specify a temperature time series, press the **Set Temperature** button on the bottom of the **Quasi-Unsteady Flow** editor (Figure 1-3). This will open the temperature series editor depicted in Figure 1-20, an irregular time series editor very similar to the other quasi-unsteady time series editors.



Select/Enter the Data's Starting Time Reference

● Use Simulation Time: Date: 01Oct1982 Time: 0100

○ Use Fixed Start Time: Date: Time:

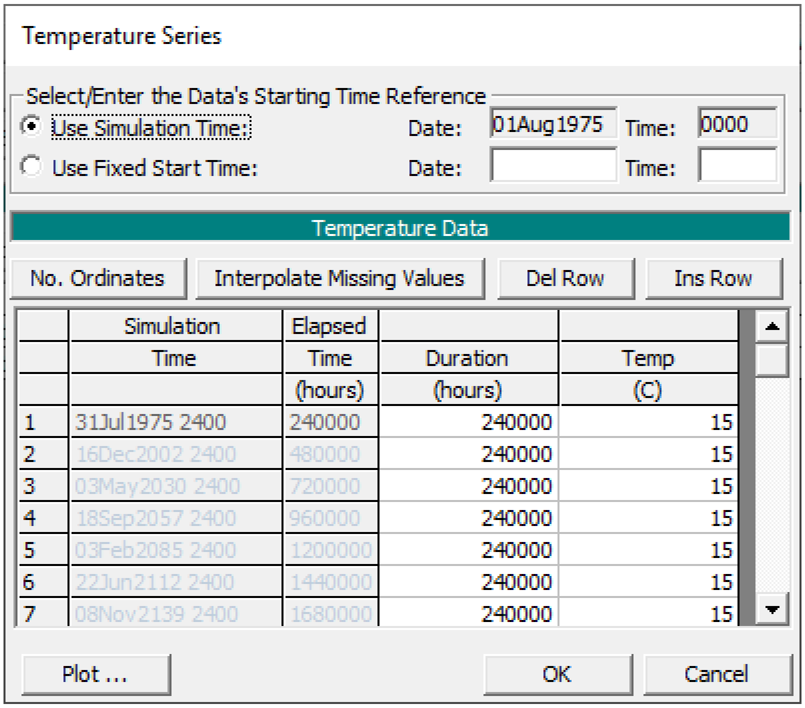
	Simulation Time	Elapsed Time (hours)	Duration (hours)	Temp (F)
1	01Oct1982 0100	24	24	55
2	02Oct1982 0100	48	24	54.91
3	03Oct1982 0100	72	24	54.83
4	04Oct1982 0100	96	24	54.74
5	05Oct1982 0100	120	24	54.65
6	06Oct1982 0100	144	24	54.57
7	07Oct1982 0100	168	24	54.48
8	08Oct1982 0100	192	24	54.39
9	09Oct1982 0100	216	24	54.3
10	10Oct1982 0100	240	24	54.22
11	11Oct1982 0100	264	24	54.13
12	12Oct1982 0100	288	24	54.04
13	13Oct1982 0100	312	24	53.96
14	14Oct1982 0100	336	24	53.87
15	15Oct1982 0100	360	24	53.78
16	16Oct1982 0100	384	24	53.7

Figure 1-20: Specifying a temperature time series.

Modeling Note – Developing Long-Term Temperature Records: Temperature data are seldom sufficient to generate a daily time series for multi-decadal, historical models. And modelers must make some temperature assumption to simulate the future.

There are a few options to define multi-decadal historical or future temperature data in the absence of a long-term temperature record (Options 1 and 3 are most common):

1. Constant Temperature: Any of the irregular time step editors in the quasi-unsteady flow boundary conditions can define a constant condition by specifying large durations (e.g. 240,000 hrs or 10,000 days/>25 years in Figure 1-21). In coarse systems (rivers with significant gravel and/or cobble), that are less sensitive to temperature, detailed temperature data may be unnecessary. Perform sensitivity analysis to evaluate this assumption.



Select/Enter the Data's Starting Time Reference

● Use Simulation Time: Date: 01Aug1975 Time: 0000

○ Use Fixed Start Time: Date: Time:

	Simulation Time	Elapsed Time (hours)	Duration (hours)	Temp (C)
1	31Jul1975 2400	240000	240000	15
2	16Dec2002 2400	480000	240000	15
3	03May2030 2400	720000	240000	15
4	18Sep2057 2400	960000	240000	15
5	03Feb2085 2400	1200000	240000	15
6	22Jun2112 2400	1440000	240000	15
7	08Nov2139 2400	1680000	240000	15

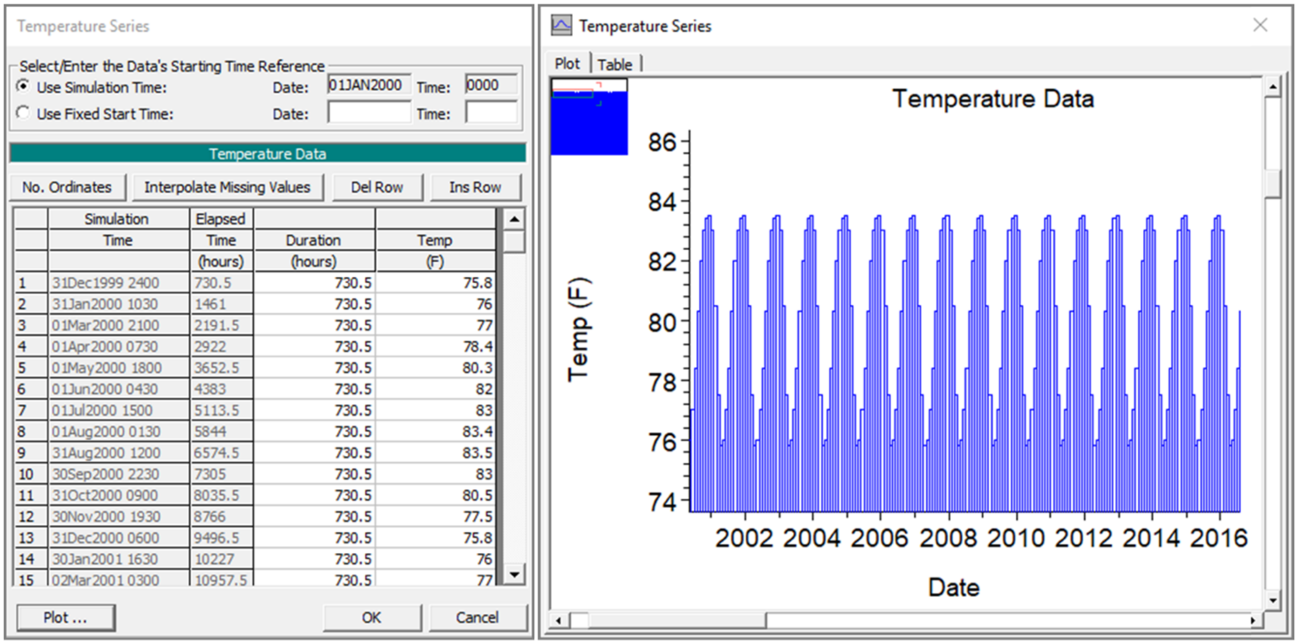
Figure 1-21: Example of a constant temperature time series in the Quasi-Unsteady Temperature Editor.

2. Interpolating Annual Highs and Lows: If results are sensitive to temperature, HEC-RAS can generate a simple time series with a little more user effort. Estimate max and min water temperatures and input them at approximate dates each year, leaving the intermediate dates blank. Then press the **Interpolate Missing Values** button.

For example a user could create a weekly time series (Durations=7*24 hrs = 168 hrs) that interpolates between an early July high and early December low by defining the high temperature in all of the rows aligned with the first week of July, the low temperature with all the rows associated with the first week of December, and pressing the **Interpolate Missing Values** button.

3. <u>Monthly Average Temperatures</u>: Often a gage has some opportunistic temperature readings. You cannot use them as a times series or even interpolate a time series from them. The gage has enough water temperature data to compute monthly averages.

   Give each monthly average temperature a **730.48 hour** (30.4368 day) durations will create an approximate average monthly temperature time series that you can repeat for multiple years (Figure 1-22) and it will remain relatively consistent over long simulations (including leap years).



Select/Enter the Data's Starting Time Reference
● Use Simulation Time: Date: 01JAN2000 Time: 0000
○ Use Fixed Start Time: Date: Time:

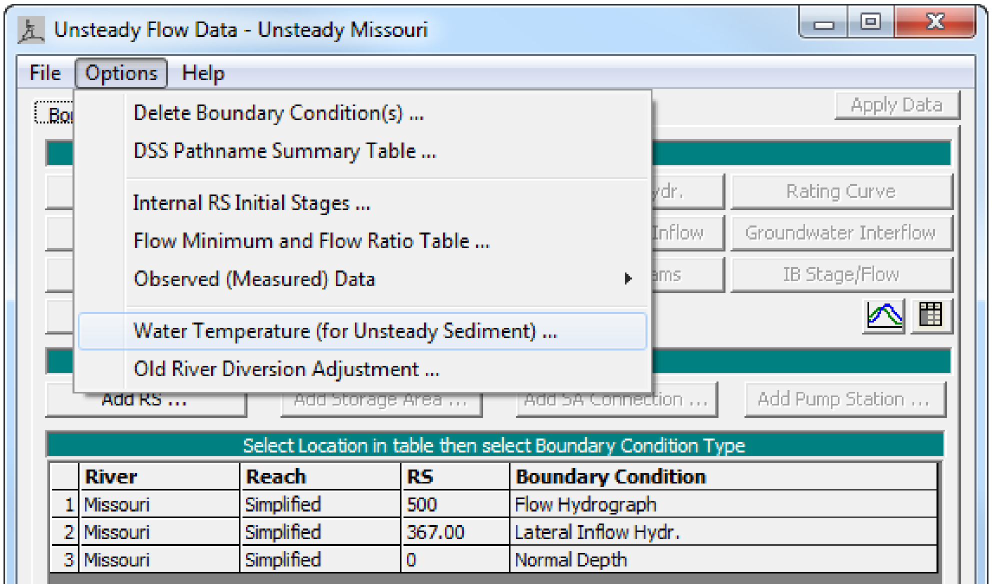
	Simulation Time	Elapsed Time (hours)	Duration (hours)	Temp (F)
1	31Dec1999 2400	730.5	730.5	75.8
2	31Jan2000 1030	1461	730.5	76
3	01Mar2000 2100	2191.5	730.5	77
4	01Apr2000 0730	2922	730.5	78.4
5	01May2000 1800	3652.5	730.5	80.3
6	01Jun2000 0430	4383	730.5	82
7	01Jul2000 1500	5113.5	730.5	83
8	01Aug2000 0130	5844	730.5	83.4
9	31Aug2000 1200	6574.5	730.5	83.5
10	30Sep2000 2230	7305	730.5	83
11	31Oct2000 0900	8035.5	730.5	80.5
12	30Nov2000 1930	8766	730.5	77.5
13	31Dec2000 0600	9496.5	730.5	75.8
14	30Jan2001 1630	10227	730.5	76
15	02Mar2001 0300	10957.5	730.5	77

Figure 1-22: Repeated sequence of monthly average temperature data developed from opportunistic temperature measurements that only account for a small portion of the historical record. The 730.5 hour duration averages to one month over long time periods.

Unsteady Temperature

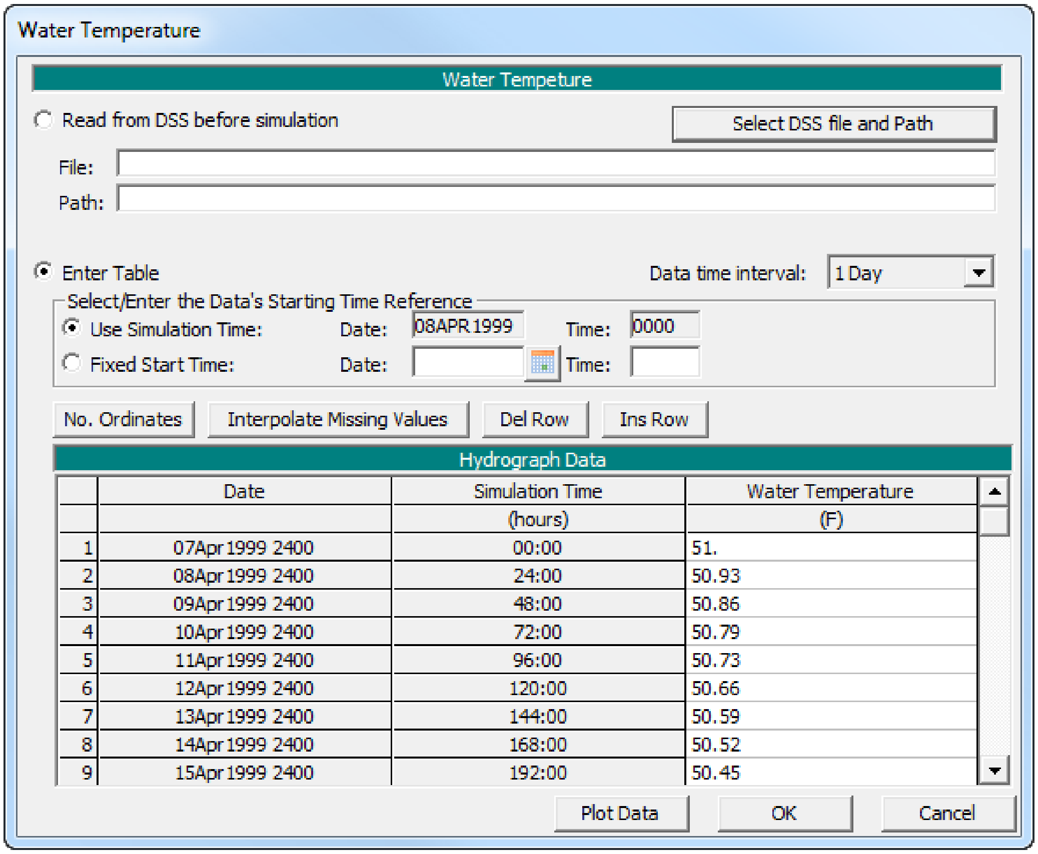
Temperature is the only data the unsteady flow editor requires for sediment transport analyses. Specify temperature for an unsteady sediment transport model in the **Unsteady Flow Editor**. Select the **Water Temperature (for Unsteady Sediment)…** option from the **Options** menu (Figure 1-23) to get an unsteady temperature time series editor, similar to the unsteady flow and stage editors (Figure 1-24). In the absence of temperature data in the unsteady flow file, HEC-RAS will assume 55° F. The unsteady temperature editor will allow users to specify actual monthly temperatures by setting the **Data time interval** to **1 Month**:

Data time interval: 1 Month



	River	Reach	RS	Boundary Condition
1	Missouri	Simplified	500	Flow Hydrograph
2	Missouri	Simplified	367.00	Lateral Inflow Hydr.
3	Missouri	Simplified	0	Normal Depth

Figure 1-23: Specifying water temperature for unsteady sediment models.



○ Read from DSS before simulation

File:

Path:

● Enter Table

Data time interval: 1 Day

Select/Enter the Data's Starting Time Reference

● Use Simulation Time: Date: 08APR1999 Time: 0000

○ Fixed Start Time: Date: Time:

	Date	Simulation Time (hours)	Water Temperature (F)
1	07Apr1999 2400	00:00	51.
2	08Apr1999 2400	24:00	50.93
3	09Apr1999 2400	48:00	50.86
4	10Apr1999 2400	72:00	50.79
5	11Apr1999 2400	96:00	50.73
6	12Apr1999 2400	120:00	50.66
7	13Apr1999 2400	144:00	50.59
8	14Apr1999 2400	168:00	50.52
9	15Apr1999 2400	192:00	50.45

Figure 1-24: Unsteady Temperature Editor.

The Histograph Generator

Averaging Low Transport Time Steps

The computational increment can subdivide Flow Durations (e.g. daily average flows) into smaller time steps to evaluate bed change feedbacks on hydraulics more frequently. However, modelers sometimes want to "go the other way" with their time steps, and combine multiple flow durations into a single computation increment (e.g. combine seven daily, low-transport, summer flows into a weekly time step).

Combining low-flow/low-transport time steps to reduce run times is a relatively standard practice (though it was more standard 10-20 years ago when computational power was more limiting). But modelers should consider the implications of transport non-linearity when averaging flows for a sediment transport model.

Consider two unit less flows (100 and 200) a simple sediment rating curve, where:

$$\text{Load} = 0.01\ \text{Flow}^2$$

Averaging the flows, and then using the average flow to compute transport will yield a different result than computing the loads and then averaging the loads. However, the latter is likely more correct.

Average Flows First

Flow 1	100	
Flow 2	200	Load from Average Flow
Average Flow	**150 →**	**225**

Compute Loads First

		Loads	
Flow 1	100 →	100	
Flow 2	200 →	400	Flow that Yields Average Load
	Average Load	**250→**	**158**

These errors might be small (though, over a 50 year simulation, they can add up, particularly if the averaging is aggressive), but it is more important to conserve sediment mass in a quasi-unsteady sediment model than water volume. Therefore, when averaging flows for a sediment model, the best practice includes computing loads for those flows, averaging the loads, and then backing out a flow that produces the average load.

This process also can be more important when the flow data is sub-daily. For example, one year of 15-minute data will nearly fill the available rows (4*24*365=35,040) in the quasi-unsteady editor and make run times unacceptable.[2] Therefore, it is critical to combine low (and moderate) flows for high resolution flow time series.

If this sounds like a lot of work, the Histograph Generator may be able to help.

The Histograph Generator Tool

Because sediment transport is non-linear, and high transport periods can punctuate long periods of low transport that may be morphologically insignificant, sediment modelers often want to optimize their time step. Particularly when computers were slower, modelers wanted to group low flow time periods into long computation increments to save run time. This practice is less common now that computers are faster, but period of record simulations can still have significant run times. Therefore, the histograph generator provides a tool to determine the time step based on the sediment flux. It scales the flow durations to bring in an equal, user specified, load over each flow period, which could be a few seconds at the peak of the flood of record, or a few weeks during a drought (Figure 1-25). These irregular, equivalent load, flow durations can then be sub-divided by the computational increment for model stability.

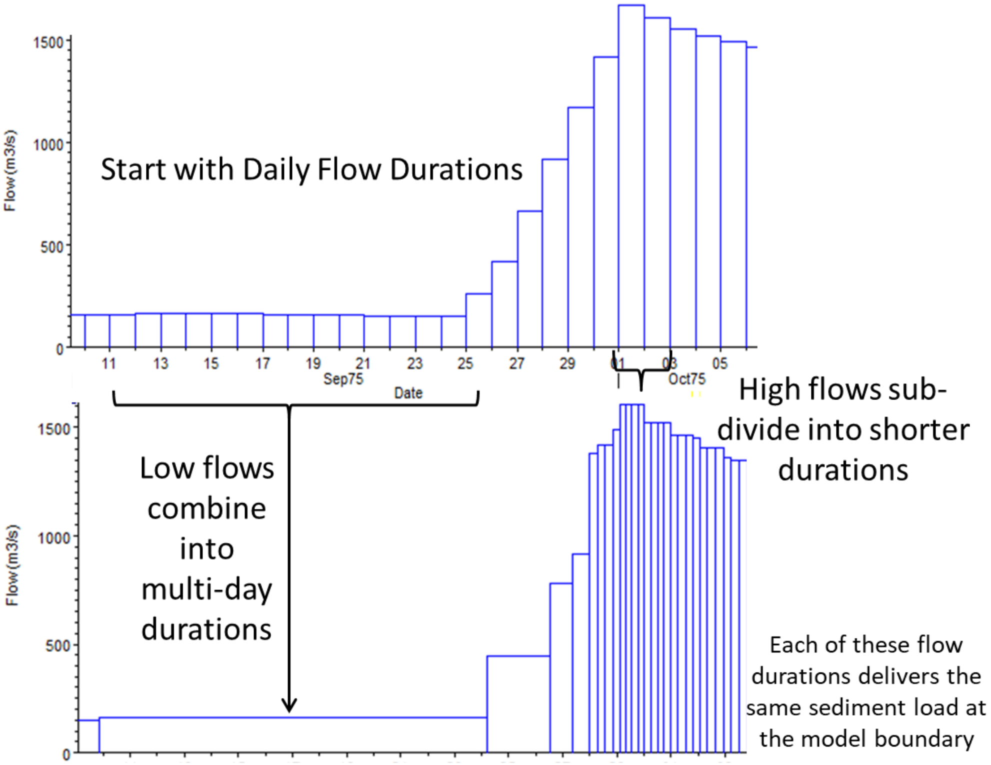
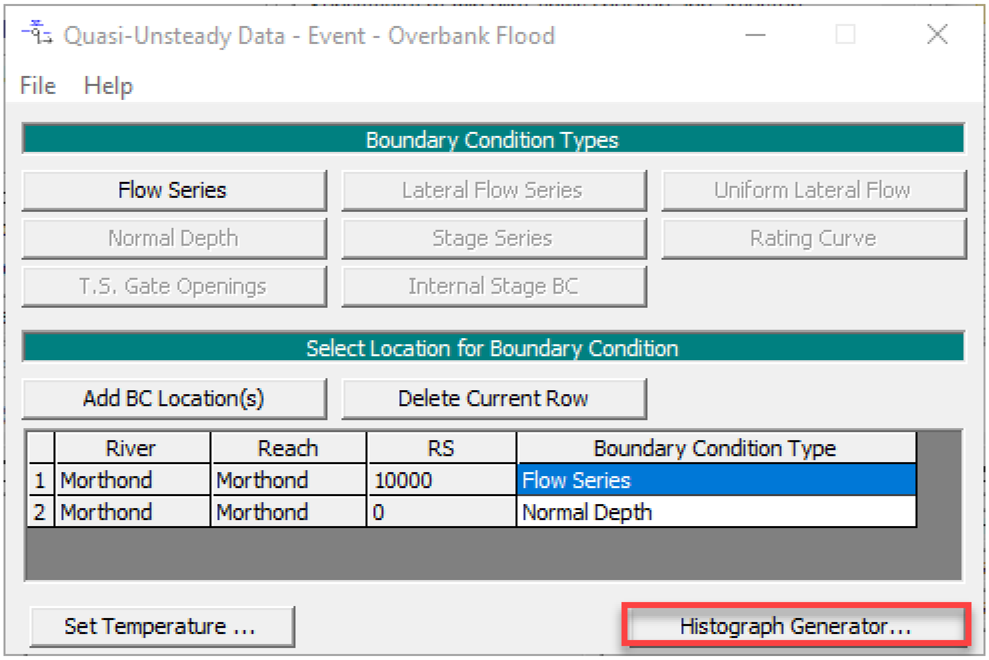


Figure 1-25: Example result from the histograph generator, combining low flow durations and subdividing high flow durations into equal load time steps.

---

[2] It used to be impossible to run multiple years of 15-minute flow data in quasi-unsteady flow because the data simply would not fit in the editor. Now users can attach and run as many years of 15 minute data as they have by specifying it as a DSS boundary condition. However, run times will still make this impractical for most models.

The Histograph Generator creates a new quasi-unsteady flow file with an irregular flow duration. If the histograph tool combines flows, it computes the flow that generates the average sediment flux (instead of the average flow). To launch the tool, select the **Histograph Generator** button on the Quasi-Unsteady Editor, from the base quasi-unsteady flow file. To launch this tool, press the **Histograph Generator** button on the **Quasi-Unsteady** flow editor (Figure 1-26).

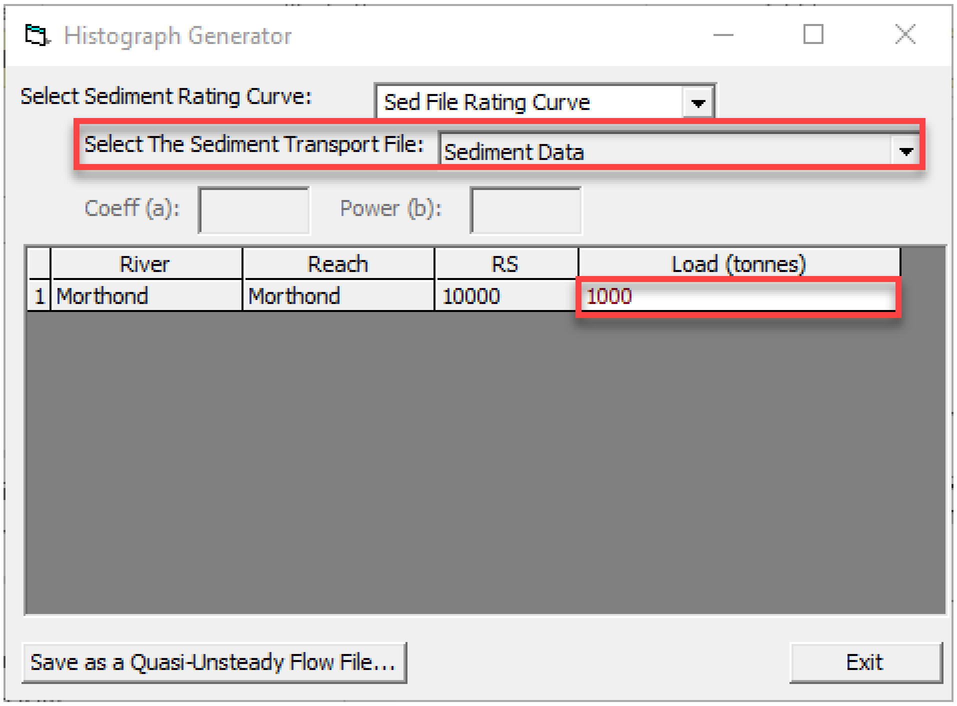


	River	Reach	RS	Boundary Condition Type
1	Morthond	Morthond	10000	Flow Series
2	Morthond	Morthond	0	Normal Depth

Figure 1-26: Button that launches the Histograph Generator Tool.

HEC-RAS requires two user inputs to create an equal-load increment flow file: a constant load and a flow-load rating curve.

First, the tool requires a user-specified load (Figure 1-27). Define the load that will determine the duration of each time step. The Histograph generator will use the flow-load relationship to determine how long each time step will be.



Select Sediment Rating Curve: Sed File Rating Curve

Select The Sediment Transport File: Sediment Data

Coeff (a):

Power (b):

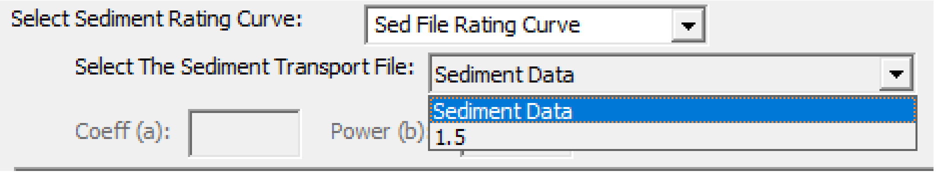
	River	Reach	RS	Load (tonnes)
1	Morthond	Morthond	10000	1000

Figure 1-27: Specify constant load. HEC-RAS will adjust the duration of each flow to bring in this load, subdividing high flow durations and combining low flow durations.

Second, the tool requires a relationship between flow and load. There are three options to define a sediment rating curve:

Sediment File Rating Curve:

If you have created a sediment transport file with a rating curve boundary condition, the Histograph generator can use that file directly. Select **Sed File Rating Curve** and then use the dropdown box labeled **Select The Sediment Transport File** (Figure 1-29) to pick the sediment file with the appropriate rating curve boundary condition.



Select Sediment Rating Curve: Sed File Rating Curve

Select The Sediment Transport File: Sediment Data

Coeff (a):

Power (b):

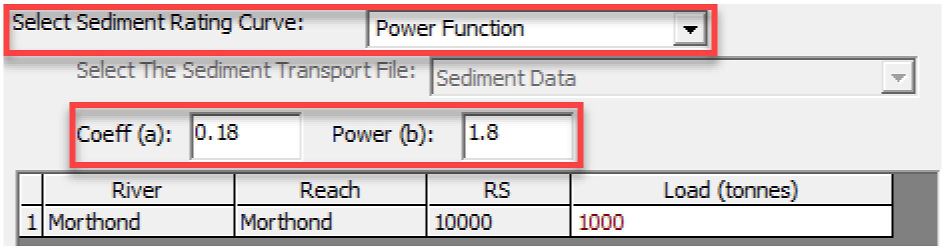
Figure 1-28: Select a sediment file with a Rating Curve boundary condition. The Histograph generator will use that relationship.

Power Function:

If the sediment relationship can be defined by a single power function, HEC-RAS can compute load data for the flow series from a simple power function, defined by two coefficients, where:

$$\text{Flow} = a\,Q^b.$$

Select "Power Function" and define the two coefficients in the fields depicted in Figure 1-29.



Select Sediment Rating Curve: Power Function

Select The Sediment Transport File: Sediment Data

Coeff (a): 0.18

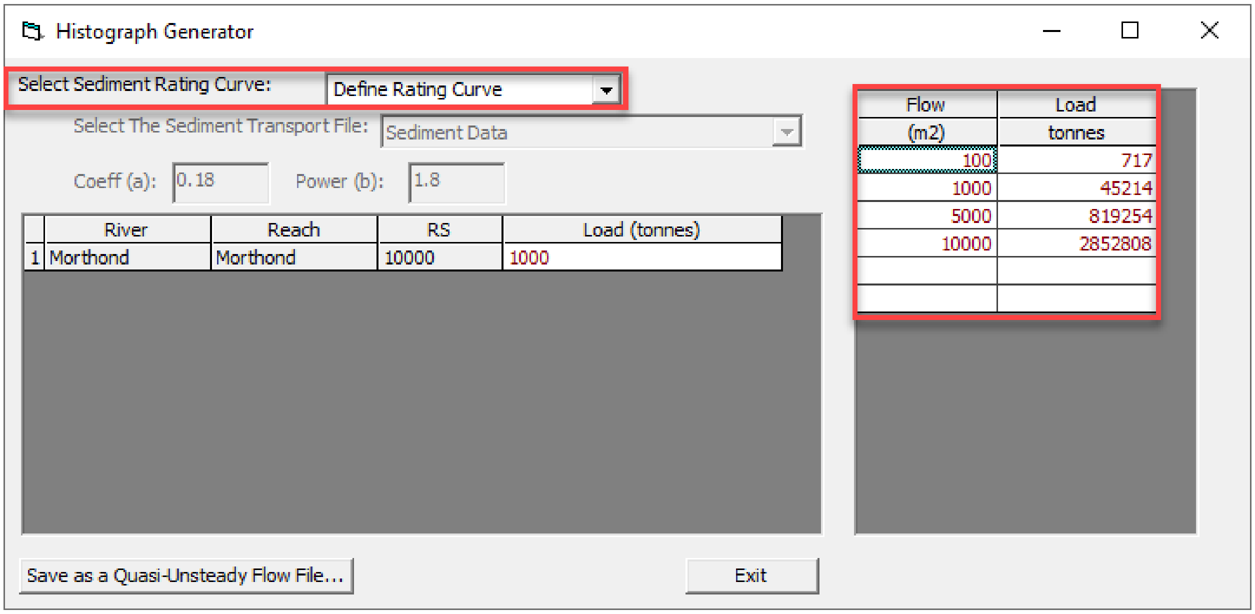
Power (b): 1.8

	River	Reach	RS	Load (tonnes)
1	Morthond	Morthond	10000	1000

Figure 1-29: Define the coefficients of a flow-load power function with the two coefficients.

<u>User Defined Rating Curve:</u>

Finally, users can enter a flow-load rating curve directly into the histograph tool by selecting **Define Rating Curve** (Figure 1-30). This can be particularly useful for "bent" or "inflected" rating curves that cannot be described by a single power function.



Select Sediment Rating Curve: Define Rating Curve

Select The Sediment Transport File: Sediment Data

Coeff (a): 0.18

Power (b): 1.8

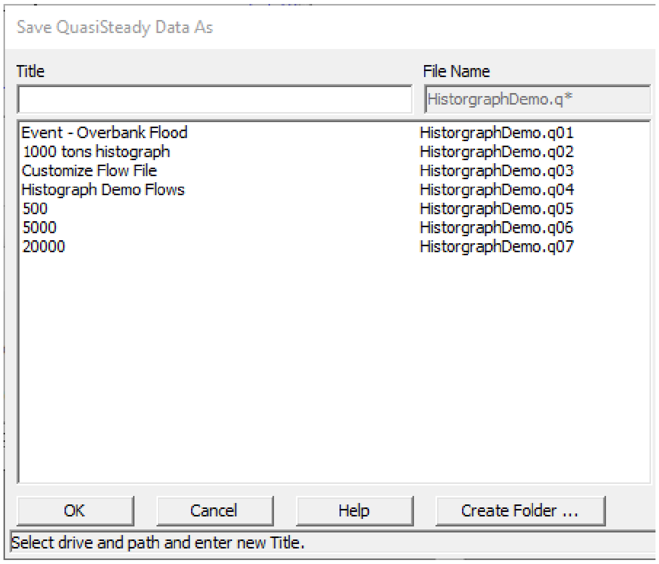
	River	Reach	RS	Load (tonnes)
1	Morthond	Morthond	10000	1000

Flow (m2)	Load tonnes
100	717
1000	45214
5000	819254
10000	2852808

Figure 1-30: Users can define a sediment rating curve for the histograph generator to compute loads for each flow.

Creating a New Equal-Load Time Step Quasi-Unsteady Flow File

Once the load increment and the flow-load relationship are specified, press **Save as a Quasi—Unsteady Flow File**. Save as a Quasi-Unsteady Flow File... This will launch a Save-As dialogue prompting the user to give the new quasi-unsteady file a name. Name the file and press OK.

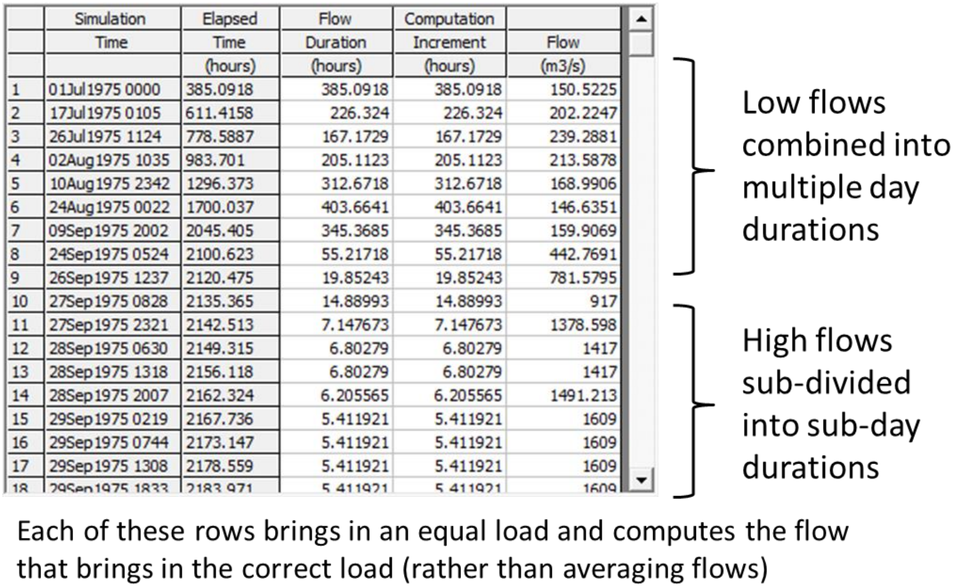


Title	File Name
	HistorgraphDemo.q*
Event - Overbank Flood	HistorgraphDemo.q01
1000 tons histograph	HistorgraphDemo.q02
Customize Flow File	HistorgraphDemo.q03
Histograph Demo Flows	HistorgraphDemo.q04
500	HistorgraphDemo.q05
5000	HistorgraphDemo.q06
20000	HistorgraphDemo.q07

Select drive and path and enter new Title.

Figure 1-31: Save the computed, equal-load time step file as a new Quasi-Unsteady file in the project.

This simply adds the computed histograph to the project as a new quasi-unsteady file. Open the quasi-unsteady file in the quasi-unsteady editor. This file will only have an upstream flow boundary condition. Open that flow boundary condition and press **Plot** to review the histograph.



	Simulation Time	Elapsed Time (hours)	Flow Duration (hours)	Computation Increment (hours)	Flow (m3/s)
1	01Jul1975 0000	385.0918	385.0918	385.0918	150.5225
2	17Jul1975 0105	611.4158	226.324	226.324	202.2247
3	26Jul1975 1124	778.5887	167.1729	167.1729	239.2881
4	02Aug1975 1035	983.701	205.1123	205.1123	213.5878
5	10Aug1975 2342	1296.373	312.6718	312.6718	168.9906
6	24Aug1975 0022	1700.037	403.6641	403.6641	146.6351
7	09Sep1975 2002	2045.405	345.3685	345.3685	159.9069
8	24Sep1975 0524	2100.623	55.21718	55.21718	442.7691
9	26Sep1975 1237	2120.475	19.85243	19.85243	781.5795
10	27Sep1975 0828	2135.365	14.88993	14.88993	917
11	27Sep1975 2321	2142.513	7.147673	7.147673	1378.598
12	28Sep1975 0630	2149.315	6.80279	6.80279	1417
13	28Sep1975 1318	2156.118	6.80279	6.80279	1417
14	28Sep1975 2007	2162.324	6.205565	6.205565	1491.213
15	29Sep1975 0219	2167.736	5.411921	5.411921	1609
16	29Sep1975 0744	2173.147	5.411921	5.411921	1609
17	29Sep1975 1308	2178.559	5.411921	5.411921	1609
18	29Sep1975 1833	2183.971	5.411921	5.411921	1609

Low flows combined into multiple day durations

High flows sub-divided into sub-day durations

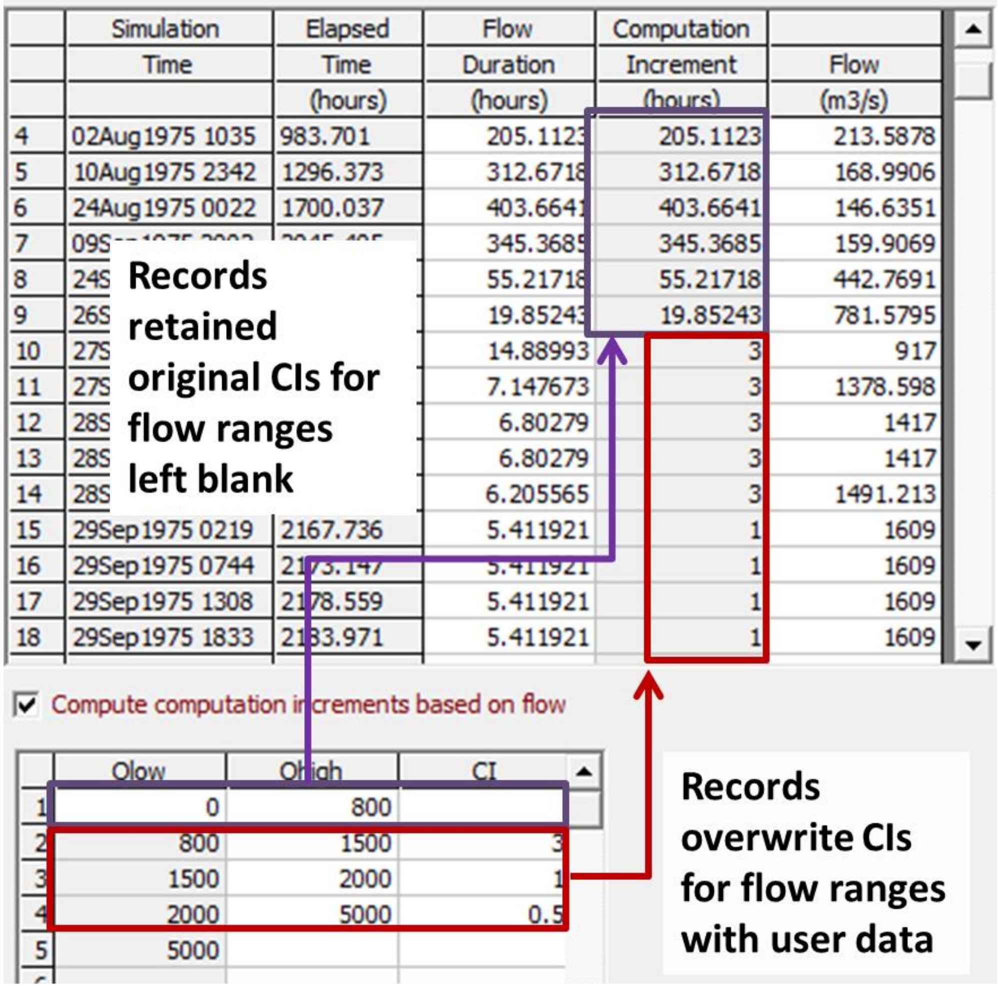
Each of these rows brings in an equal load and computes the flow that brings in the correct load (rather than averaging flows)

Figure 1-32: Example Histograph generator result, a quasi-unsteady boundary condition where each flow-duration transports an equivalent load.

Preserving Low Flow Computational Increments

The tool only computes equal-load **Flow Durations** so it sets the **Computational Increments** equal to the durations. Users can edit the computational increments to sub-divide the high flows further. However, this is tedious to do manually. The option to Compute Computational Increments Based on Flow can be a helpful tool to automate that.

But if users want to subdivide high flow durations but keep the computational increments equal to the flow duration for lower flows, they need to use this tool in a particular way. The tool was designed to *NOT* overwrite computational increments in flow ranges left blank for this particular purpose. So in the example in Figure 1-33, flow records between 0 and 800 cms keep the Computational Increment from the histograph analysis (= the Flow Duration, so HEC-RAS runs it in one sediment time step) and those >800 cms get the user specified sub-divisions.



	Simulation Time	Elapsed Time (hours)	Flow Duration (hours)	Computation Increment (hours)	Flow (m3/s)
4	02Aug1975 1035	983.701	205.1123	205.1123	213.5878
5	10Aug1975 2342	1296.373	312.6718	312.6718	168.9906
6	24Aug1975 0022	1700.037	403.6641	403.6641	146.6351
7	09S		345.3685	345.3685	159.9069
8	24S		55.21718	55.21718	442.7691
9	26S		19.85243	19.85243	781.5795
10	27S		14.88993	3	917
11	27S		7.147673	3	1378.598
12	28S		6.80279	3	1417
13	28S		6.80279	3	1417
14	28S		6.205565	3	1491.213
15	29Sep1975 0219	2167.736	5.411921	1	1609
16	29Sep1975 0744	2173.147	5.411921	1	1609
17	29Sep1975 1308	2178.559	5.411921	1	1609
18	29Sep1975 1833	2183.971	5.411921	1	1609

☑ Compute computation increments based on flow

	Qlow	Qhigh	CI
1	0	800	
2	800	1500	3
3	1500	2000	1
4	2000	5000	0.5
5	5000		

Figure 1-33: Histograph result from the previous figure with the high flow Computational Increments sub-divided and the low flows retained (by leaving the field blank).

Figure 1-34 includes an example of a 15-minute flow series converted into an equal-load increment qausi-unsteady flow file (from Gibson and Helminiack, 2020).

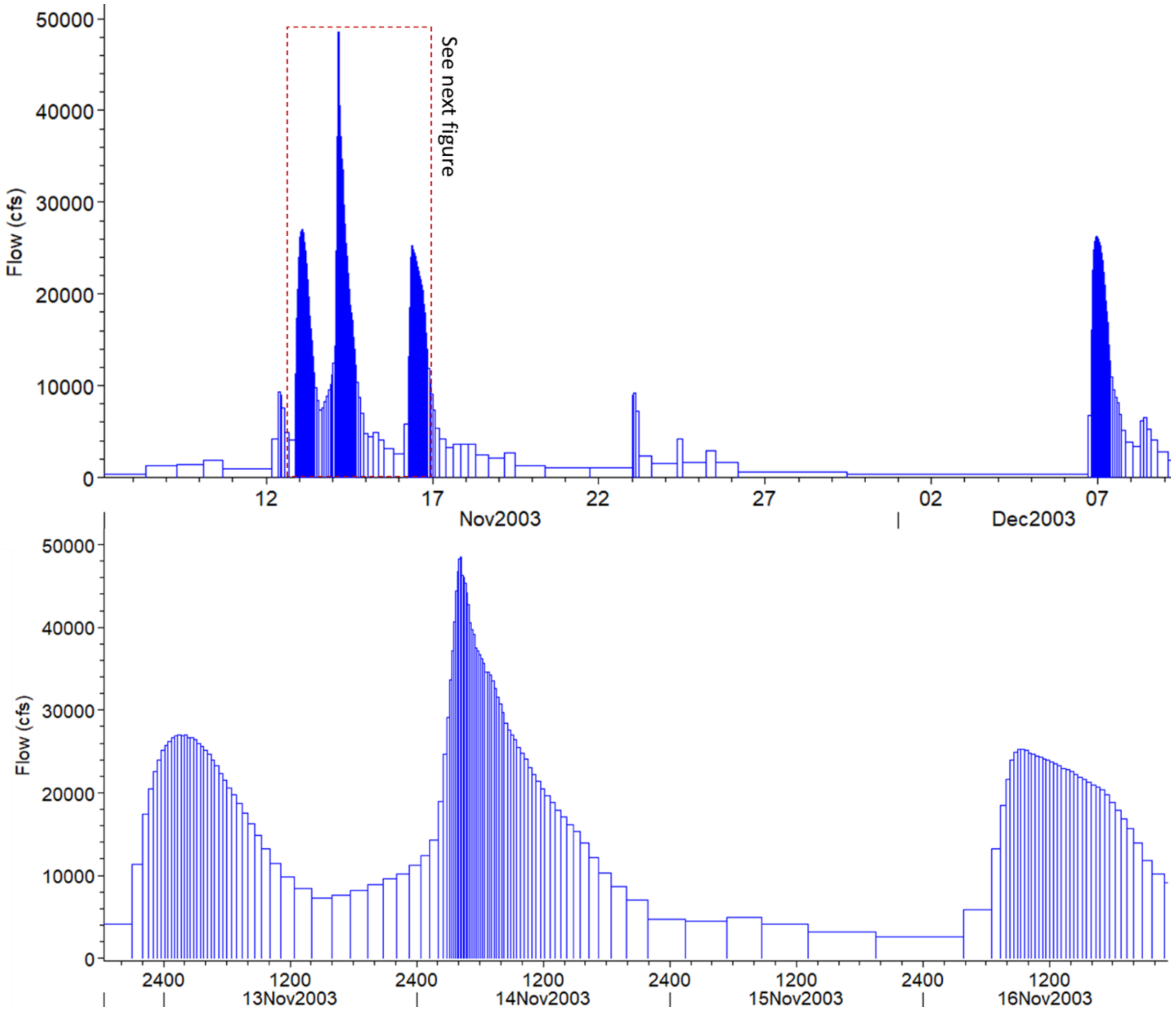


Figure 1-34: Irregular time series developed from 15-minute flow data with the histograph generator. Each flow duration introduces 1,000 tons at the model boundary (Gibson and Helminiack, 2020).

Modeling Note: This tool is available but not widely used for daily data. For most studies, the computational expense of running daily flows during low-transport months is acceptable. But it becomes very useful if the flow data comes in 15-minute increments.

Modeling Note – Testing Histograph: It is important to test the histograph against the base flow file to make sure it reproduces the results.

Modeling Note – Multiple Upstream Boundary Conditions: The histograph generator works best for models with just one upstream, sediment boundary condition. Dendritic models will populate multiple load fields to specify and the tool will try to find a common denominator, but stripping the analysis to a single boundary flow and load relationship will usually yield better results.

Modeling Note – 15 Minute Tidal Data: The other data that sometimes come in 15-minute increments are tide data. Again, the 40,000 maximum rows in the stage editor will not hold much more than 1 year of 15-minute data. So tidal stages must be averaged. Depending on the model objectives, some simulations can use a single representative stage, and other use a 6-hour representative stages (not necessarily averages) around the maximum and minimum cycle. However, downstream stages have non-linear effects as well, that are more difficult to tease out. It is a good practice to run a year of the sediment transport simulation with the 15-minute stage data and the proposed simplification to make sure the simplification reproduces the full time series.

Wish List – Currently, the historgraph generator is built around the "equal mass per time step" principle. However, it would be useful to have simpler, more flexible, averaging tools available that create flow series based on load conservation principles, but are not constrained to the constant load approach. We would like to add a simpler feature that retains the flow duration and computational increments selected above a specified flow and simply combines low flows (under a certain threshold – or combines different flow ranges into different. We'd also like to add a DSS record to the downstream stage series editor and average it at the dynamic scale of the flow computational increment.

Wish List – Plotting feature that plots the result before it writes to a new Quasi-Unsteady file. At this point users have to create a new quasi-file and open it to evaluate the load increment and results. A Plot feature would run the analysis and plot the result without creating the file, which would be quicker and cleaner.

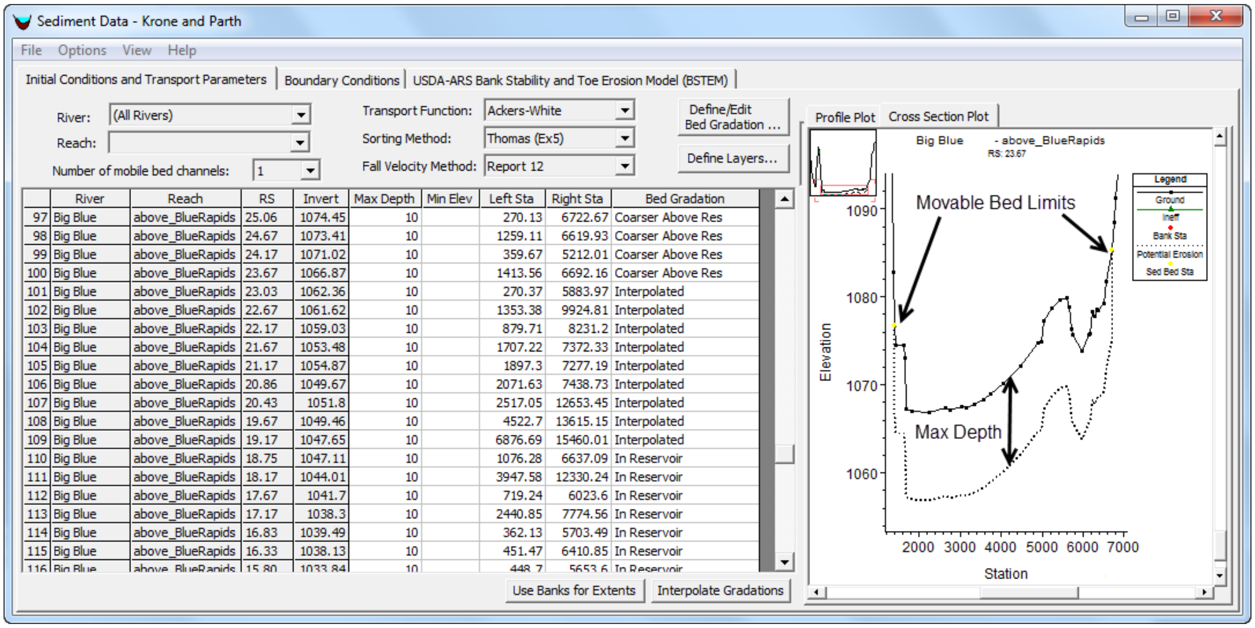
Entering and Editing Sediment Data

Hydraulic models in HEC-RAS require three files: a flow file (steady or unsteady), a geometry file, and a plan file to tie them together. Sediment analyses (steady or unsteady) require a fourth file: a sediment data file (Figure 1-2). Specify sediment data after the geometry file is complete. Some mandatory sediment parameters are specified by cross section. If the geometry changes (e.g. cross sections change, new cross sections are added, cross sections are interpolated a new resolutions or in new locations) sediment data will need updates before it can run.

Sediment results are very sensitive to hydraulic results (e.g. roughness parameters and ineffective flow areas). An HEC-RAS sediment model will not be robust or reliable if it is not built on a well-constructed hydraulic geometry (USACE, 1993, Thomas and Cheng, 2008). Before adding sediment data, test the hydraulic model over the expected range of flows using the HEC-RAS Steady Flow Analysis option (or the Unsteady Flow Analysis option if the sediment model will be unsteady), calibrating the n-values for various flows, identifying ineffective flow areas, and evaluating cross section spacing. Identify hydraulics model problems before adding the bed change complexity. Only add sediment data after crafting a careful, robust, hydraulic model.

To enter sediment data select **Sediment Data** from the **Edit** menu or press the sediment data icon.

The sediment data editor will appear as depicted in Figure 1-35. The sediment data editor has three tabs: **Initial Conditions and Transport Parameters,** Sediment **Boundary Conditions**, and the **USDA-ARS Bank Stability and Toe Erosion Model (BSTEM)**. The first two tabs are mandatory. The third (BSTEM) is only for bank process computations and is not required for a sediment transport model.



River: (All Rivers)
Reach:
Number of mobile bed channels: 1
Transport Function: Ackers-White
Sorting Method: Thomas (Ex5)
Fall Velocity Method: Report 12

	River	Reach	RS	Invert	Max Depth	Min Elev	Left Sta	Right Sta	Bed Gradation
97	Big Blue	above_BlueRapids	25.06	1074.45	10		270.13	6722.67	Coarser Above Res
98	Big Blue	above_BlueRapids	24.67	1073.41	10		1259.11	6619.93	Coarser Above Res
99	Big Blue	above_BlueRapids	24.17	1071.02	10		359.67	5212.01	Coarser Above Res
100	Big Blue	above_BlueRapids	23.67	1066.87	10		1413.56	6692.16	Coarser Above Res
101	Big Blue	above_BlueRapids	23.03	1062.36	10		270.37	5883.97	Interpolated
102	Big Blue	above_BlueRapids	22.67	1061.62	10		1353.38	9924.81	Interpolated
103	Big Blue	above_BlueRapids	22.17	1059.03	10		879.71	8231.2	Interpolated
104	Big Blue	above_BlueRapids	21.67	1053.48	10		1707.22	7372.33	Interpolated
105	Big Blue	above_BlueRapids	21.17	1054.87	10		1897.3	7277.19	Interpolated
106	Big Blue	above_BlueRapids	20.86	1049.67	10		2071.63	7438.73	Interpolated
107	Big Blue	above_BlueRapids	20.43	1051.8	10		2517.05	12653.45	Interpolated
108	Big Blue	above_BlueRapids	19.67	1049.46	10		4522.7	13615.15	Interpolated
109	Big Blue	above_BlueRapids	19.17	1047.65	10		6876.69	15460.01	Interpolated
110	Big Blue	above_BlueRapids	18.75	1047.11	10		1076.28	6637.09	In Reservoir
111	Big Blue	above_BlueRapids	18.17	1044.01	10		3947.58	12330.24	In Reservoir
112	Big Blue	above_BlueRapids	17.67	1041.7	10		719.24	6023.6	In Reservoir
113	Big Blue	above_BlueRapids	17.17	1038.3	10		2440.85	7774.56	In Reservoir
114	Big Blue	above_BlueRapids	16.83	1039.49	10		362.13	5703.49	In Reservoir
115	Big Blue	above_BlueRapids	16.33	1038.13	10		451.47	6410.85	In Reservoir
116	Big Blue	above_BlueRapids	15.80	1033.84	10		448.7	5653.6	In Reservoir

Figure 1-35. The Sediment Data Editor.

Initial Conditions and Transport Parameters

The **Initial Conditions and Transport Parameters** is the first tab in the **Sediment Data** editor and opens by default when the editor launches. From this editor the user can specify the transport function, sorting method, fall velocity method for the entire model. For each cross section, users must specify the sediment control volume and the bed gradation.

Transport Function

Select a transport function from the drop-down box near the top of the editor. The current version of HEC-RAS includes eight transport one-dimensional functions:

- Ackers and White
- England and Hansen
- Copeland's form of Laursen
- Meyer-Peter and Müller (MPM)
- Toffaleti
- MPM-Toffaleti
- Yang (sand and gravel eqns.)
- Wilcock and Crowe

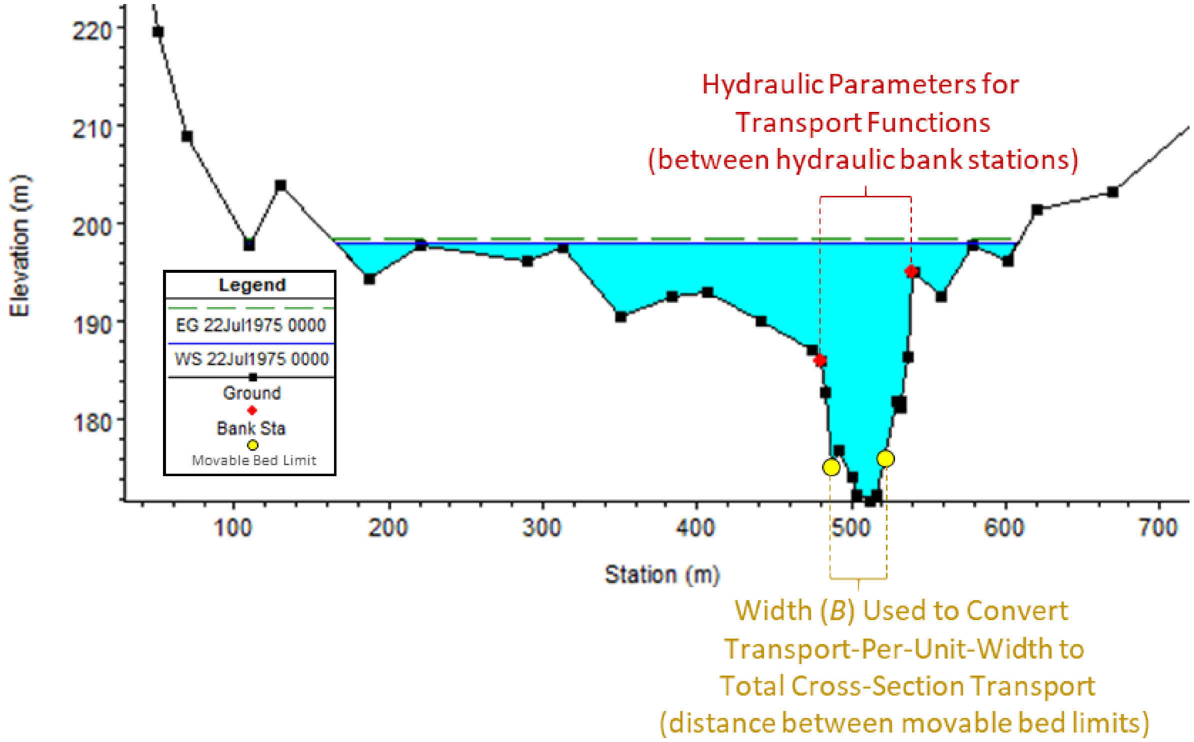
The other three transport functions (Soulsby-van Rijn, van Rijn, and Wu) are only available for 2D transport in the current version of HEC-RAS.

See the transport function section of the Technical Reference Manual for detailed descriptions of each of these functions.

Modeling Note – Transport Function Sensitivity: Sediment transport functions simulate non-linear transport processes and produce very different results. Model results are very sensitive to selected function. Carefully review the range of assumptions, hydraulic conditions, and grain sizes for which each method was developed. Select the method developed under conditions that most closely represent the system of interest, and calibrate results to actual river bed change.

Modeling Note – Transport Based on ***channel*** hydraulics: The transport functions compute a transport capacity for each cross section based on they hydrodynamic results (e.g. shear stress, shear velocity, friction slope, velocity, fall velocity, etc…) of the ***channel***. By default, the 1D hydraulic simulations in HEC-RAS uses "bank stations" to divide each cross section laterally in into a "channel" zone and two "overbank" zones (LOB, ROB). The transport functions only use the channel hydraulics. (not the cross section average hydraulics and not the hydraulics between the movable bed limits, which are the most common misunderstandings).

However, because HEC-RAS uses channel hydraulics for transport, does not mean overbank hydraulics are not important. Flow that spills out to the overbanks is "lost" to transport. So users must choose good overbank n values and apply ineffective flow areas skillfully, to make sure that transport capacity transitions relatively smoothly from bank-full flow to floodplain inundation.



Hydraulic Parameters for Transport Functions (between hydraulic bank stations)

Width (*B*) Used to Convert Transport-Per-Unit-Width to Total Cross-Section Transport (distance between movable bed limits)

Figure 1-36: Transport functions use hydraulic results from the channel (between the channel banks). If the transport function computes transport per unit width, the maximum width is the distance between the Movable Bed Limits.

Sorting Method

Transport functions compute transport potential without accounting for sediment availability. The bed sorting method (sometimes called the mixing or armoring method) keeps track of the bed gradation which HEC-RAS uses to compute grain-class specific transport capacities and can also simulate armoring processes which regulate supply. Select a bed mixing and armoring algorithm from the drop-down box titled **Sorting Method** below the transport function. Three methods are currently available:

- **Thomas (Ex5)** – This method uses a three-layer bed model that forms an independent coarse armor layer which limits erosion of deeper layers. HEC-RAS 4.1 and earlier called this method Exner 5 and was the default method in HEC-6.

- **Copeland (Ex7)** – Copeland (1993) developed an alternate version of the Thomas mixing algorithm. This method was designed for sand bed rivers because it forms armor layers more slowly and computes more erosion.

- **Active Layer** – The two armoring methods above have been successfully applied on many river systems. However, they are complex and can suffer from 'black box' effects, producing results that users have trouble interpreting. Both armoring methods also have numerical thresholds that generate gradational non-linearities introducing noise in the gradational results. Therefore, HEC-RAS also includes a simple two-layer active layer method. The active layer thickness is set equal to the

d_{90} by default (an assumption is only appropriate for gravel beds) but is editable since version 5.0 (**Sediment Options→Bed Mixing Options**).

See the Sorting and Armoring Section in the Technical Reference Manual for detailed descriptions of the three sorting methods.

Users can specify separate gradations for the active or cover layers, either manually or with a model hotstart (using Bed Mixing Options or Gradational Hotstarts).

Modeling Note – Mixing Method Sensitivity: Sediment transport results can be as sensitive to the mixing method selected as the transport function.

Modeling Note – Hiding: HEC-RAS assumes grain class independence. HEC-RAS 5.1 and earlier did not include any hiding functions except for those embedded in the Wilcock and Crowe transport function. Version 6.0 and later include additional hiding functions that can be used with other transport functions.

Modeling Note – Wilcock and Crow → Active Layer: The Wilcock and Crowe sediment transport function is a surface based method, which accounts for armoring implicitly. Therefore, selecting both Wilcock and Crowe and the Thomas/Copland armoring methods would double-count armoring effects. Select the Active Layer mixing method with the default active layer thickness when using Wilcock and Crowe.

Fall Velocity Methods

Several methods are available for computing fall velocity and the user should select the most appropriate algorithm. The options include:

- Ruby
- Toffaleti
- Van Rijn
- Dietrich
- Report 12 (Default method in HEC-6)

Maximum Depth or Minimum Elevation

The **Initial Conditions and Transport Parameters** tab includes a list of model cross sections where users specify initial sediment conditions for *each* cross section. The editor will filter sections with the **River:** and **Reach:** drop down lists to focus the display on a particular study river or reach, however the sediment model will not run unless the user specifies the control volume (two movable bed limits and either a depth or elevation) and bed gradation for each cross section.

Modeling Note – Geometry Changes and Sediment Files: Sediment files depend on the geometry and hydrodynamic files for their data structure. Each cross section requires data and the boundary condition locations inherit from the flow boundary conditions. Like other files in HEC-RAS, users can mix and match sediment files in a plan. However, if users make major changes to geometry files (e.g. adding or deleting cross sections, interpolating, or moving the boundary conditions) it will change the sediment file structure. Two models with different cross section layouts or boundary condition locations cannot share a sediment file. If you make significant

> changes to the cross sections in your model and – particularly – if you change the boundary condition locations, the Sediment Editor will try to adjust. But it is often easier to just create a new sediment file which will start with a clean data structure that matches the active geometry and hydraulic boundary conditions than to try to edit an old sediment file that is tied to different cross sections and boundary conditions.

HEC-RAS sediment control volumes are 'centered' around each cross section as depicted in Figure 1-37. Control volumes extend from the midpoint between the cross section and the next one upstream to the same midpoint downstream. The user must specify the width and vertical thickness of the control volume, however. The dotted line in the **Cross Section** Plot traces the vertical and lateral control volume extents. The control volume contains the available erodible sediment, which can be thought of as a 'sediment reservoir' (Figure 1-35).

Specify the sediment control volume's vertical dimension in _either_ **Max Depth** or **Min Elev** column. (Note: The editor will only allow one of these per cross section, deleting the first if the user specifies both.) The **Max Depth** (Figure 1-35) approach is more common. With **Max Depth** the user sets the bottom of the control volume to a distance below the original invert of the channel.

The second option, **Min Elev**, sets a 'hard' elevation below which the model cannot erode. This option often simulates known bedrock control, grade control structure, a flume bottom, or a concrete channel lining. The model allows erosion as long as the *thalweg* is higher than this elevation, but will not scour below it.

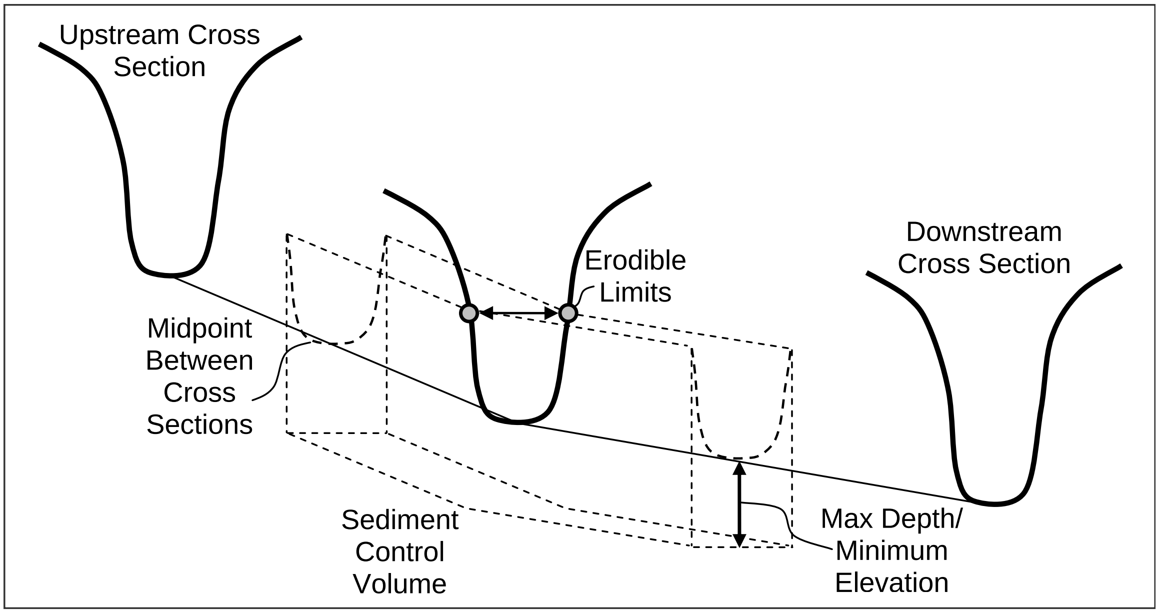
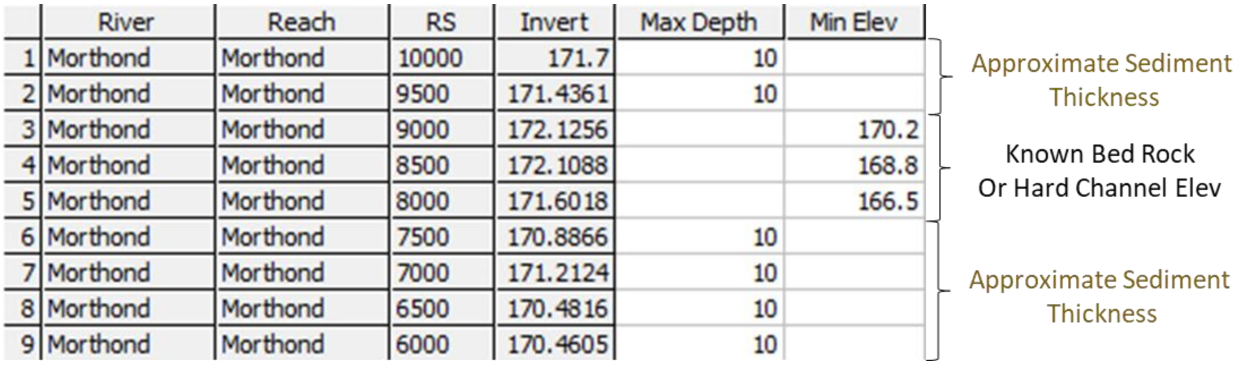


Figure 1-37. Schematic of sediment control volume associated with each cross section.



	River	Reach	RS	Invert	Max Depth	Min Elev
1	Morthond	Morthond	10000	171.7	10	
2	Morthond	Morthond	9500	171.4361	10	
3	Morthond	Morthond	9000	172.1256		170.2
4	Morthond	Morthond	8500	172.1088		168.8
5	Morthond	Morthond	8000	171.6018		166.5
6	Morthond	Morthond	7500	170.8866	10	
7	Morthond	Morthond	7000	171.2124	10	
8	Morthond	Morthond	6500	170.4816	10	
9	Morthond	Morthond	6000	170.4605	10	

Approximate Sediment Thickness

Known Bed Rock Or Hard Channel Elev

Approximate Sediment Thickness

Figure 1-38: Example uses of Max Depth and Min Elev.

Modeling Note – When to use Min Elev: Good data on non-erodible depth is rare. Therefore, most models use the Max Depth option, and increase the max depth if credible simulation results erode all the way through it. Min Elev is used in two primary cases: known bed rock or hard pan elevations from blow-count or geophysical data and 2) concrete channels, where the Min Elev is the same as the invert (which would be equivalent to a Max Depth = 0) or buried beneath deposition but built at a known slope and elevation.

Movable Bed Limits

Finally, each sediment control volume requires width. Specify lateral '**Movable Bed Limits**,' in the **Sta Left** and **Sta Right** columns, which constrain erosion and deposition to the cross-section nodes between them (see other options in the Bed Change Options section below). **Movable Bed Limits** are ***inclusive***. If the movable bed limits have the same station as a station-elevation point, that point will move. They are the last nodes to move, not the first points that can't move (this worked differently in very early versions of HEC-RAS sediment).

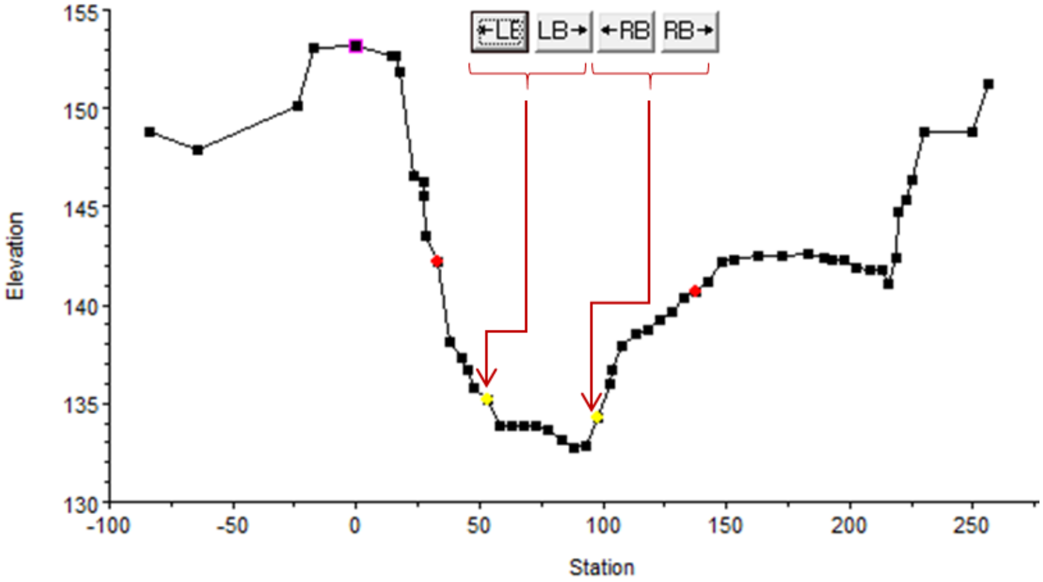
HEC-RAS will only deposit or erode *wet* cross section points between these lateral limits by default. Select lateral limits carefully. The wetted top width between the **Movable Bed Limits** is also the width used to scale some transport functions that compute transport per-unit-width. So if inundated, the movable bed limits selected can also influence transport capacity.

Movable bed limits should be selected carefully and do not always, or even often correspond to channel banks. However, for the cases in which they do, the **Use Banks for Extents** button sets all erodible bed limits to the main channel bank stations as an initial estimate.

Movable Bed Limit Tools

HEC-RAS includes two tools to help modelers define movable bed limits quickly. The first is the **Use Banks for Movable Bed** button Use Banks for Movable Bed at the bottom of the Sediment Data editor. This button automatically sets all of the movable bed limits to the bank stations from the geometry file. Bank stations are not necessarily the best choice for movable bed limits. It is usually appropriate to adjust movable bed limits based on bank stations. But this button helps populate the data quickly for exploratory runs and to initialize these cross-section parameters before adjusting them at each cross sections.

Modelers should review movable bed limits at each cross section and make intentional decisions about where they should be located. Current versions of HEC-RAS make this more convenient, including buttons from the Graphical Cross Section Editor to adjust these nodes. The ←LB and LB→ buttons move the left movable bed limit and the ←RB and RB→ buttons adjust the right movable bed limit (each by one cross section node per button-push).



Using these two tools together, setting all the movable bed limits to the bank stations and then using the buttons to adjust them at each cross section is often the most efficient and reliable way to choose these parameters.

Modeling Note –Movable Bed Limits Sensitivity: Select movable bed limits carefully. Model results can be sensitive to this parameter. They affect deposition rate, converting mass change to bed change. However, they can also affect transport. Several of the transport functions compute transport *per unit width*. The unit transport is applied to the "movable" portion of the cross section (i.e. G_s=f(W), where G_s is transport and W is the distance between movable bed limits). Therefore, moving the movable bed limits out can have a complicated effect on transport, slowing the invert change by distributing mass change over a larger area, but also increasing transport capacity by increasing the width that HEC-RAS applies the unit transport rate to.

Modeling Note – Identifying the Movable Bed: Just because HEC-RAS offers a convenient tool to set the movable bed limits to the channel banks, does not mean that that is always the best place for them. Movable bed limits are often more appropriate at the toe of the banks. Carefully consider the morphology of the system you are modeling and decide which portion of the cross section is actually vertically active (e.g. Figure 1-39 – Left).

Modeling Note – Avoiding Cross Section "Inversion": Selecting movable bed limits close to the bank toe (Figure 1-39 – Left) can lead to unrealistic cross section shapes in depositional conditions. In Figure 1-39, the movable nodes inside the movable bed limits deposit enough that they end up significantly higher than the immediately adjacent nodes. This cross-section inversion is common when the MBL is inside of a similar station-elevation point and the model only deposits between the movable bed limits.

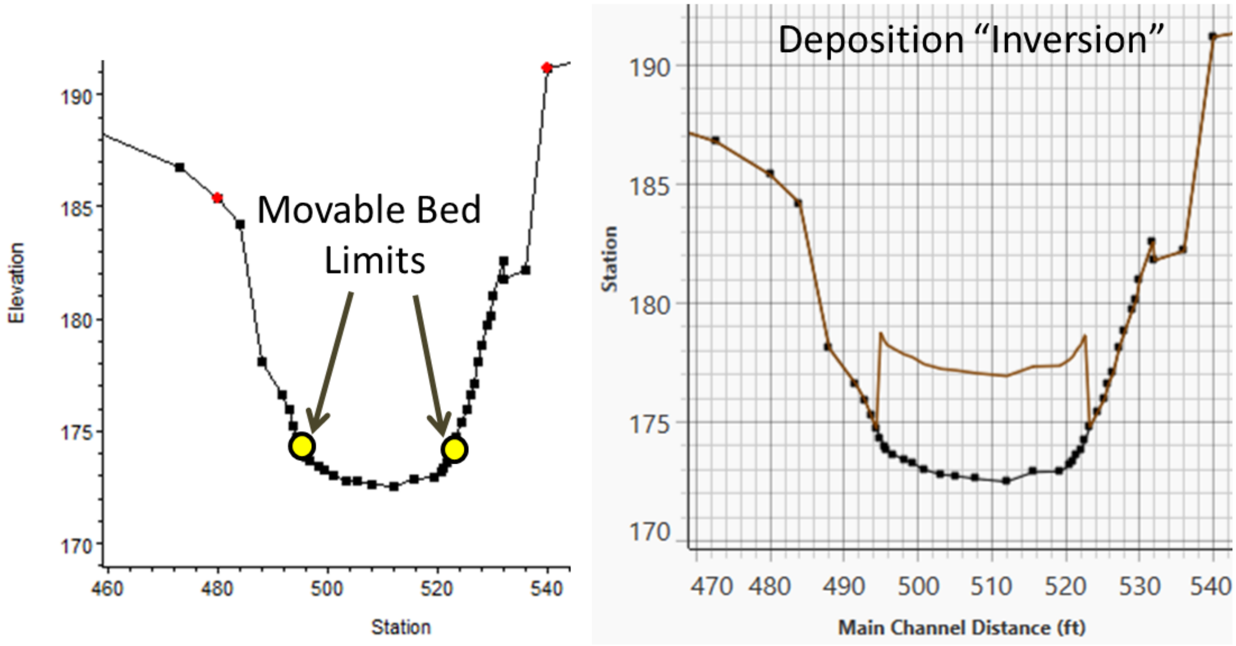


Figure 1-39: When placing the movable bed limits at the bank toe, deposition can cause "inverted" cross section shapes, where the depositing nodes rise above those that do not move.

This condition has a few reasonable fixes:

- First, the modeler could turn on the option to allow deposition outside of the movable bed limits (Figure 1-40 – Left).
- The modeler could experiment with moving the movable bed limits out to include all of the movable nodes.
- Or the modeler could simplify the cross section to get rid of the intermediate nodes between the movable bed limits and the banks (Figure 1-40 – Right). Filtering cross sections to <100 station elevation nodes (and often <60) is usually good modeling practice for 1D sediment models.

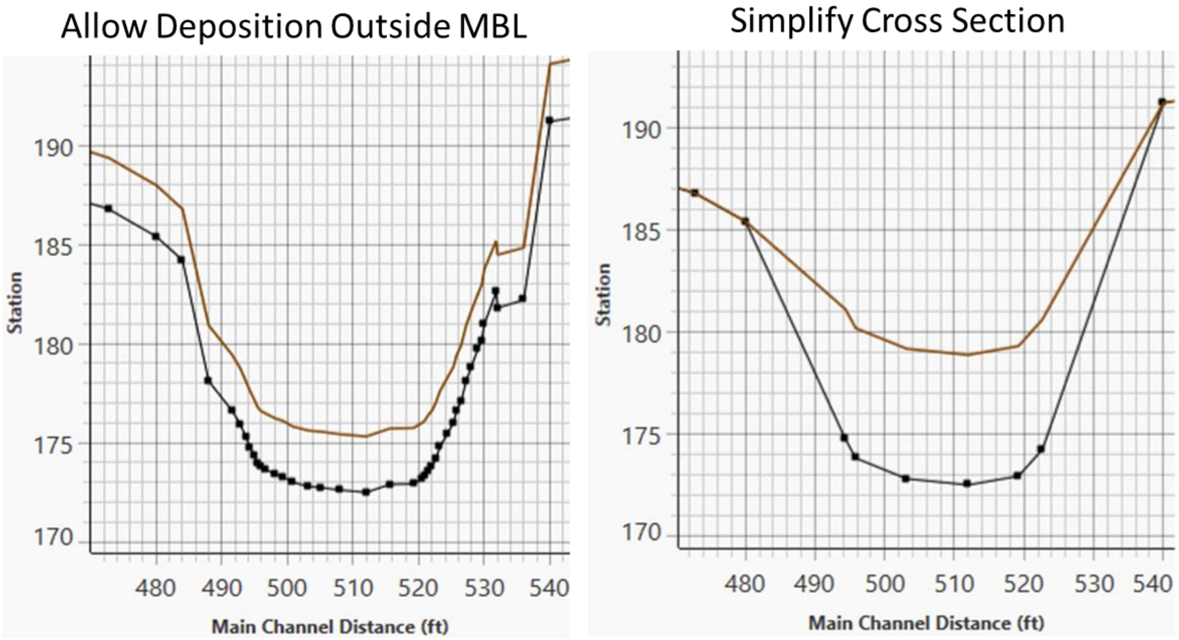


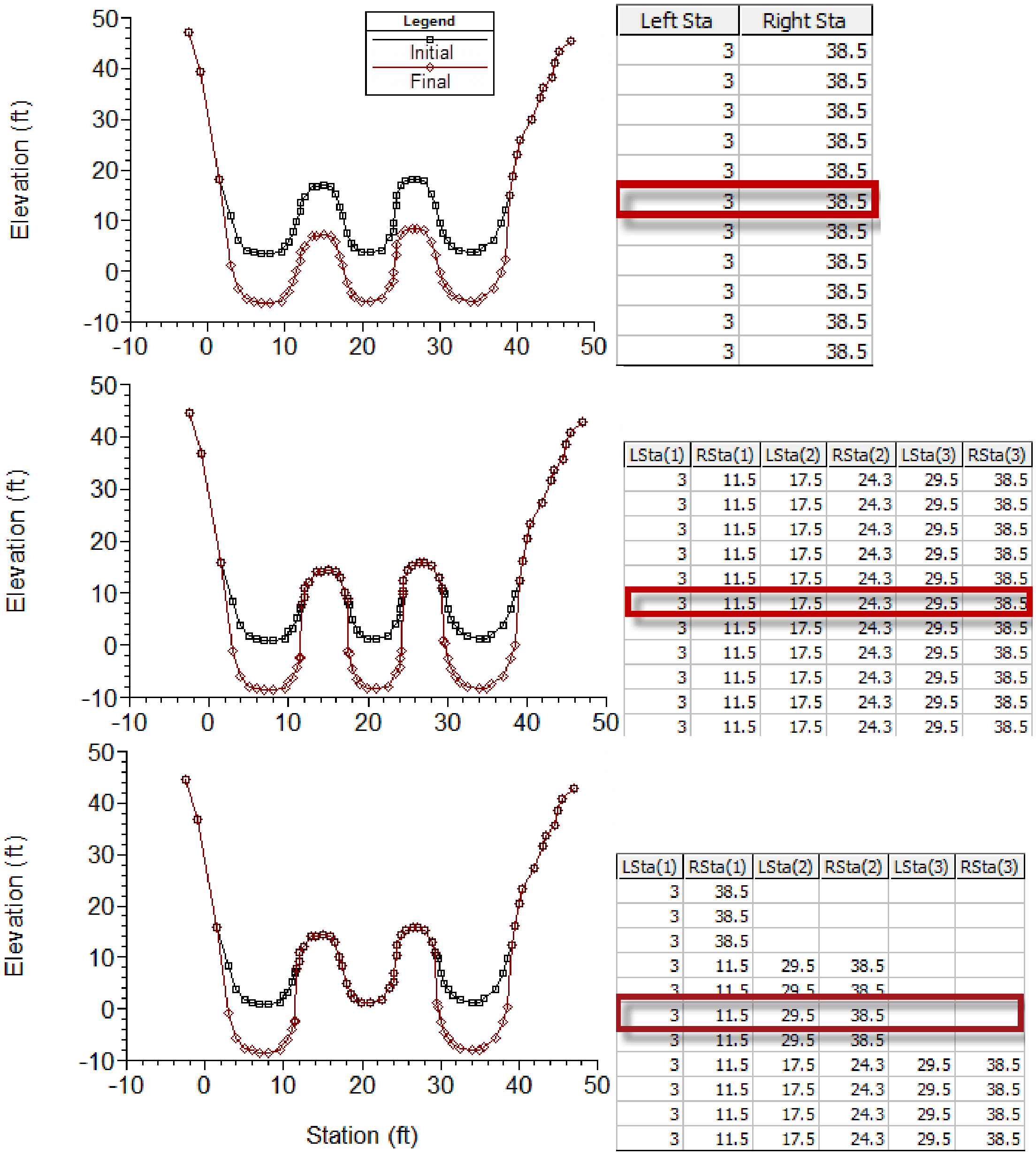
Figure 1-40: Options to avoid deposition inversion numerical artifact.

These approaches all embed assumptions that may or may not be acceptable for the analysis and objective. Of course, the first question the modeler would want to ask in this situation is: "is this result credible"? Is the modeled period of record likely to deposit 5m of sediment or is this a symptom of a larger mode problem (e.g. overloaded boundary condition or upstream erosion)?

Multiple Movable Bed Limits

HEC-RAS computes bed change with the "veneer method" by default, raising or lowering all of the wetted nodes within the movable bed limits an equal distance to translate mass change into cross section change. This is often a reasonable 1D assumption but sometimes produces unrealistic cross section change. HEC-RAS includes several features allowing users to diverge from the veneer assumption when advantageous, mostly in the **Bed Change Options** editor (under the **Options** menu, see section below). However, one of these features is on the **Initial Conditions and Transport Parameters** tab of the **Sediment Data** editor.

The **Multiple Movable Bed Limits** feature allows user to select several 'active channels' that can erode, leaving 'islands' of 'non-movable- cross section, between them. These 'islands' outside or between the movable bed limits will not erode and will only deposit if the option to deposit outside movable bed limits is selected.



Left Sta	Right Sta
3	38.5
3	38.5
3	38.5
3	38.5
3	38.5
3	38.5
3	38.5
3	38.5
3	38.5
3	38.5
3	38.5

LSta(1)	RSta(1)	LSta(2)	RSta(2)	LSta(3)	RSta(3)
3	11.5	17.5	24.3	29.5	38.5
3	11.5	17.5	24.3	29.5	38.5
3	11.5	17.5	24.3	29.5	38.5
3	11.5	17.5	24.3	29.5	38.5
3	11.5	17.5	24.3	29.5	38.5
3	11.5	17.5	24.3	29.5	38.5
3	11.5	17.5	24.3	29.5	38.5
3	11.5	17.5	24.3	29.5	38.5
3	11.5	17.5	24.3	29.5	38.5
3	11.5	17.5	24.3	29.5	38.5
3	11.5	17.5	24.3	29.5	38.5

LSta(1)	RSta(1)	LSta(2)	RSta(2)	LSta(3)	RSta(3)
3	38.5				
3	38.5				
3	38.5				
3	11.5	29.5	38.5		
3	11.5	29.5	38.5		
3	11.5	29.5	38.5		
3	11.5	29.5	38.5		
3	11.5	17.5	24.3	29.5	38.5
3	11.5	17.5	24.3	29.5	38.5
3	11.5	17.5	24.3	29.5	38.5
3	11.5	17.5	24.3	29.5	38.5

Figure 1-41: Cross section change for an inundated multi-channel cross section with the default veneer method (top) the multiple movable channel feature with three channels for all XS (middle) and the same cross section with two external channels (bottom).

For example, consider the cross section in Figure 1-41a. If capacity exceeds supply, this cross section will erode all of the wetted nodes equally (Figure 1-41b). However if the raised portions of the cross section are stabilized, vegetated islands, that do not scour appreciably even during flood flows, the veneer assumption will not match field observations. The cross section change in Figure 1-41c will simulate these processes better.

To define multiple mobile channels, select the **Number of Mobile Bed Channels** drop down box in the upper left of the **Initial Conditions and Transport Parameters** tab of the **Sediment Data** editor. Selecting more than one mobile bed channel expands the input table to include more movable bed station pairs, left and right movable bed limits for each discrete channel (Figure 1-41). HEC-RAS only requires one set of movable bed limits per cross section, even multiple bed limits are selected. Users can also vary the number of ineffective flow limits between cross sections, ignoring any left undefined after the first pair.

Modeling Note –Multiple Movable Bed Limit Applications: Users have applied this feature to two primary morphological conditions: modeling flow splits and modeling reservoir deltas. First, modeling flow splits or islands with sediment in HEC-RAS can be challenging. So anatomizing channels or braided channels assumed laterally fixed on simulation time scales can be modeled with multiple movable channels. The limitations of this approach should be taken seriously. HEC-RAS is a 1D model, it does not confine flow or sediment continuity to the sub channels from cross section to cross section, and it still assumes that all the wetted nodes within the movable bed limits change uniformly, even in separate channels.

The multiple movable bed limits method also performed well in reservoir models. Reservoir deltas often form multiple channels that scour during floods, separated by stable vegetated islands. This method captured those processes well. (Gibson and Boyd, 2015)

Bed Gradation

Each cross section requires initial bed gradation data. Instead of requiring users to input gradations for each cross section individually, HEC-RAS uses a template concept similar to that in the Channel Modification Editor. Users define sediment gradations in a database and then associate them with the appropriate cross sections.

HEC-RAS first requires the creation of bed material gradation templates. Then the bed gradation templates can be associated with the appropriate range of cross sections using pick and drag functionalities.

Bed Gradation Templates:

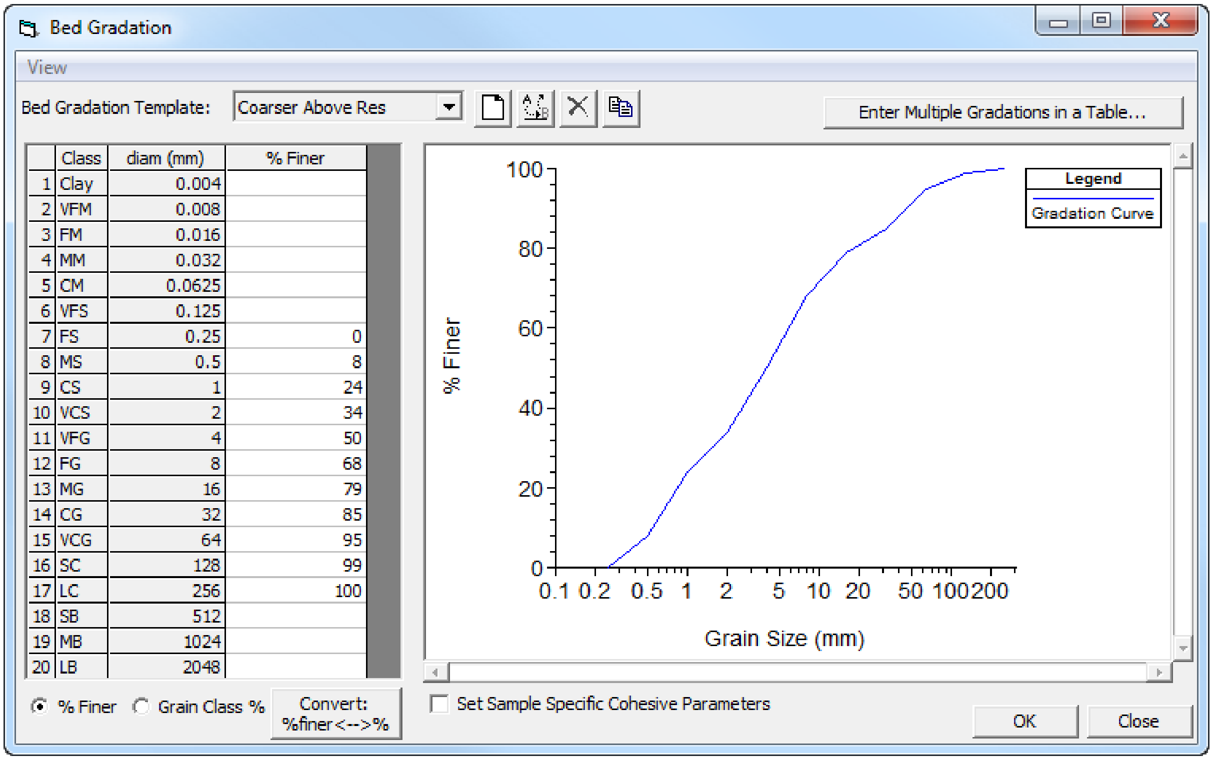
To assign bed gradations to the cross section, first create bed gradation templates. In many applications, these templates will correspond to individual bed samples taken in the project reach. Templates are created and edited by pressing the **Define/Edit Bed Gradation** button, which will launch the dialog depicted in Figure 1-42.

First, create a new bed gradation template by selecting the **New Bed Gradation Sample** button: 🗋 and entering a name for the sample. (Alternatively, data for several different samples can be entered at once; see the section, **Multiple Bed Gradation Table,** below.)

The gradation of the bed sample can be input in either of two forms by toggling between the radio buttons at the bottom of the form:

- **% Finer**: % Finer defines the sample using as a cumulative bed gradation curve with percent finer defined by the upper bound of each grain class. The diameter listed for each grain class is the upper bound of that grain class and values should be entered as percent. (e.g. since this is specified in Percent Finer, 50% should be input as 50 and *NOT* as 0.5)

- **Grain Class Fraction/Weight**: the sample fraction of each grain class is specified. These values will be normalized so values do not have to add up to one or 100% and can be input as simple masses if preferred. (e.g. if 20% of the sample is fine sand, input the value 0.2 or 20 as long as the rest follow that convention). The upper and lower bound grain diameter is associated with each grain class to delineate the range of the class.



Bed Gradation

Bed Gradation Template: Coarser Above Res

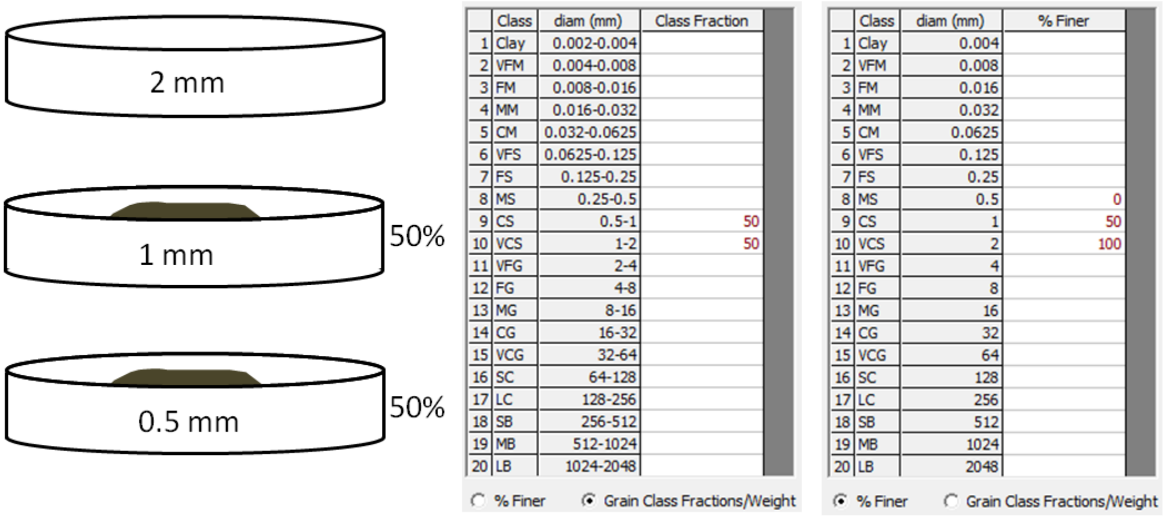
	Class	diam (mm)	% Finer
1	Clay	0.004	
2	VFM	0.008	
3	FM	0.016	
4	MM	0.032	
5	CM	0.0625	
6	VFS	0.125	
7	FS	0.25	0
8	MS	0.5	8
9	CS	1	24
10	VCS	2	34
11	VFG	4	50
12	FG	8	68
13	MG	16	79
14	CG	32	85
15	VCG	64	95
16	SC	128	99
17	LC	256	100
18	SB	512	
19	MB	1024	
20	LB	2048	

● % Finer ○ Grain Class %

☐ Set Sample Specific Cohesive Parameters

Figure 1-42. Gradation template editor.

Modeling Note – Percent Finer Diameter: The % finer feature in HEC-RAS can be confusing. The % per grain glass option is much more intuitive. However, geotechnical and soil sample convention defines soil gradations with cumulative, "% finer" notation. In HEC-RAS, % finer is defined by the *Upper Bound* of the grain class. Consider the example in Figure 1-43, a simplified 3 sieve system with 50% retained on the 0.5 and 1 mm sieves respectively. In the **Grain Class Fraction** method, this would translate to 50 in the VCS (0.5-1 mm) and VFG (1-2 mm) grain class. The comparable **% Finer** notation includes 100 in the VCS class (Upper Bound 2), 50 in the CS class (Upper bound 1) and 0 in the MS class (Upper Bound 0.5).



	Class	diam (mm)	Class Fraction
1	Clay	0.002-0.004	
2	VFM	0.004-0.008	
3	FM	0.008-0.016	
4	MM	0.016-0.032	
5	CM	0.032-0.0625	
6	VFS	0.0625-0.125	
7	FS	0.125-0.25	
8	MS	0.25-0.5	
9	CS	0.5-1	50
10	VCS	1-2	50
11	VFG	2-4	
12	FG	4-8	
13	MG	8-16	
14	CG	16-32	
15	VCG	32-64	
16	SC	64-128	
17	LC	128-256	
18	SB	256-512	
19	MB	512-1024	
20	LB	1024-2048	

○ % Finer ● Grain Class Fractions/Weight

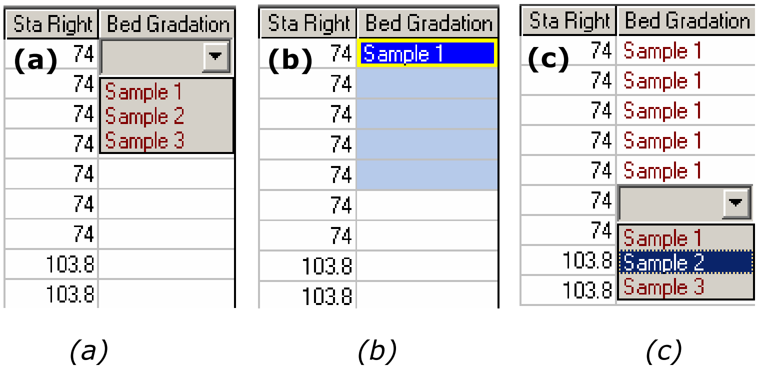
	Class	diam (mm)	% Finer
1	Clay	0.004	
2	VFM	0.008	
3	FM	0.016	
4	MM	0.032	
5	CM	0.0625	
6	VFS	0.125	
7	FS	0.25	
8	MS	0.5	0
9	CS	1	50
10	VCS	2	100
11	VFG	4	
12	FG	8	
13	MG	16	
14	CG	32	
15	VCG	64	
16	SC	128	
17	LC	256	
18	SB	512	
19	MB	1024	
20	LB	2048	

● % Finer ○ Grain Class Fractions/Weight

Figure 1-43: Guidelines for converting between Grain class fraction (left) and Cumulative % finer (right).

Selecting a Template:

After users define the sediment templates, they are available in a drop down pick list under the Bed Gradation column of the **Sediment Data** grid. Clicking on a cell of the Bed Gradation column generates a drop down list of the defined bed sample templates (Figure 1-44a). A single bed sample is frequently associated with multiple cross sections. Therefore, once selected; a sample can be easily copied into multiple cells by placing the mouse pointer over the bottom right corner of the selected cell and dragging vertically (Figure 1-44b).



Sta Right	Bed Gradation
74	
74	
74	
74	
74	
74	
74	
103.8	
103.8	

Sta Right	Bed Gradation
74	Sample 1
74	
74	
74	
74	
74	
74	
103.8	
103.8	

Sta Right	Bed Gradation
74	Sample 1
74	Sample 1
74	Sample 1
74	Sample 1
74	Sample 1
74	
74	
103.8	
103.8	

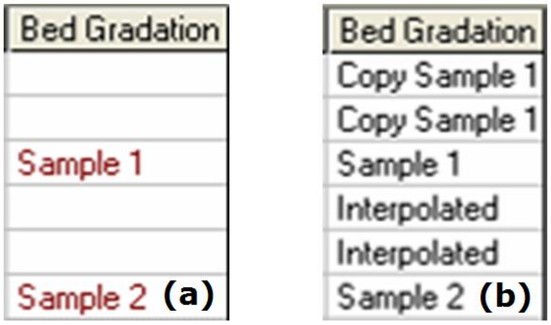
(a) (b) (c)

Figure 1-44. Illustration of process of associating sample templates with cross sections.

Interpolation:

In cases where channel geology justifies assumptions of gradual bed gradation transitions between samples the option to interpolate between specified gradational templates is available. To interpolate, select the appropriate bed gradation templates for the known cross sections, leaving the other rows of the **Bed Gradation** field blank (Figure 1-45b). Then press the **Interpolate Gradations** button on the **Sediment Data** editor (Figure 1-35).

HEC-RAS will interpolate a bed gradation at any station that occurs between two defined gradations within a reach and write "Interpolated" in the **Bed Gradation** field for those nodes. If a cross section occurs between one defined gradation and either the upstream or downstream end of the reach, the closest gradation template will be copied to the node as depicted in the first two fields of Figure 1-45.



Bed Gradation
Sample 1
Sample 2

(a)

Bed Gradation
Copy Sample 1
Copy Sample 1
Sample 1
Interpolated
Interpolated
Sample 2

(b)

Figure 1-45. Gradation interpolation process.

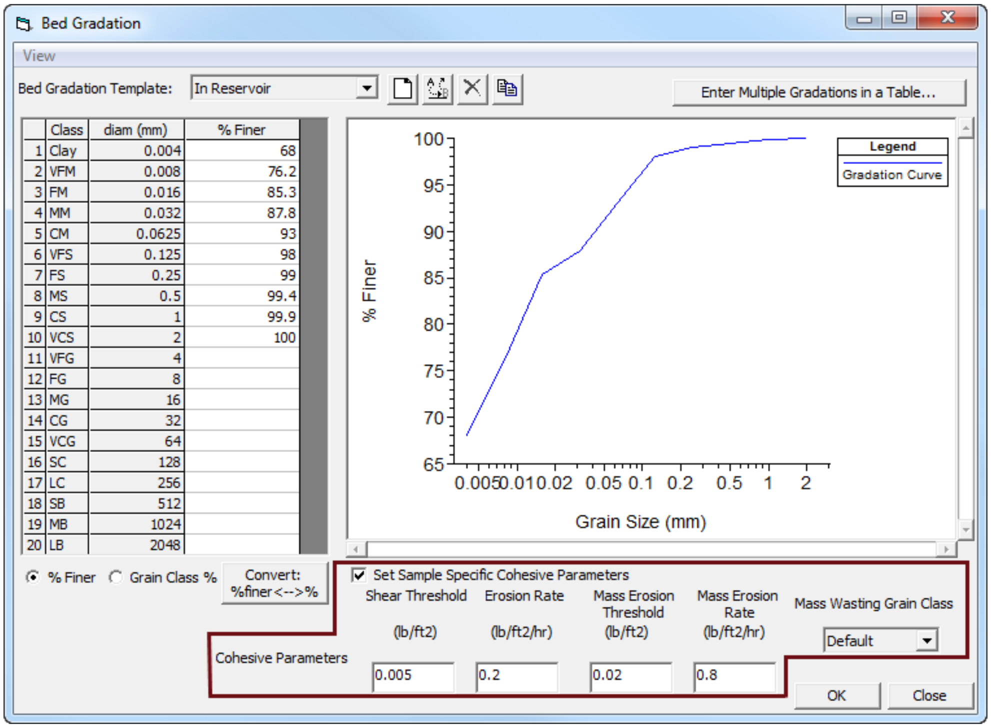
Modeling Note – Copy/Paste to the Bed Gradation Column: While the Bed Gradation column is populated with a drop-down box of the sample database, it stores the data as text. Therefore, the text in these columns can be copied and pasted. This can be useful for large models where selecting each gradation individually would be tedious. But the modeler must be careful when pasting test gradations that each one corresponds precisely to a sample title in the database.

Sample Specific Cohesive Parameters (Optional):

Previous versions of HEC-RAS used global cohesive parameters, assigning a single set of shear thresholds and erodibility coefficients (see **Cohesive Parameters** section) to all cross sections. Version 5.0 retains this capability, but also allows spatially varied cohesive parameters.

Specify spatially varied cohesive parameters by assigning cohesive parameters to bed gradation samples. In some cases different samples might have the same gradation but distinct cohesive parameters. Then assign the samples with the appropriate cohesive parameters to the appropriate cross section or layers. Users do not have to assign **Sample Specific Cohesive Parameters** for all **Bed Gradation Samples** if they do it for one or several. Any samples without local parameters defined will default to global parameters.

Check the **Set Sample Specific Cohesive Parameter** box to define cohesive parameters for a sample. Any cross section or bed layer associated with that gradation will adopt the local cohesive parameters.



Bed Gradation Template: In Reservoir

	Class	diam (mm)	% Finer
1	Clay	0.004	68
2	VFM	0.008	76.2
3	FM	0.016	85.3
4	MM	0.032	87.8
5	CM	0.0625	93
6	VFS	0.125	98
7	FS	0.25	99
8	MS	0.5	99.4
9	CS	1	99.9
10	VCS	2	100
11	VFG	4	
12	FG	8	
13	MG	16	
14	CG	32	
15	VCG	64	
16	SC	128	
17	LC	256	
18	SB	512	
19	MB	1024	
20	LB	2048	

● % Finer ○ Grain Class %

☑ Set Sample Specific Cohesive Parameters

Shear Threshold (lb/ft2)	Erosion Rate (lb/ft2/hr)	Mass Erosion Threshold (lb/ft2)	Mass Erosion Rate (lb/ft2/hr)	Mass Wasting Grain Class
0.005	0.2	0.02	0.8	Default

Figure 1-46: Defining sample specific cohesive parameters

Multiple Bed Gradation Table

Large models can include many bed gradations, (e.g. Shelley and Gibson, 2015). Inputting dozens of samples one at a time can be tedious. Therefore, HEC-RAS includes a tabular input to upload large bed gradation databases. By conforming to a simple input format, multiple gradations can be copied from a spreadsheet directly into an HEC-RAS editor and HEC-RAS will create **Bed Gradation Templates** for each record as if they were added manually (Figure 1-48).

To input multiple gradations, press the **Enter Multiple Gradations in a Table...** button on the upper right of the **Bed Gradation** editor (Figure 1-46). This button launches the table shown in Figure 1-47.

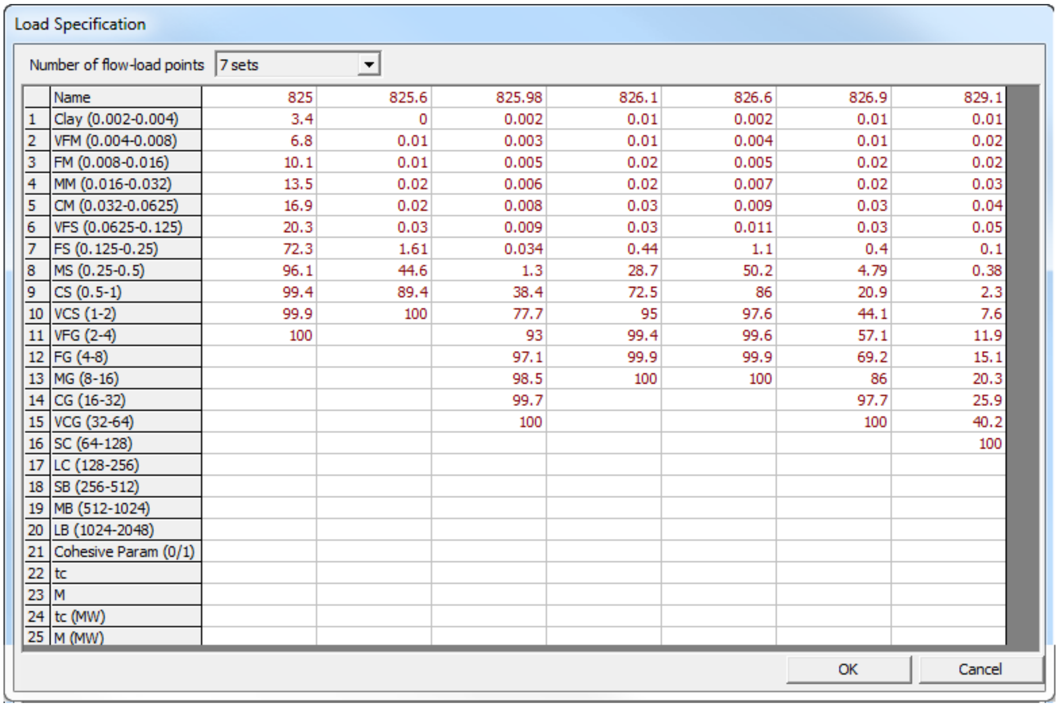
Order data in adjacent columns with rows corresponding to the following:

Header Row (Name): Unique Sample Name

Rows 1-20: The cumulative percentage of each grain class. Note: this editor only supports the % finer input format from Figure 1-42 and Figure 1-46.

Row 21 (Cohesive Param): Sample Specific Cohesive Parameters Flag. This corresponds to the **Set Sample Specific Cohesive Parameters** check box in Figure 1-42 and Figure 1-46. "0" or blank will deselect this feature while "1" will turn it on. Note: Users can specify sample specific cohesive parameters but de-select the method. HEC-RAS will store the parameters as 'dormant.' They will be stored in the model and available but will not be used unless the box is subsequently checked.

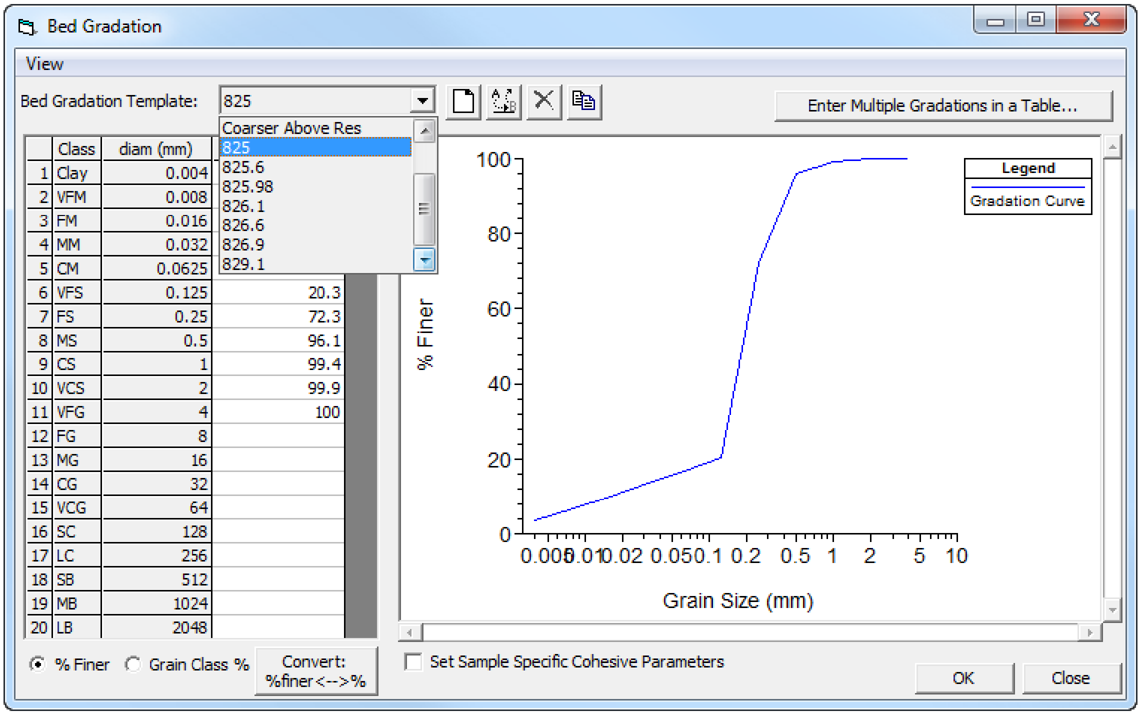
Rows 22-25 (Optional): Sample Specific Cohesive Parameters. *tc* is the critical shear stress for particle erosion, *M* is the erosion rate, *tc (MW)* is the critical shear above which the cohesive model transitions to the “mass wasting” erosion rate and *M (MW)* is the erosion rate for shear stresses above *tc (MW)*.



Number of flow-load points: 7 sets

	Name	825	825.6	825.98	826.1	826.6	826.9	829.1
1	Clay (0.002-0.004)	3.4	0	0.002	0.01	0.002	0.01	0.01
2	VFM (0.004-0.008)	6.8	0.01	0.003	0.01	0.004	0.01	0.02
3	FM (0.008-0.016)	10.1	0.01	0.005	0.02	0.005	0.02	0.02
4	MM (0.016-0.032)	13.5	0.02	0.006	0.02	0.007	0.02	0.03
5	CM (0.032-0.0625)	16.9	0.02	0.008	0.03	0.009	0.03	0.04
6	VFS (0.0625-0.125)	20.3	0.03	0.009	0.03	0.011	0.03	0.05
7	FS (0.125-0.25)	72.3	1.61	0.034	0.44	1.1	0.4	0.1
8	MS (0.25-0.5)	96.1	44.6	1.3	28.7	50.2	4.79	0.38
9	CS (0.5-1)	99.4	89.4	38.4	72.5	86	20.9	2.3
10	VCS (1-2)	99.9	100	77.7	95	97.6	44.1	7.6
11	VFG (2-4)	100		93	99.4	99.6	57.1	11.9
12	FG (4-8)			97.1	99.9	99.9	69.2	15.1
13	MG (8-16)			98.5	100	100	86	20.3
14	CG (16-32)			99.7			97.7	25.9
15	VCG (32-64)			100			100	40.2
16	SC (64-128)							100
17	LC (128-256)							
18	SB (256-512)							
19	MB (512-1024)							
20	LB (1024-2048)							
21	Cohesive Param (0/1)							
22	tc							
23	M							
24	tc (MW)							
25	M (MW)							

Figure 1-47: Gradation table for loading multiple bed gradations into the sediment sample data base.



Bed Gradation Template: 825

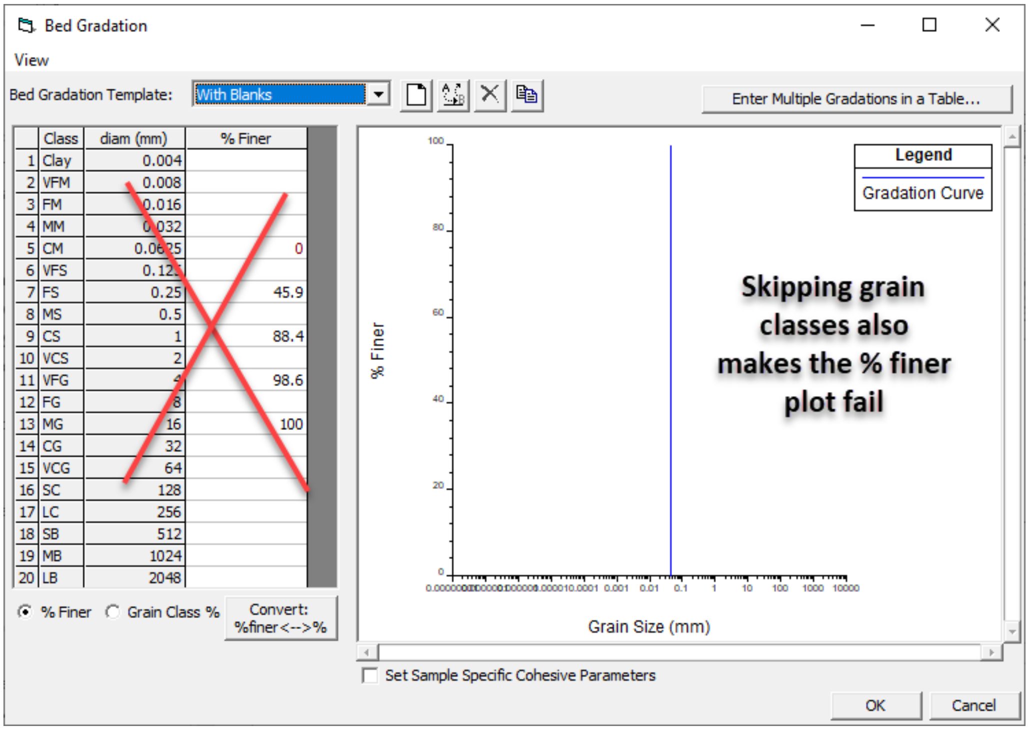
	Class	diam (mm)	
1	Clay	0.004	
2	VFM	0.008	
3	FM	0.016	
4	MM	0.032	
5	CM	0.0625	
6	VFS	0.125	20.3
7	FS	0.25	72.3
8	MS	0.5	96.1
9	CS	1	99.4
10	VCS	2	99.9
11	VFG	4	100
12	FG	8	
13	MG	16	
14	CG	32	
15	VCG	64	
16	SC	128	
17	LC	256	
18	SB	512	
19	MB	1024	
20	LB	2048	

● % Finer ○ Grain Class %

☐ Set Sample Specific Cohesive Parameters

Figure 1-48: Samples from previous figure added to the bed gradation data.

Modeling Note – Interpolate Bed Gradations: Often sieve data do not align with the grain classes in HEC-RAS. In those cases, users can either change their grain classes to line up with their sieve data or interpolate the sieve data to populate the standard grain classes. Skipping grain classes is not recommended. Skipping grain classes in the bed gradations will generate numerical artifacts unless the grain class is excluded from the model entirely (all bed gradations and boundary conditions). Including all grain classes also generates smoother results.



Bed Gradation Template: With Blanks

	Class	diam (mm)	% Finer
1	Clay	0.004	
2	VFM	0.008	
3	FM	0.016	
4	MM	0.032	
5	CM	0.0625	0
6	VFS	0.125	
7	FS	0.25	45.9
8	MS	0.5	
9	CS	1	88.4
10	VCS	2	
11	VFG	4	98.6
12	FG	8	
13	MG	16	100
14	CG	32	
15	VCG	64	
16	SC	128	
17	LC	256	
18	SB	512	
19	MB	1024	
20	LB	2048	

● % Finer ○ Grain Class %

☐ Set Sample Specific Cohesive Parameters

Skipping grain classes also makes the % finer plot fail

Figure 1-49: Avoid skipping grain classes in the bed gradations.

Sediment Parameters for Bridges:

The **Sediment Data** editor will populate rows for all HEC-RAS nodes (e.g. cross sections, bridges, culverts, lateral structures, inline structures, etc…) but only requires sediment data for cross sections. Bridges and other non-cross section nodes are grayed out to indicate they do not require sediment data.

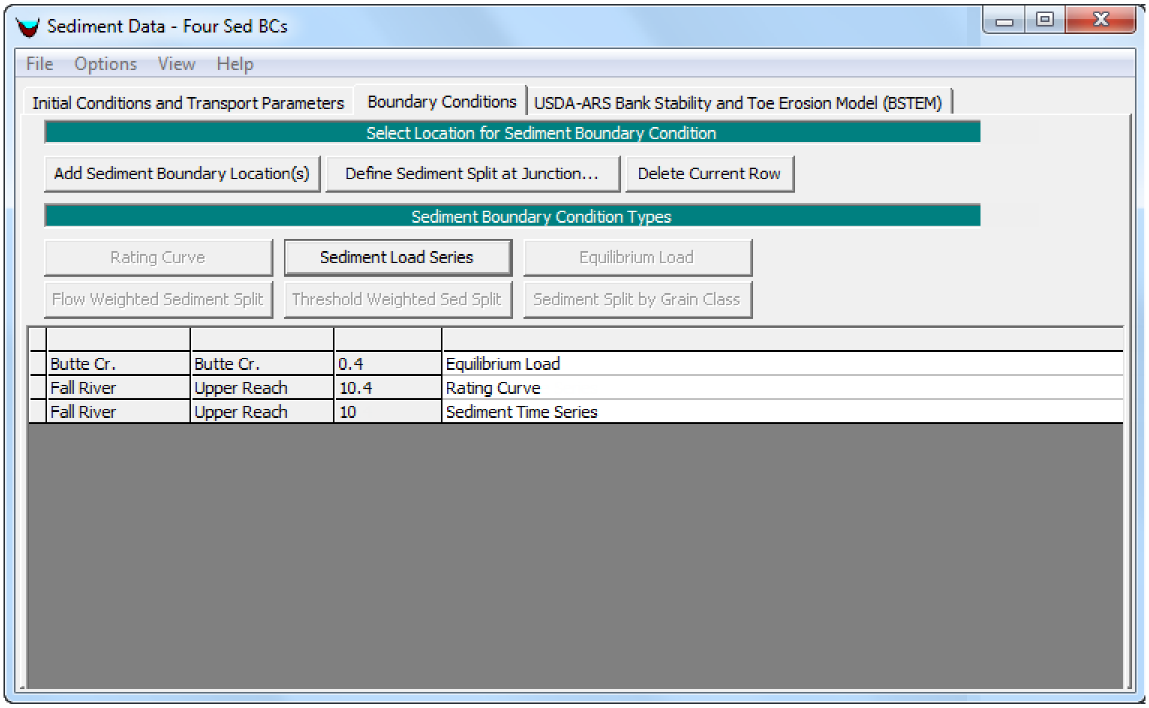
Unlike other non-cross section nodes, however, bridges include cross sections that can deposit or erode. Bridges in HEC-RAS replicate the upstream and downstream cross sections on the upper and lower face of the structure and the sediment model will adjust these cross section nodes (link). HEC-RAS will also project the initial sediment conditions associated with the upstream and downstream cross sections with the respective internal cross section.

Modeling Note – Local Scour and Bridge Sediment Limitations: The bridge approaches in HEC-RAS can pose be challenging to apply in a sediment transport model. See the section on bridges and sediment modeling for more on this topic.

Modeling Note – Local Scour and Bridge Sediment Limitations: Federal Highway Guidance for Bridge Scour analysis includes three major components: regional bed level change, contraction scour, and local scour (i.e. pier and abutment effects). The movable bed sediment transport capabilities in HEC-RAS **ONLY** account for one of those three processes: regional bed change. To compute contraction and local scour use the **Bridge Scour** tool in the **Hydraulic Design** editor.

Sediment Boundary Conditions

The second tab on the **Sediment Data Editor** defines sediment boundary conditions (Figure 1-50). Like the unsteady and quasi-unsteady flow boundary conditions, HEC-RAS requires sediment data at each upstream model boundary and can include optional, local, lateral sediment loads where necessary. The editor automatically lists external model boundaries and users can add local sediment loads at internal cross sections by pressing the **Add Sediment Boundary Location(s)** button.



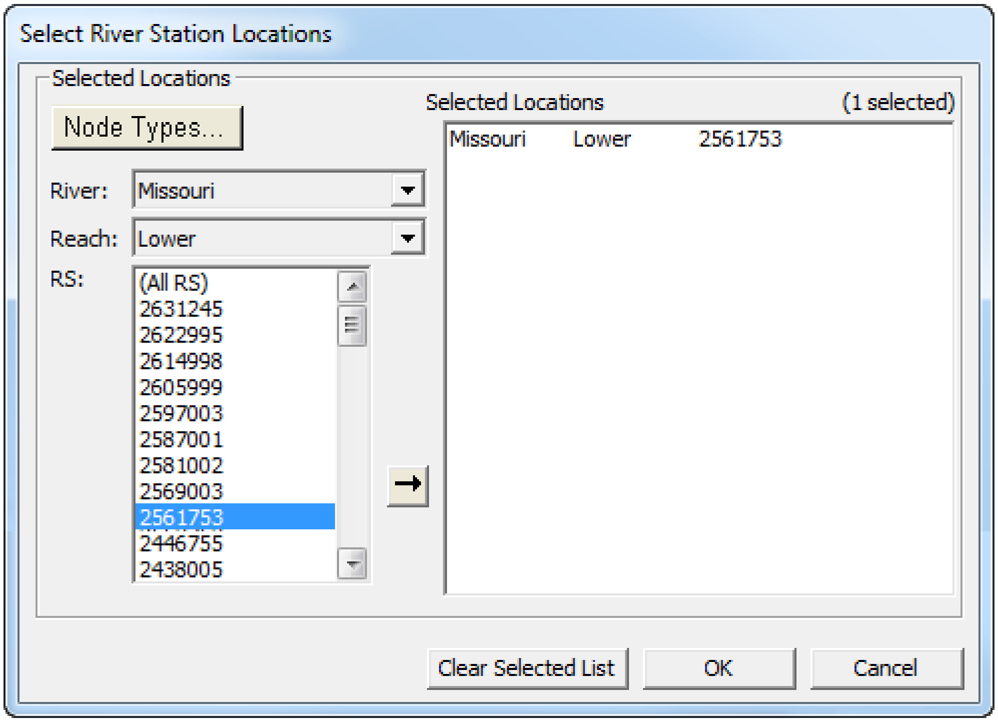
Butte Cr.	Butte Cr.	0.4	Equilibrium Load
Fall River	Upper Reach	10.4	Rating Curve
Fall River	Upper Reach	10	Sediment Time Series

Figure 1-50. Boundary conditions tab of the sediment data editor.

Add Sediment Boundary Location

Although HEC-RAS will automatically list external boundaries, the user must specify internal locations where sediment boundary conditions are required. To add an internal boundary, press the **Add Sediment Boundary Location(s)** button, which will launch the river station selector depicted in Figure 1-51. Select one or more of these river stations by double clicking on the list or selecting locations while holding down the control or shift button then pressing the arrow key. Remove cross sections from the selected locations list by double clicking on them or pressing the **Clear Selected List** button.

Chose sediment boundary conditions by selecting the row associated with the cross section. HEC-RAS will populate the sediment boundaries allowed at the selected node.



River: Missouri

Reach: Lower

Selected Locations (1 selected)

Missouri	Lower	2561753

Figure 1-51. Editor for selecting a lateral flow load boundary location.

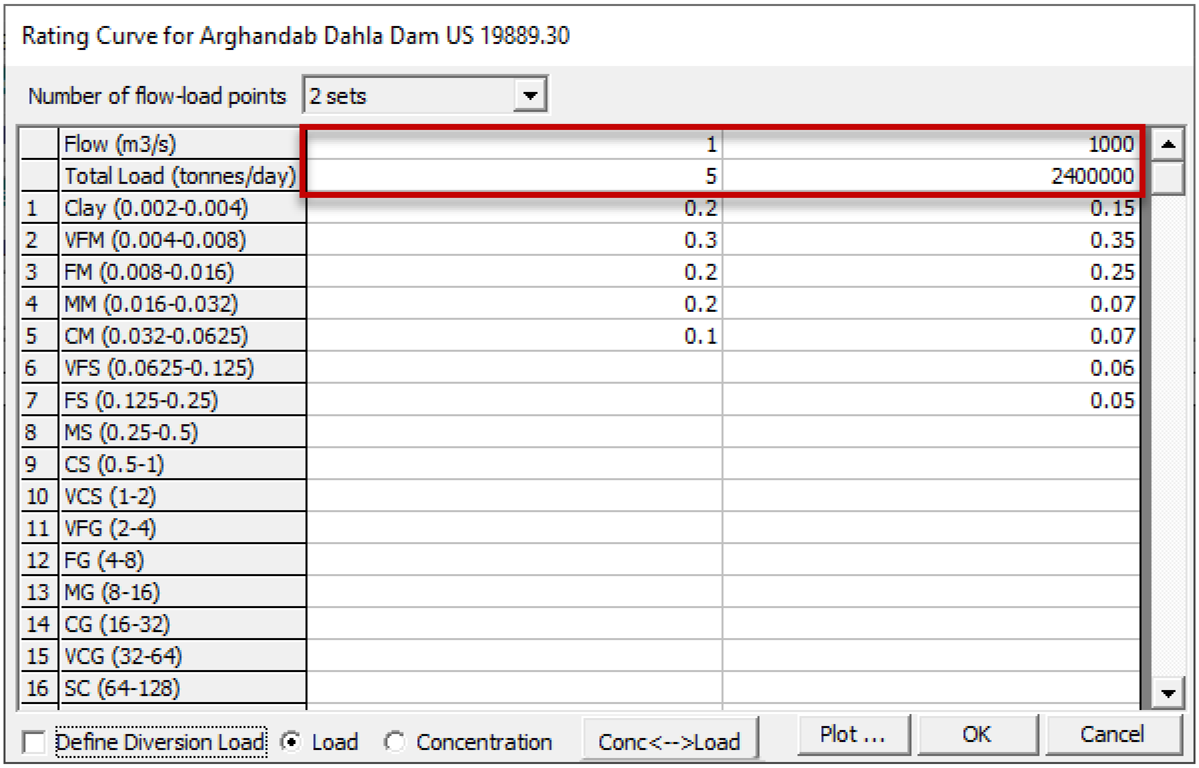
Equilibrium Load

The **Equilibrium Load** boundary condition is only available for upstream boundaries. This method computes the boundary sediment load from the bed gradation and the transport capacity. HEC-RAS computes the equilibrium sediment transport capacity – for each time step and grain class – at the upstream cross section and introduces these capacities as load time series into the next cross section. Since load is set to capacity at this boundary, equilibrium load cross sections are essentially pass through nodes. They will not aggrade or degrade.

Warning – Use Equilibrium Load with Caution: Like the Normal Depth downstream flow condition, the equilibrium load sediment boundary condition is popular because it is easy. It avoids difficult and data intensive preprocessing involved in developing a sediment rating curve or a sediment time series. However, the equilibrium load sediment boundary is often insufficient. Most sediment models are commissioned because the modeled reach is either depositing or eroding, departing from equilibrium by definition. Additionally, the equilibrium boundary condition is extremely sensitive to the bed gradation at the upstream cross section and the selected transport function, which can easily distort it by orders of magnitude. Even without data, users are often better off specifying a speculative rating curve and then calibrating it to observed bed change. When the equilibrium load boundary condition is used, assign it to a cross section well upstream of the area of interest, in a reach know to be in dynamic equilibrium.

Rating Curve

A rating curve computes sediment boundary loads based on boundary flows. Select sediment **Rating Curves at** any cross section with a boundary flow series: upstream, lateral, or lateral uniform. The sediment **Rating Curve** boundary condition is always available for upstream boundaries. If the user selects an internal cross section in the **Sediment Data** editor **Boundary Condition** tab, the **Rating Curve** button will only activate if a selected internal cross section has an associated flow boundary condition. If a **Rating Curve** is associated with a **Uniform Lateral Flow Series**, HEC-RAS distributes sediment loads in the same proportion it distributes flow. This option will open the **Rating Curve** editor depicted in Figure 1-52.



Rating Curve for Arghandab Dahla Dam US 19889.30

Number of flow-load points: 2 sets

	Flow (m3/s)	1	1000
	Total Load (tonnes/day)	5	2400000
1	Clay (0.002-0.004)	0.2	0.15
2	VFM (0.004-0.008)	0.3	0.35
3	FM (0.008-0.016)	0.2	0.25
4	MM (0.016-0.032)	0.2	0.07
5	CM (0.032-0.0625)	0.1	0.07
6	VFS (0.0625-0.125)		0.06
7	FS (0.125-0.25)		0.05
8	MS (0.25-0.5)		
9	CS (0.5-1)		
10	VCS (1-2)		
11	VFG (2-4)		
12	FG (4-8)		
13	MG (8-16)		
14	CG (16-32)		
15	VCG (32-64)		
16	SC (64-128)		

☐ Define Diversion Load ● Load ○ Concentration

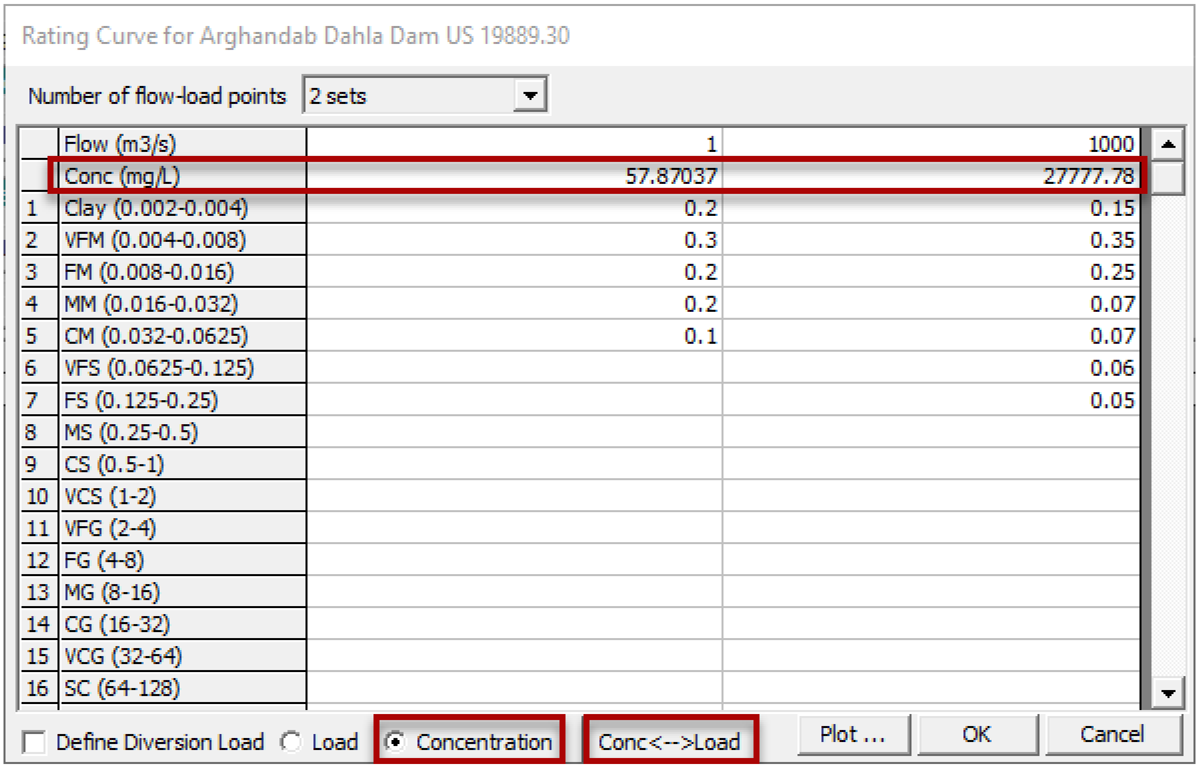
Figure 1-52. Load specification editor.

Flow-Load Data:

To correlate sediment loads with boundary discharge, the Rating Curve includes paired Flow-Load data. The number of columns, one for each Flow-Load pair, is set using the **Number of flow-load points** drop down box at the top of the dialog. Blank columns are not allowed. Select a range of flows that completely encompasses the flows expected during the simulation. If flows occur that exceed the upper bound of the rating curve, HEC-RAS will not extrapolate, but will use the largest sediment load specified in the table. HEC-RAS will interpolate loads below the smallest entered flow, assuming a zero-sediment load at zero flow. The **Plot...** button plots flow versus total load in log space.

Flow-Concentration Data:

The rating curve editor uses load (mass/time) data by default. But users can also specify a sediment rating curve in Concentration units (mass/volume) (Figure 1-53). Like particle size, Concentration is always in SI units in HEC-RAS (mg/L). To define a rating curve with Concentration data, click the Concentration Radio button ○ Load ● Concentration on the bottom of the editor. This radio button only defines the entered data as Concentration, it does not convert it. But the Conc←→Load Button Conc<-->Load allows users to move back and forth between concentration and Load.



Rating Curve for Arghandab Dahla Dam US 19889.30

Number of flow-load points: 2 sets

	Flow (m3/s)	1	1000
	Conc (mg/L)	57.87037	27777.78
1	Clay (0.002-0.004)	0.2	0.15
2	VFM (0.004-0.008)	0.3	0.35
3	FM (0.008-0.016)	0.2	0.25
4	MM (0.016-0.032)	0.2	0.07
5	CM (0.032-0.0625)	0.1	0.07
6	VFS (0.0625-0.125)		0.06
7	FS (0.125-0.25)		0.05
8	MS (0.25-0.5)		
9	CS (0.5-1)		
10	VCS (1-2)		
11	VFG (2-4)		
12	FG (4-8)		
13	MG (8-16)		
14	CG (16-32)		
15	VCG (32-64)		
16	SC (64-128)		

☐ Define Diversion Load ○ Load ● Concentration

Figure 1-53: The same rating curve from the previous figure, converted to concentration with the Conc←→Load Button.

Rating Curve Data and Best Practices

Modeling Note – Flow-Load gage data: In the United States, the US Geological survey publishes sediment load samples at gages that have them online. If the system you are modeling has a gage, go to the "Water Quality" data portal:

https://nwis.waterdata.usgs.gov/usa/nwis/qwdata

to see if the gage has sediment data. The easiest way to search is by Gage #, but you can also search by other criteria (e.g. gage name, river, location). You can download the file with all of the data

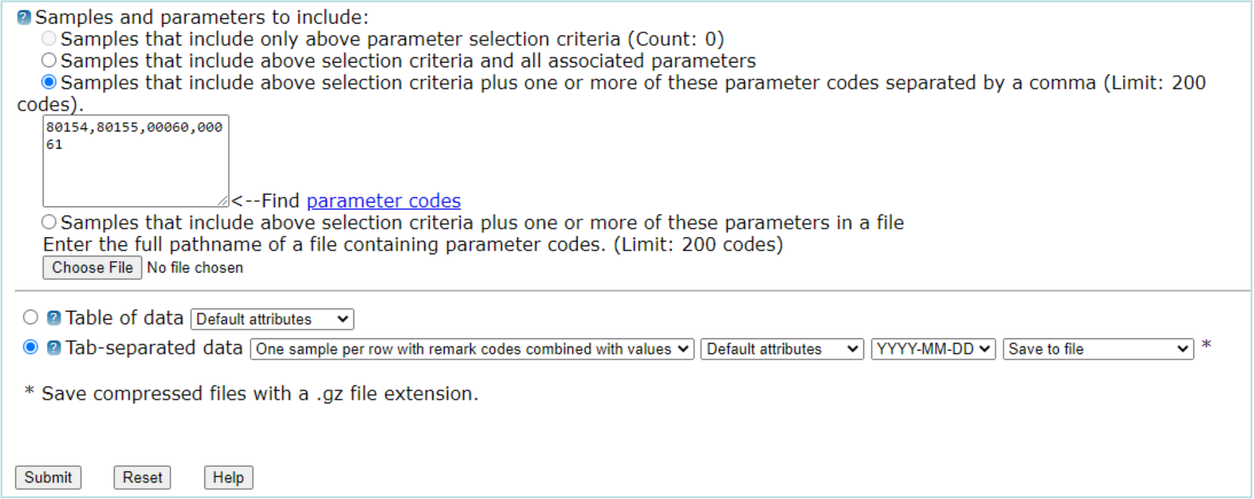
You can also limit the search to records that only have sediment loads or concentrations. The USGS data codes for these measurements are:

00060 - Discharge, cubic feet per second
00061 - Discharge, instantaneous, cubic feet per second[3]

---

[3] Load measurements are usually associated with instantaneous measurements, but sometimes associated with the period-averaged flows, so it is often useful to download both even though this usually generates a file with

80154 - Suspended sediment concentration, milligrams per liter
80155 - Suspended sediment discharge, tons per day



Samples and parameters to include:
○ Samples that include only above parameter selection criteria (Count: 0)
○ Samples that include above selection criteria and all associated parameters
● Samples that include above selection criteria plus one or more of these parameter codes separated by a comma (Limit: 200 codes).

```
80154,80155,00060,000
61
```

<--Find parameter codes
○ Samples that include above selection criteria plus one or more of these parameters in a file
Enter the full pathname of a file containing parameter codes. (Limit: 200 codes)
Choose File No file chosen

○ Table of data: Default attributes
● Tab-separated data: One sample per row with remark codes combined with values; Default attributes; YYYY-MM-DD; Save to file *

* Save compressed files with a .gz file extension.

Figure 1-54: Example flow-load/concentration query for the USGS NWIS website.

Alternately, the USGS has excellent tools available to retrieve these data with R. See the USGS R library tools and tutorials.

Modeling Note – Estimating a Flow-Load Curve from Noisy Data: Flow load data, if available, are usually noisy, spanning one or two orders of magnitude. Seasonal effects, non-stationarity, hysteresis, sample error and random processes make flow an imperfect predictor of load. (This video provides some discussion of these principles). Therefore, defining a single flow-load rating curve requires approximating the 'data cloud' with a single curve of flow-load points. Four considerations should guide flow-load estimation:

1. Consider Unmeasured Load:
   Most sediment load measurements exclude bed load and near-bed, high concentration suspended load. If the river has substantial bed load, particularly at high flows, augment the flow-load curve to reflect these.

2. Use Predictor-Correctors to Un-bias Flow-Load Rating Curves:
   The most common way to fit a noisy data cloud, with a general, linear trend in log-log space, is a transformed regression. When Excel or R fit a power function to flow-load data, they log transform the data and then fit a straight line to the log-transformed data with a least-root-mean-squared (LMRE) regression.

   However, when the regression is untransformed, the positive residuals are always larger than the negative residuals. Figure 1-55 shows equal log transformed residuals, that balance in a transformed, LRME, regression (left). But after the reverse transform, the positive residual is almost twice the negative residual. This asymmetry of the transformed residuals biases power fits low. A standard power fit of flow-load data in Excel will underestimate load substantially (often by 5-60%).

---

more data to simplify. Sometimes sediment concentrations or loads are not reported with flows, but for larger rivers, the daily flows associated with the sample are available outside the water quality database.

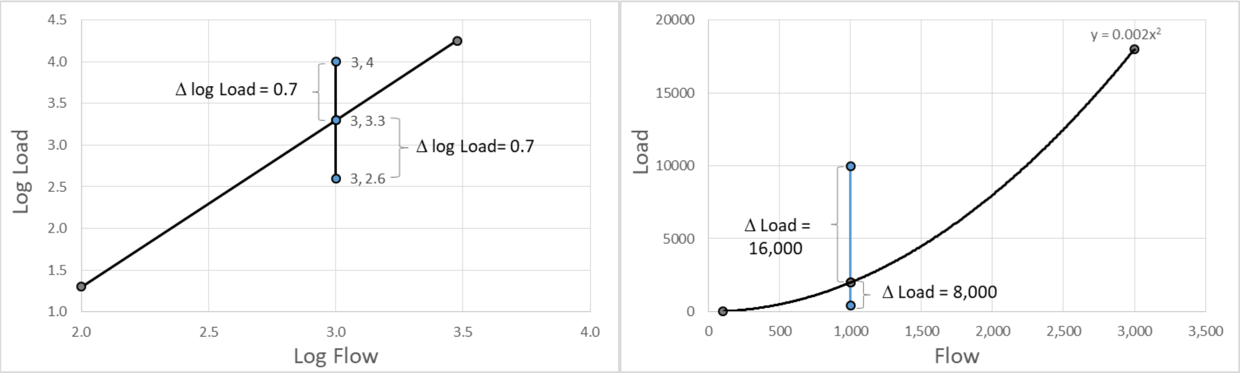


Figure 1-55: Power function (Load = 0.002 Flow2) plotted with two observations with equal log-transformed residuals. But after the reverse transform (right) the positive residual is much larger. This bias in log-transformed regression

Modelers should unbias their rating curve when fitting a power function to flow-load data. USACE modelers (Copeland and Lombard, 2009) have used Ferguson (1986) correct the transform bias in a flow-load power function. More recently, the USBR, USGS, and USACE modelers tend to use the Duan (1983) 'smearing factor' to[4] unbias rating curves. At the least, be prepared to increase the loads by 10-60% during model calibration when using an un-corrected, power fit to represent measured flow-load data.

3. <u>Select the as Few Flow Load Points as Possible</u>:
A flow-load curve should span the entire range of flows, including a minimum of two points, a low flow and a high flow that bound observed or expected flows and their accompanying loads. A common error involves developing a flow-load rating curve that only extends to the maximum flow with a concentration sample, and not the maximum flow in the model.

Keep boundary conditions as simple as possible, but no simpler. There are two reasons to add intermediate flow-load points:

- Rating Curve Slope Change: HEC-RAS uses log interpolation to associate loads with flows between specified flow-load pairs. Sometimes sediment load curves have inflection points, though. Supply limitation may flatten the upper portion of the curve or the curve might steepen in the higher flows. Add intermediate points to capture these inflection points. (Figure 1-56).

---

[4] HEC is working on a Rating Curve calculator to help with this analysis.

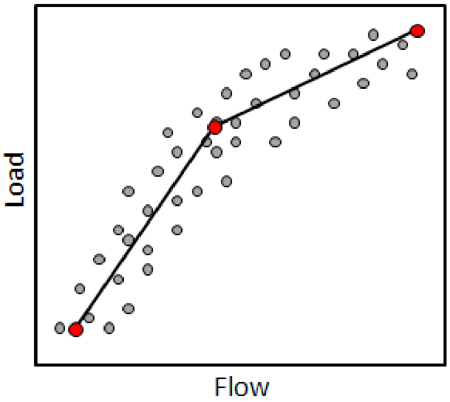


Figure 1-56: Idealized flow-load curve with inflection point.

- Gradation Change: Users must enter gradational breakdowns for each point on the flow-load curve (see next section). However, gradational changes also require flow-load records. Define intermediate flow-load points at any flow that requires unique gradation data, even if it approximates the load that the rating curve would select automatically.

4. Calibration:
   Sediment models must be calibrated to provide reliable predictive results. Calibration parameters, those adjusted to replicate historical bed change, should be those that are most uncertain and most sensitive. Sediment models are often highly sensitive to the load boundary condition, which is uncertain even if good data are available. Therefore, estimated flow-load curves should be provisional, refined during the calibration process.

5. Stationarity Analysis
   Sediment load changes over time. Agricultural impacts, land use changes, fires, mass wasting events, dam removals, and eruptions while dams, pavement, and improved agricultural practices can decrease sediment loads (Walling and Fang (2003).[5] Because sediment load data are often scarce, modelers want to make use of all the data available. But it is important to test the load stationarity (does it change over time). Plot and analyze the data in time blocks, particularly before and after know system changes like a dam or gravel mining policies. If there is a big shift in the rating curve over time, consider using the most recent data to develop the future conditions rating curve. The effects of climate change on future sediment loads is regional and uncertain. But those considerations can be part of a stationarity analysis as well.

---

[5] Walling D.E. and Fang D. (2003) "Recent trends in the suspended sediment loads of the world's rivers." Global and Planetary Change 39:111–126.

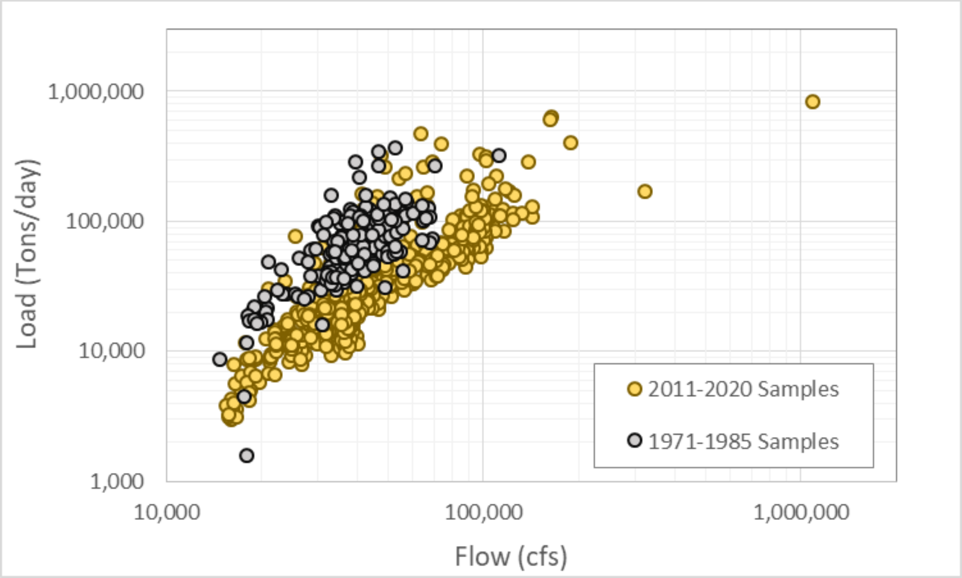


Figure 1-57: Stationarity analysis of a USGS gage indicating that flows from the 1970s and 80s carried more load than more recent flows.

6. <u>Serial Correlation</u>

Regression analyses – including the transformed, LMSE regression used to fit a power function and unbiasing corrections – assume observation independence. However, most sediment load data are opportunistic. It is common to find several of the load measurements in the flow-load measurements at a gage are collected on the same day.

When developing a flow-load curve, the analyst must decide if these same-day samples are replicates or independent enough to add value. Including replicates, over-weights those observation in the regression and biases the sample (i.e. serial correlation or autocorrelation).

But if the rate-of-rise of the hydrograph is sufficient, these samples can be independent enough to include several or all of them, particularly when the represent and under-sampled portion of the curve (e.g. high, 07Oct2010 flows in Figure 1-59). Figure 1-58 and Figure 1-59 include two examples of flow-load data with same-day sample clusters. However, each sampling day in Figure 1-58 covers a constrained flow range, making these more like replicates. The 07Oct2010 samples in Figure 1-59, however, cover a wide range of flows.

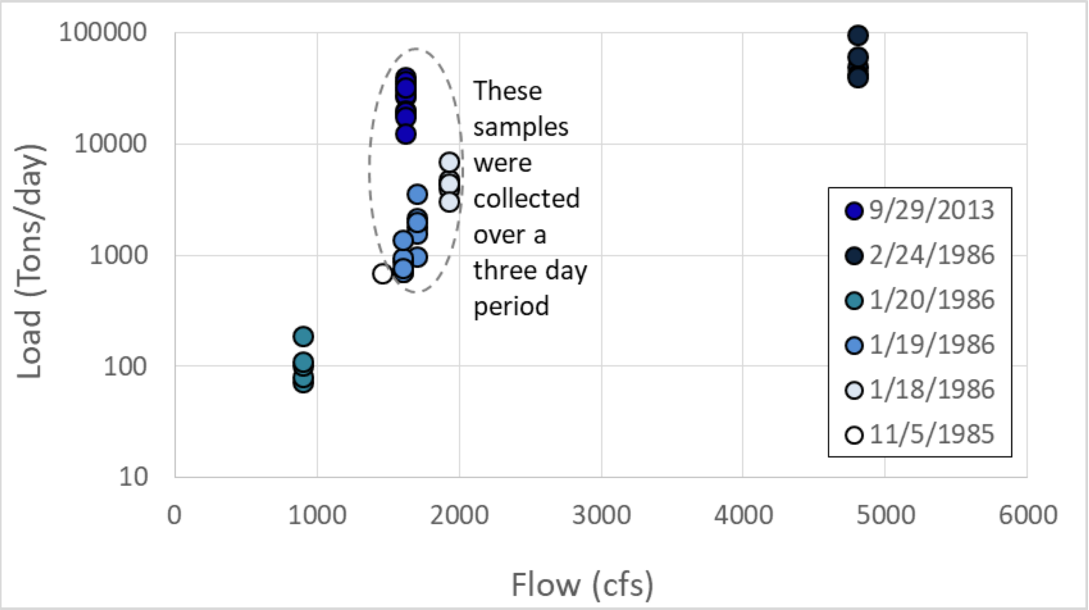


Figure 1-58: Flow load data that include 41 observations but were only collected over 6 days, including three adjacent days.

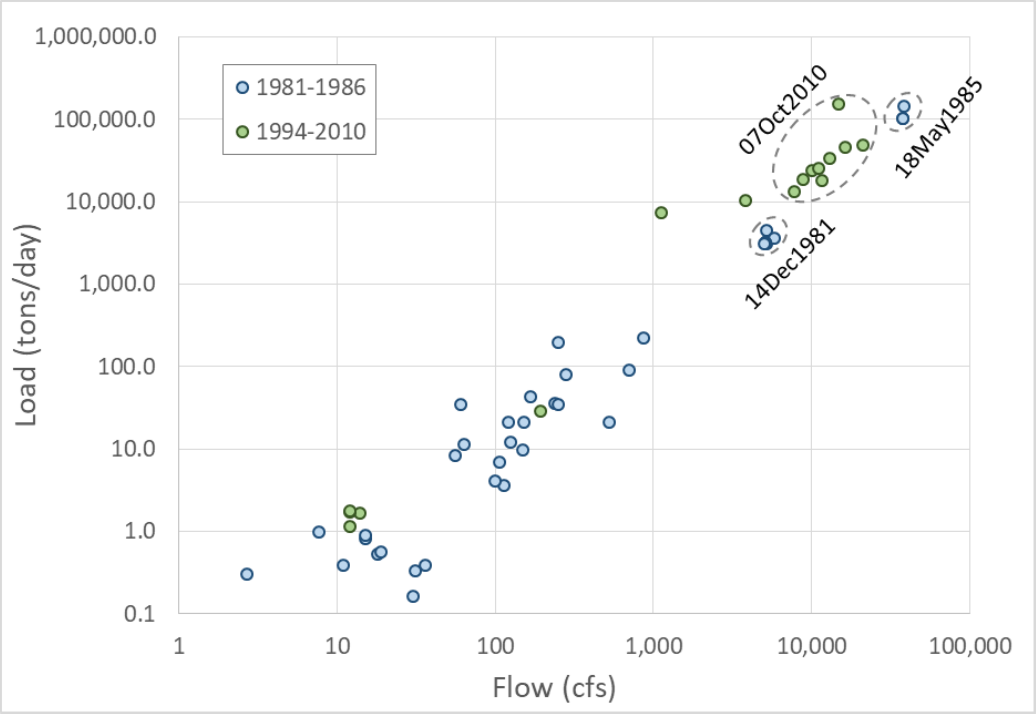


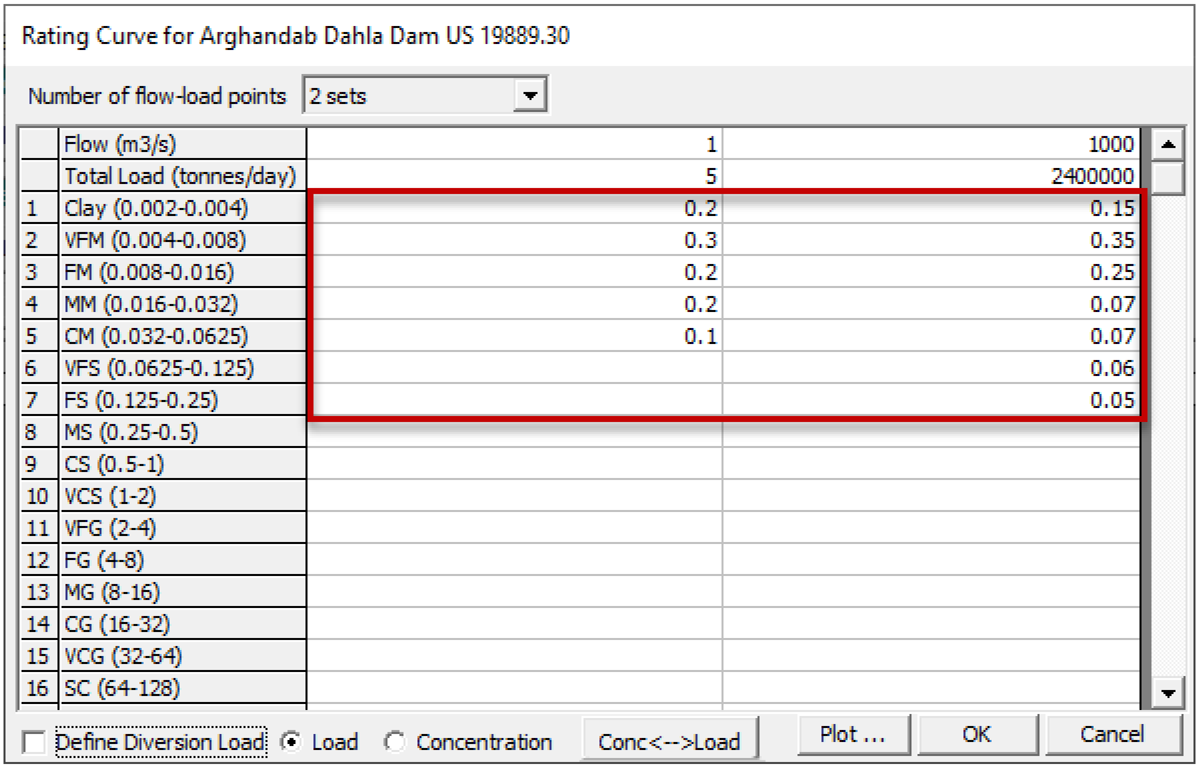
Figure 1-59; Flow-load measurements associated with a USGS gage. Several of the measurement clusters were collected on the same day. However this is a flashy system, so the measurements collected on 07Oct2010 span flows between 8,000 and 21,000 cfs and loads that span an order of magnitude.

Modelers should – at least - make this decision, whether to include temporally clustered data as independent observations or average them as replicates. But the best practice includes a statistical test to determine the independence of these data. The USGS software package SAID (The Surrogate Analysis and Index Developer Tool) includes serial correlation analyses and quantitative methods to distinguish observations from replicates.

7. Statistical Power of Low Flow Samples:
   Most sediment samples are collected at low flows when sampling conditions are safe. However, these loads are not very important morphologically. So many rating curve regressions over-weight the influence of the least significant samples. Use common sense to evaluate the rating curve, recognizing that the 50% recurrence-interval flow (and larger events) will do most of the morphological work in the system. If a quantitative fit of the available data does not reflect the flow-load relationship of the most morphologically significant flows and loads, an estimated hand fit (and using load as a calibration parameter) might be more appropriate.

Load-Gradation Data:

Each column of the sediment rating curve has a flow and an associated total load entered as mass per time (e.g. tons/day). Users must also specify the *gradation* of each of these sediment loads (Figure 1-60). (Note: These are **incremental percentages or fractions not cumulative curves**. (Figure 1-61) Do not use %Finer conventions here.) Percentages (or decimal fractions) can be entered for each grain class for each load. If the total of the percentages (decimal fractions) does not equal 100 (or 1.0), HEC-RAS will normalize the total during computations (so that a given flow will produce the entered total load based on the ratios of the grain sizes).



Rating Curve for Arghandab Dahla Dam US 19889.30

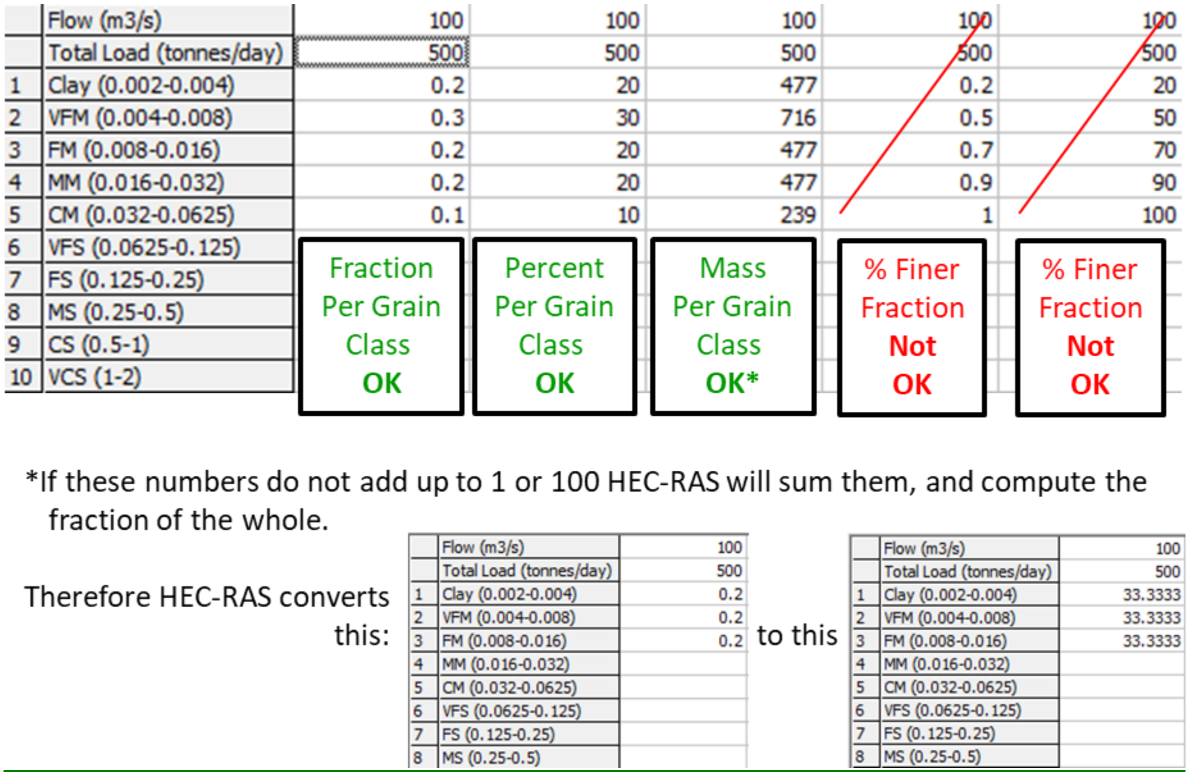
Number of flow-load points: 2 sets

	Flow (m3/s)	1	1000
	Total Load (tonnes/day)	5	2400000
1	Clay (0.002-0.004)	0.2	0.15
2	VFM (0.004-0.008)	0.3	0.35
3	FM (0.008-0.016)	0.2	0.25
4	MM (0.016-0.032)	0.2	0.07
5	CM (0.032-0.0625)	0.1	0.07
6	VFS (0.0625-0.125)		0.06
7	FS (0.125-0.25)		0.05
8	MS (0.25-0.5)		
9	CS (0.5-1)		
10	VCS (1-2)		
11	VFG (2-4)		
12	FG (4-8)		
13	MG (8-16)		
14	CG (16-32)		
15	VCG (32-64)		
16	SC (64-128)		

☐ Define Diversion Load ● Load ○ Concentration

Figure 1-60: Gradational subdivisions for each sediment load in the flow-load boundary condition.

Warning – Do Not Enter Cumulative Gradations in this Editor – This editor does not take cumulative % finer data. This causes confusion, because the bed gradation editor (Figure 1-48) can take data either in % finer or %/fraction per grain class. Do not enter % finer data in the rating curve editor. These should be incremental fractions (e.g. 0.3) or incremental % (30) in each grain classes (Figure 1-61).



	Flow (m3/s)	100	100	100	100	100
	Total Load (tonnes/day)	500	500	500	500	500
1	Clay (0.002-0.004)	0.2	20	477	0.2	20
2	VFM (0.004-0.008)	0.3	30	716	0.5	50
3	FM (0.008-0.016)	0.2	20	477	0.7	70
4	MM (0.016-0.032)	0.2	20	477	0.9	90
5	CM (0.032-0.0625)	0.1	10	239	1	100
6	VFS (0.0625-0.125)					
7	FS (0.125-0.25)					
8	MS (0.25-0.5)					
9	CS (0.5-1)					
10	VCS (1-2)					

*If these numbers do not add up to 1 or 100 HEC-RAS will sum them, and compute the fraction of the whole.

Therefore HEC-RAS converts this:

	Flow (m3/s)	100
	Total Load (tonnes/day)	500
1	Clay (0.002-0.004)	0.2
2	VFM (0.004-0.008)	0.2
3	FM (0.008-0.016)	0.2
4	MM (0.016-0.032)	
5	CM (0.032-0.0625)	
6	VFS (0.0625-0.125)	
7	FS (0.125-0.25)	
8	MS (0.25-0.5)	

to this

	Flow (m3/s)	100
	Total Load (tonnes/day)	500
1	Clay (0.002-0.004)	33.3333
2	VFM (0.004-0.008)	33.3333
3	FM (0.008-0.016)	33.3333
4	MM (0.016-0.032)	
5	CM (0.032-0.0625)	
6	VFS (0.0625-0.125)	
7	FS (0.125-0.25)	
8	MS (0.25-0.5)	

Figure 1-61: Enter incremental (not cumulative or % finer) gradations in the rating curve editor.

Modeling Note – Flow-Gradation gage data: In the United States, the US Geological survey publishes sediment load gradation samples at gages that have them online. These are not common, and where they exist they are not numerous. If the system you are modeling has a gage, go to the "Water Quality" data portal:

https://nwis.waterdata.usgs.gov/usa/nwis/qwdata

and download all of the water quality data. There are many ways to report sediment gradation data. The most common records (particularly for historical sieve and hydrometer data) are 70326-70347.

Modeling Note – Estimating a Flow-Gradation – HEC-RAS requires precise gradational subdivisions of each boundary load in order to compute grain-class specific transport. However, these data rarely exist, and when they do they are usually either unhelpfully biased towards low flows that do little morphological work or are so noisy that it is difficult to infer a trend. Sediment load can also coarsen or fine with flow, making it difficult to estimate how to vary these data.

Gibson and Cui (2011)[6] examined the flow-gradation relationships from 78 US gages and provide some guidance on estimating this parameter. But estimating this parameter is part of the ‘art’ of sediment transport modeling, combining data, system process understanding, scientific intuition, and engineering judgment. Because load gradation is among the least certain and most sensitive data, it often emerges as a target calibration parameter (Gibson and Pridal, 2015).

Diversion Load

Sediment **Rating Curves** require positive flows and loads. Sometimes lateral flow boundary conditions simulate bidirectional flow, modeling inflows with positive values and abstractions with negative flows. Large weirs in large rivers have been modeled this way in legacy models (e.g. HEC-6T). HEC-RAS computes weir flow and sediment diversion with Lateral Structures. However, sometimes users want more control over diversion assumptions, defining them explicitly with diversion coefficients. This feature should be restricted to lateral flow series.

The **Rating Curve** option includes a diversion feature that gives users control over diversion mass and gradation. If the lateral flows are positive (into the cross section) HEC-RAS will use the rating curve, but if flows are negative (out of the cross section) the **Diversion Rating Curve** will control the sediment diverted by grain class.

To define a sediment diversion relationship, specify a sediment rating curve at a cross section with a lateral flow boundary condition and select the **Define Diversion Load** checkbox. This option expands the editor to include a second rating curve that ties grain class specific diversion data to negative flows (Figure 1-62).

The diversion rating curve will have the same number of flow-load points as the standard rating curve. The user must populate the first row of the diversion data with negative flows that span the range of negative flows expected in the lateral flow series.

Columns: The diversion rating curve columns are coupled to the flow-load curve. The **Number of Flow-Load Points** drop down box controls both. Both must have the same number of columns.

Flow: Like the rating curve, the diversion curve is tied to flows in the lateral flow series associated with the cross section. However, the diversion curve flows are negative, decreasing (larger negative numbers) from left to right.

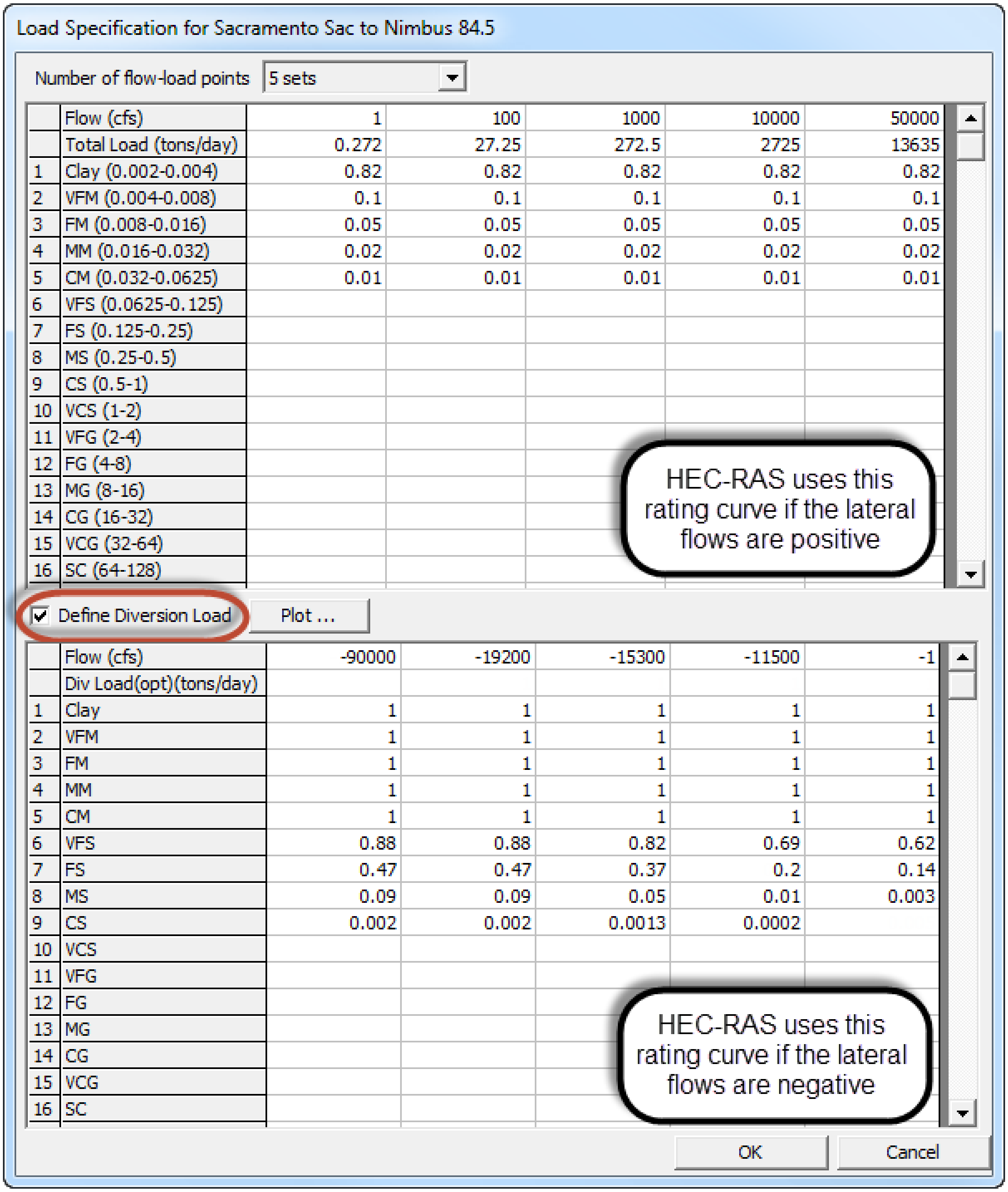
Total Load (Optional): By default, the diversion option removes sediment proportional to the diverted flow (e.g. if the lateral flow series removes 10% of the flow, HEC-RAS removes 10% of the sediment). Users can override this default, however, directing the program to remove defined masses for particular flows.

Grain Class Coefficients (the next 20 rows): After HEC-RAS computes the total sediment mass of diverted it subdivides the diverted mass by grain class. The initial gradation of the diverted sediment adopts the gradation of the transported sediment (mass into the control volume). However, diversions do not divert all sediment equally. Finer grain classes, more evenly distributed in the water column, are more likely to

---

[6] Gibson, S. and Cai, C. (2017) “Flow Dependence of Suspended Sediment Gradations,” *Water Resources Research,* 53(11), 9546-9563, doi.org/10.1002/2016WR020135 (proof)

divert in proportion to the flow. Coarser materials, concentrated near the bed will divert less sediment than flow and the coarsest grain classes often do not divert at all.



Number of flow-load points: 5 sets

	Flow (cfs)	1	100	1000	10000	50000
	Total Load (tons/day)	0.272	27.25	272.5	2725	13635
1	Clay (0.002-0.004)	0.82	0.82	0.82	0.82	0.82
2	VFM (0.004-0.008)	0.1	0.1	0.1	0.1	0.1
3	FM (0.008-0.016)	0.05	0.05	0.05	0.05	0.05
4	MM (0.016-0.032)	0.02	0.02	0.02	0.02	0.02
5	CM (0.032-0.0625)	0.01	0.01	0.01	0.01	0.01
6	VFS (0.0625-0.125)					
7	FS (0.125-0.25)					
8	MS (0.25-0.5)					
9	CS (0.5-1)					
10	VCS (1-2)					
11	VFG (2-4)					
12	FG (4-8)					
13	MG (8-16)					
14	CG (16-32)					
15	VCG (32-64)					
16	SC (64-128)					

HEC-RAS uses this rating curve if the lateral flows are positive

☑ Define Diversion Load

	Flow (cfs)	-90000	-19200	-15300	-11500	-1
	Div Load(opt)(tons/day)					
1	Clay	1	1	1	1	1
2	VFM	1	1	1	1	1
3	FM	1	1	1	1	1
4	MM	1	1	1	1	1
5	CM	1	1	1	1	1
6	VFS	0.88	0.88	0.82	0.69	0.62
7	FS	0.47	0.47	0.37	0.2	0.14
8	MS	0.09	0.09	0.05	0.01	0.003
9	CS	0.002	0.002	0.0013	0.0002	
10	VCS					
11	VFG					
12	FG					
13	MG					
14	CG					
15	VCG					
16	SC					

HEC-RAS uses this rating curve if the lateral flows are negative

Figure 1-62: Lateral Flow-Load Rating Curve with Sediment Diversion.

The grain class coefficients apply a screen for each grain class diversion, reducing mass diversion by grain class for these effects. Assign a coefficient of "1" to divert the total computed grain class mass. Coefficients less than one reduce the diverted mass (e.g. 0.35

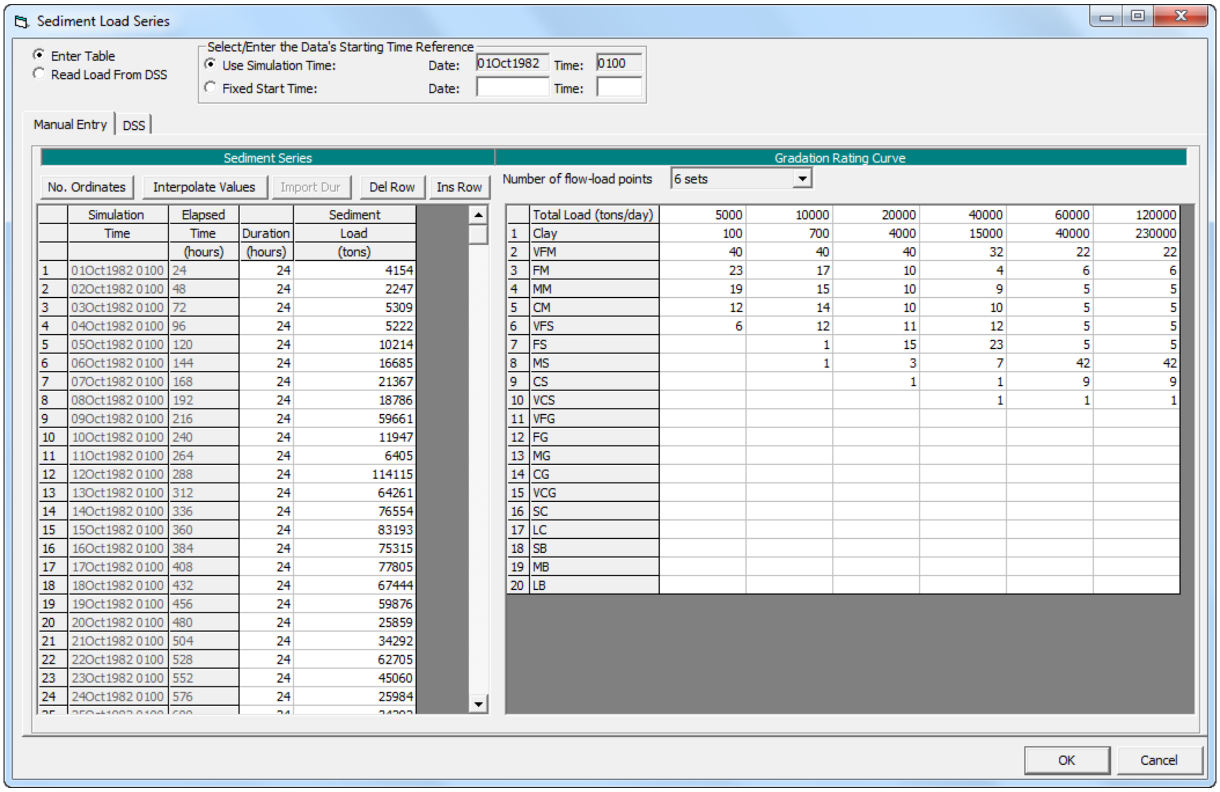
will only divert 35% of the grain class). Blank or "0" coefficients divert no mass in those grain classes.

Modeling Note – Diversion Relationship Application: The load diversion rating curve either requires copious data with good vertical concentration resolution or analytical estimates (e.g. with a Rouse computation). In general, especially with unsteady sediment transport available in versions since version 5.0, lateral structures can model sediment diversions more directly. Modeling a sediment diversion with a lateral structure will almost certainly be easier, and - unless the project has excellent gradation data of the gradation sediment or high confidence in analytical distributions – may perform comparably.

Defining a Sediment Time Series Boundary Condition

Sediment Time Series: Manual Data Entry

If sediment load cannot be coupled to flow, include it as a Sediment Load Series (Figure 1-63). Since the sediment series boundary does not depend on a flow boundary, it introduces sediment to any cross section whether it has a flow series or not (except for the downstream boundary). For example, if the sediment load rate is 1,000 tons per day, the load would be 1,000 tons for a 24-hour duration but 250 for a 6 hour duration.



● Enter Table
○ Read Load From DSS

Select/Enter the Data's Starting Time Reference
● Use Simulation Time: Date: 01Oct1982 Time: 0100
○ Fixed Start Time: Date: Time:

	Simulation Time	Elapsed Time (hours)	Duration (hours)	Sediment Load (tons)
1	01Oct1982 0100	24	24	4154
2	02Oct1982 0100	48	24	2247
3	03Oct1982 0100	72	24	5309
4	04Oct1982 0100	96	24	5222
5	05Oct1982 0100	120	24	10214
6	06Oct1982 0100	144	24	16685
7	07Oct1982 0100	168	24	21367
8	08Oct1982 0100	192	24	18786
9	09Oct1982 0100	216	24	59661
10	10Oct1982 0100	240	24	11947
11	11Oct1982 0100	264	24	6405
12	12Oct1982 0100	288	24	114115
13	13Oct1982 0100	312	24	64261
14	14Oct1982 0100	336	24	76554
15	15Oct1982 0100	360	24	83193
16	16Oct1982 0100	384	24	75315
17	17Oct1982 0100	408	24	77805
18	18Oct1982 0100	432	24	67444
19	19Oct1982 0100	456	24	59876
20	20Oct1982 0100	480	24	25859
21	21Oct1982 0100	504	24	34292
22	22Oct1982 0100	528	24	62705
23	23Oct1982 0100	552	24	45060
24	24Oct1982 0100	576	24	25984

Number of flow-load points: 6 sets

	Total Load (tons/day)	5000	10000	20000	40000	60000	120000
1	Clay	100	700	4000	15000	40000	230000
2	VFM	40	40	40	32	22	22
3	FM	23	17	10	4	6	6
4	MM	19	15	10	9	5	5
5	CM	12	14	10	10	5	5
6	VFS	6	12	11	12	5	5
7	FS		1	15	23	5	5
8	MS		1	3	7	42	42
9	CS			1	1	9	9
10	VCS				1	1	1
11	VFG						
12	FG						
13	MG						
14	CG						
15	VCG						
16	SC						
17	LC						
18	SB						
19	MB						
20	LB						

Figure 1-63. Point load sediment time series editor.

HEC-RAS requires all sediment data by grain class. Therefore, the sediment load series also needs gradation data. Enter a rating curve that defines grain size distributions for load rates. Like the flow-load rating curve, these are individual fractions or percentages (HEC-RAS will normalize them assigning each grain class the respective percentage of the sum) not a cumulative gradation curve. These gradations are tied to sediment transport *rates* in mass per day, so they only match up with the sediment loads if the durations are 24 hours. For example, if an entry on the sediment time series was 250 tons over a 6 hour duration, it would select/interpolate a gradation for 1,000 tons/day.

Coupling gradation to the load can constrain this boundary condition, making it unhelpful for some applications. The **DSS** tab provides more flexibility, defining more general sediment loads the **Manual Entry** sediment time series.

Sediment Load Series: From DSS - Sediment Load Time Series by Grain Class

The HEC-DSS Sediment Load Series editor is the most general sediment boundary condition option, allowing users to specify independent sediment time series for each grain class.

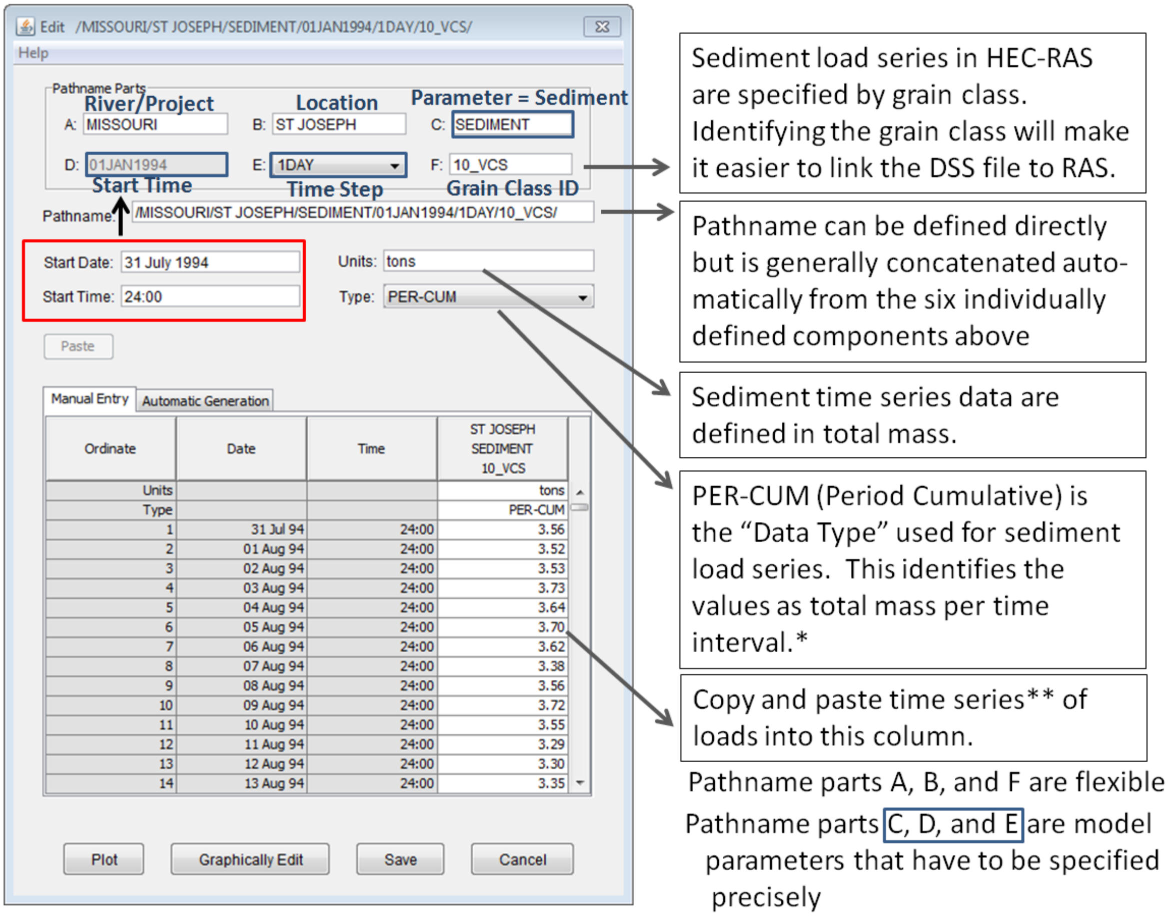
HEC-DSS is a database that all HEC models read from and write to. It is a powerful tool to store hydrologic time series and pass data between HEC tools (e.g. parsing flows and sediment loads from HEC-HMS to HEC-RAS). This boundary condition requires an HEC-DSS file, populated with sediment time series records for each modeled grain class, and requires the HEC-DSS model to follow a several conventions to make it compatible with the sediment model.

Setting Up an HEC-DSS Sediment Time Series File:

Unless another HEC software generates the sediment DSS file automatically, users must create HEC-DSS sediment time file before using the DSS sediment Boundary. In HEC-DSSVue (or the DSS editor in HEC-RAS) create a single HEC-DSS file, with a separate DSS record, with a unique DSS path name following the conventions in Figure 1-64.

HEC-DSS identifies, stores, and retrieves time series with six-part path names (A-F). A, B, D, and E are common to all DSS time series. A and B identify the series location, and D and E set the start time and time step. The C and F pathname parts are sediment specific. Set the C part to "Sediment". HEC-RAS *requires* this convention to recognize the time series as sediment data. The last pathname part (F) is a user note. Name the grain class in this field to make it easier to identify when linking it to HEC-RAS. Finally, the HEC-RAS sediment model assumes sediment time series are Period-Cumulative (**PER-CUM**), indicating that the sediment mass represents the total associated with the time step rather than an instantaneous rate. This is different from the manual sediment time series.

Users can create HEC-DSS time series from non-stationary data, non-HEC sediment delivery model output (e.g. GESHA, SWAT, etc..), or synthetic/stochastic loads. These data can be imported or pasted to HEC-DSS directly from Excel if it is in the correct Excel format. Split the date and time into separate columns, with the loads in another column, and then set the Excel Number type for the date and time columns to "Custom", defining "**ddmmmyyyy"** for the date and "**00:00"** for the time (Figure 1-65).



Edit /MISSOURI/ST JOSEPH/SEDIMENT/01JAN1994/1DAY/10_VCS/

A: MISSOURI
B: ST JOSEPH
C: SEDIMENT
D: 01JAN1994
E: 1DAY
F: 10_VCS
Pathname: /MISSOURI/ST JOSEPH/SEDIMENT/01JAN1994/1DAY/10_VCS/
Start Date: 31 July 1994
Start Time: 24:00
Units: tons
Type: PER-CUM

Ordinate	Date	Time	ST JOSEPH SEDIMENT 10_VCS
Units			tons
Type			PER-CUM
1	31 Jul 94	24:00	3.56
2	01 Aug 94	24:00	3.52
3	02 Aug 94	24:00	3.53
4	03 Aug 94	24:00	3.73
5	04 Aug 94	24:00	3.64
6	05 Aug 94	24:00	3.70
7	06 Aug 94	24:00	3.62
8	07 Aug 94	24:00	3.38
9	08 Aug 94	24:00	3.56
10	09 Aug 94	24:00	3.72
11	10 Aug 94	24:00	3.55
12	11 Aug 94	24:00	3.29
13	12 Aug 94	24:00	3.30
14	13 Aug 94	24:00	3.35

Sediment load series in HEC-RAS are specified by grain class. Identifying the grain class will make it easier to link the DSS file to RAS.

Pathname can be defined directly but is generally concatenated automatically from the six individually defined components above

Sediment time series data are defined in total mass.

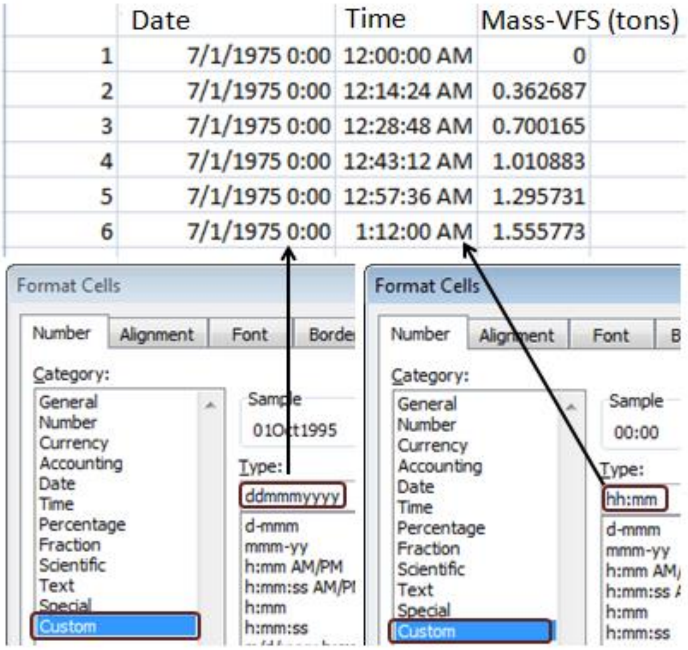
PER-CUM (Period Cumulative) is the “Data Type” used for sediment load series. This identifies the values as total mass per time interval.*

Copy and paste time series** of loads into this column.

Pathname parts A, B, and F are flexible

Pathname parts C, D, and E are model parameters that have to be specified precisely

Figure 1-64: Adding a grain class specific sediment load time series in HEC-DSS.



	Date	Time	Mass-VFS (tons)
1	7/1/1975 0:00	12:00:00 AM	0
2	7/1/1975 0:00	12:14:24 AM	0.362687
3	7/1/1975 0:00	12:28:48 AM	0.700165
4	7/1/1975 0:00	12:43:12 AM	1.010883
5	7/1/1975 0:00	12:57:36 AM	1.295731
6	7/1/1975 0:00	1:12:00 AM	1.555773

Sample: 01Oct1995
Type: ddmmmyyyy

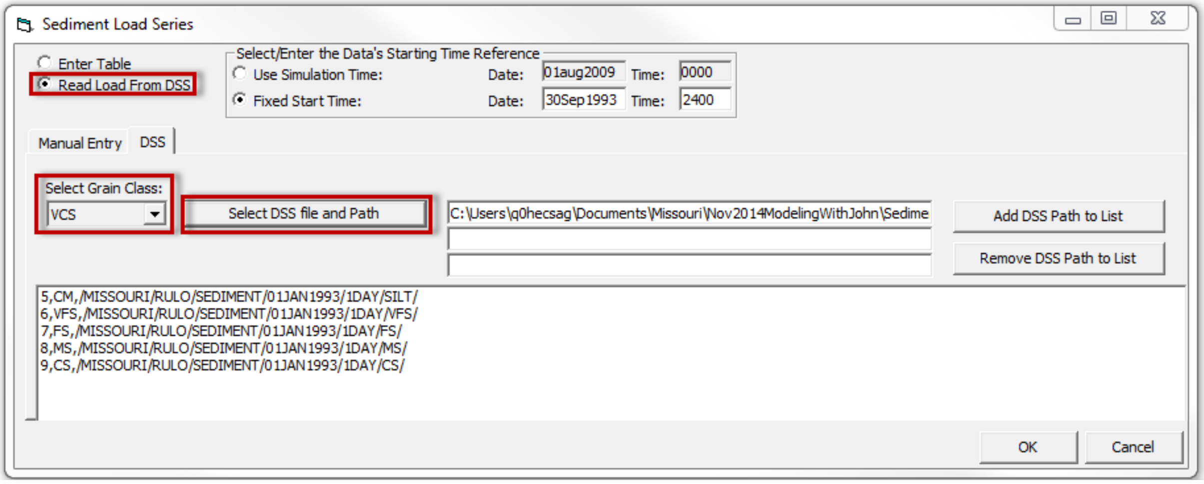
Sample: 00:00
Type: hh:mm

Figure 1-65: Formatting Excel data to import into HEC-DSS.

Specifying HEC-DSS Sediment Time Series in HEC-RAS:

After populating the HEC-DSS file with sediment mass records for each pertinent grain class, open the **Sediment Load Series Editor** and select **DSS** tab. A Sediment Load Series can contain both **Manual Entry** and **DSS boundary conditions**. Make HEC-RAS use the DSS data by selecting the **Read Load From DSS** option in the upper left of the dialogue (Figure 1-66).

Specify load series by grain class. First **Select Grain Class** with the drop down box. Then Select press the **Select DSS file and Path** button to launch the **Pick DSS Path** editor and select the DSS file and path associated with the grain class (Figure 1-66). Select *one* DSS path, using the filters to isolate the correct path in a large file. If multiple paths appear, identical in everything but date, select the first one (Figure 1-67). Click **OK** to write this file and pat to the time series editor. Finalize the connection between the grain class and the DSS record by pressing **Add DSS Path to List** (Figure 1-68). This will add a line to the list box below that indicates the Grain Class Index, Grain Class Name, DSS Path. To delete a record, double click on the record in the list.



○ Enter Table
● Read Load From DSS

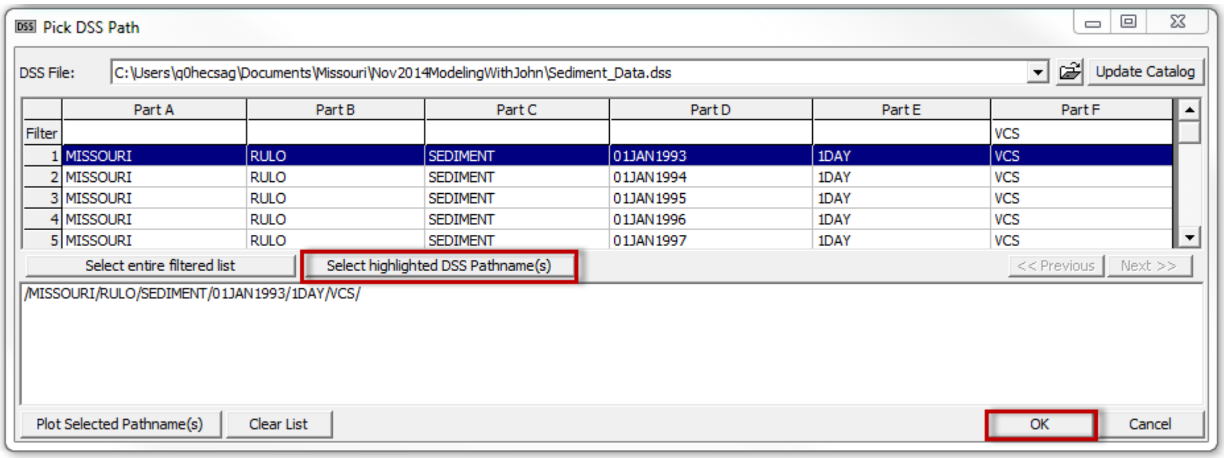
Select/Enter the Data's Starting Time Reference
○ Use Simulation Time: Date: 01aug2009 Time: 0000
● Fixed Start Time: Date: 30Sep1993 Time: 2400

Select Grain Class: VCS

C:\Users\q0hecsag\Documents\Missouri\Nov2014ModelingWithJohn\Sedime

```
5,CM,/MISSOURI/RULO/SEDIMENT/01JAN1993/1DAY/SILT/
6,VFS,/MISSOURI/RULO/SEDIMENT/01JAN1993/1DAY/VFS/
7,FS,/MISSOURI/RULO/SEDIMENT/01JAN1993/1DAY/FS/
8,MS,/MISSOURI/RULO/SEDIMENT/01JAN1993/1DAY/MS/
9,CS,/MISSOURI/RULO/SEDIMENT/01JAN1993/1DAY/CS/
```

Figure 1-66: Select a grain class from the drop down menu and press the Select DSS file and path to associate a load series with that grain class. Select the Read DSS radio button to get sediment data from DSS.

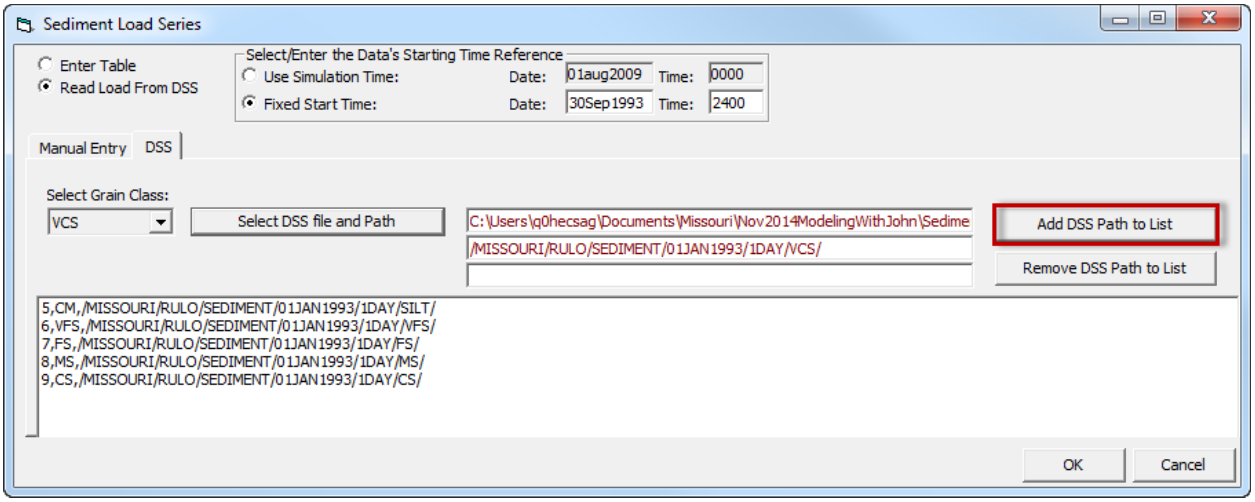


DSS File: C:\Users\q0hecsag\Documents\Missouri\Nov2014ModelingWithJohn\Sediment_Data.dss

	Part A	Part B	Part C	Part D	Part E	Part F
Filter						VCS
1	MISSOURI	RULO	SEDIMENT	01JAN1993	1DAY	VCS
2	MISSOURI	RULO	SEDIMENT	01JAN1994	1DAY	VCS
3	MISSOURI	RULO	SEDIMENT	01JAN1995	1DAY	VCS
4	MISSOURI	RULO	SEDIMENT	01JAN1996	1DAY	VCS
5	MISSOURI	RULO	SEDIMENT	01JAN1997	1DAY	VCS

/MISSOURI/RULO/SEDIMENT/01JAN1993/1DAY/VCS/

Figure 1-67: Use the DSS editor to select a DSS Path.



○ Enter Table
● Read Load From DSS

Select/Enter the Data's Starting Time Reference
○ Use Simulation Time: Date: 01aug2009 Time: 0000
● Fixed Start Time: Date: 30Sep1993 Time: 2400

Select Grain Class: VCS

C:\Users\q0hecsag\Documents\Missouri\Nov2014ModelingWithJohn\Sedime
/MISSOURI/RULO/SEDIMENT/01JAN1993/1DAY/VCS/

```
5,CM,/MISSOURI/RULO/SEDIMENT/01JAN1993/1DAY/SILT/
6,VFS,/MISSOURI/RULO/SEDIMENT/01JAN1993/1DAY/VFS/
7,FS,/MISSOURI/RULO/SEDIMENT/01JAN1993/1DAY/FS/
8,MS,/MISSOURI/RULO/SEDIMENT/01JAN1993/1DAY/MS/
9,CS,/MISSOURI/RULO/SEDIMENT/01JAN1993/1DAY/CS/
```

Figure 1-68: Once a DSS path is selected, add the grain class-DSS Path association to the list with the Add button. To remove an association double click on the list.

Modeling Note – DSS Path Workflow: To avoid selecting a new DSS file and path each time, users can select a new grain class and edit the path name manually (if, for example, the only difference is the F pathname part, which reflects the grain class).

Modeling Note – Sediment Time Series/DSS Applications: Lateral flow series are appropriate whenever flow and load are uncoupled. It is appropriate for sediment added without flows (e.g. gravel augmentation) or tributary loads driven by reservoir releases or dam removals rather than flows. They are also used to model non-stationary relationships where the flow-load relationship or the gradation changes over a long simulation (e.g. Shelley and Gibson, 2015). The DSS sediment series can also import sediment data computed by the HEC-HMS sediment model automatically (Gibson et al. 2010) or can be created from time series from other sediment delivery models. Negative sediment series can also remove sediment from a system (e.g. to simulate interception technology).

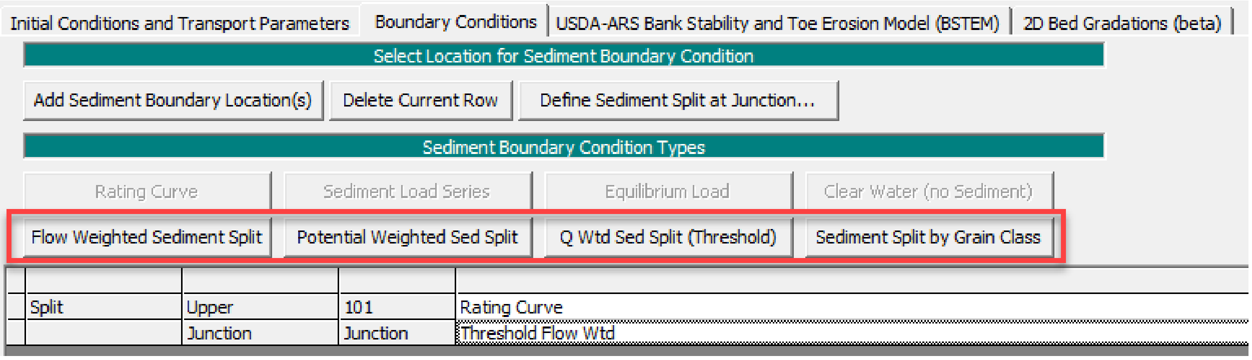
Clear Water Boundary Condition

Clear Water (no Sediment)

HEC-RAS 6.0 and later include a "Clear Water" boundary condition. The clear water boundary condition is just a simple way to define a no-sediment boundary. A clear water boundary can simulate a high trap-efficiency dam outlet or other flow boundaries without appreciable sediment.

Junctions and Flow Splits

HEC-RAS 6.0 does not require user input to model sediment at junctions. Dendritic junctions, those with two upstream reaches and one downstream reach, simply combine sediment. Flow splits, junctions with one upstream reach and multiple downstream reaches, split the sediment of each grain class proportional to the flow split.



Split	Upper	101	Rating Curve
	Junction	Junction	Threshold Flow Wtd

Figure 1-69: Junction options to compute sediment splits.

Modeling Note - Side Channel Filling: Because sediment transport is non-linear (e.g. doubling the flow generally more than doubles the transport) flow splits tend to deposit. In particular, the lower flow channel tends to deposit quickly as the flow weighted sediment partition puts more sediment in the low flow channel relative to the transport than the higher flow channel. These theoretical considerations do translate to the field, as side channels tend to deposit. However, multi-dimensional effects and perched channels tend to keep prototype channels open longer than one-dimensional split flow models. If one channel downstream of a flow split fills unreasonably, consider modeling the flow split without the junction, using single cross sections to capture both channels. Multiple movable bed limits may also be helpful.

Perched distributaries can pose another challenge to modeling flow splits. When the two downstream channels have different thalweg elevations, so most of the bed load follows one of the channels, a flow weighted split may not be appropriate for a perched distributary. Users sometimes model systems like this with lateral weirs (with grain class filters) instead of junctions. However, the current version of HEC-RAS includes grain class-specific flow split methods for junctions as well.Flow Weighted Sediment Split

This is the default calculation at a sediment split. Sediment flux in each reach is proportional to the flow. For example, if 80% of the flow goes into one reach and 20% into another, the sediment flux will have the same 80%/20% split for each grain class. If users do not add the junction to the sediment boundary condition editor, HEC-RAS will automatically split sediment this way. This feature is in the interface to help users toggle between methods and select the default without deleting the junction.

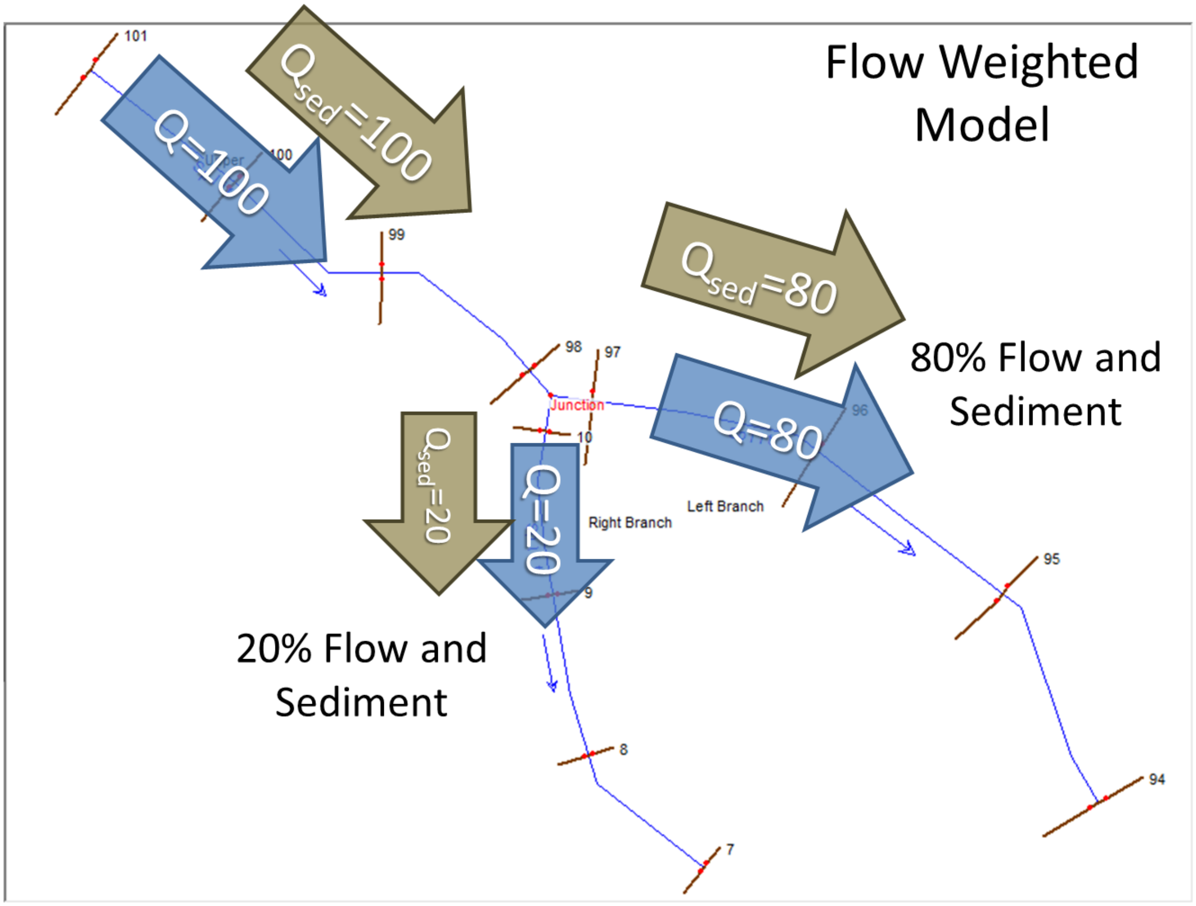


Figure 1-70: The flow-weighted sediment split is the default method for distributing sediment between downstream reaches. It distributes sediment with the same proportion as the flow.

Potential Weighted Sediment Split

Potential Weighted Sed Split

Because sediment transport is non-linear, a distributary with more flow will transport disproportionately more sediment. Therefore, a flow-weighted split tends to overestimate sediment diverted to the lower-flow distributary, which can cause the lower flow reach to deposit quickly.

The potential weighted sediment split addresses this issue, computing the sediment split based on the computed transport potential instead of the flow. Figure 1-71 reproduces the example in Figure 1-70 with a simple transport potential (Gs) equation ($Gs=0.01Q^2$) to illustrate the potential weighted approach.

Because of the non-linearity (i.e. power function) of the sediment transport potential equation, the 80%/20% flow split does not produce the same capacity split. The larger tributary has 94% of the capacity ($Gs=0.001(80)^2=64$~94%) while the smaller tributary only has 6% of the capacity ($Gs=0.001(20)^2=4$~6%).

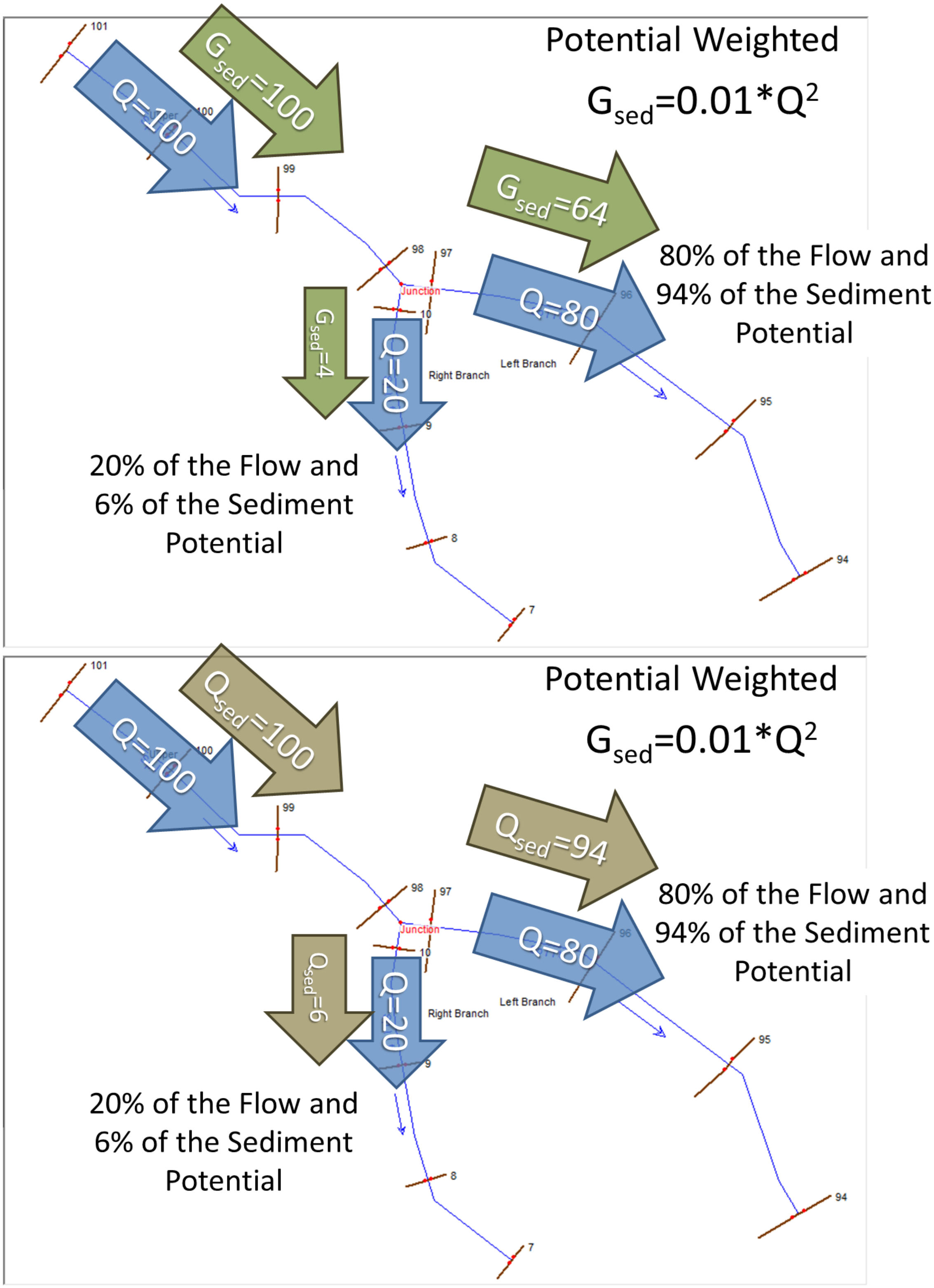


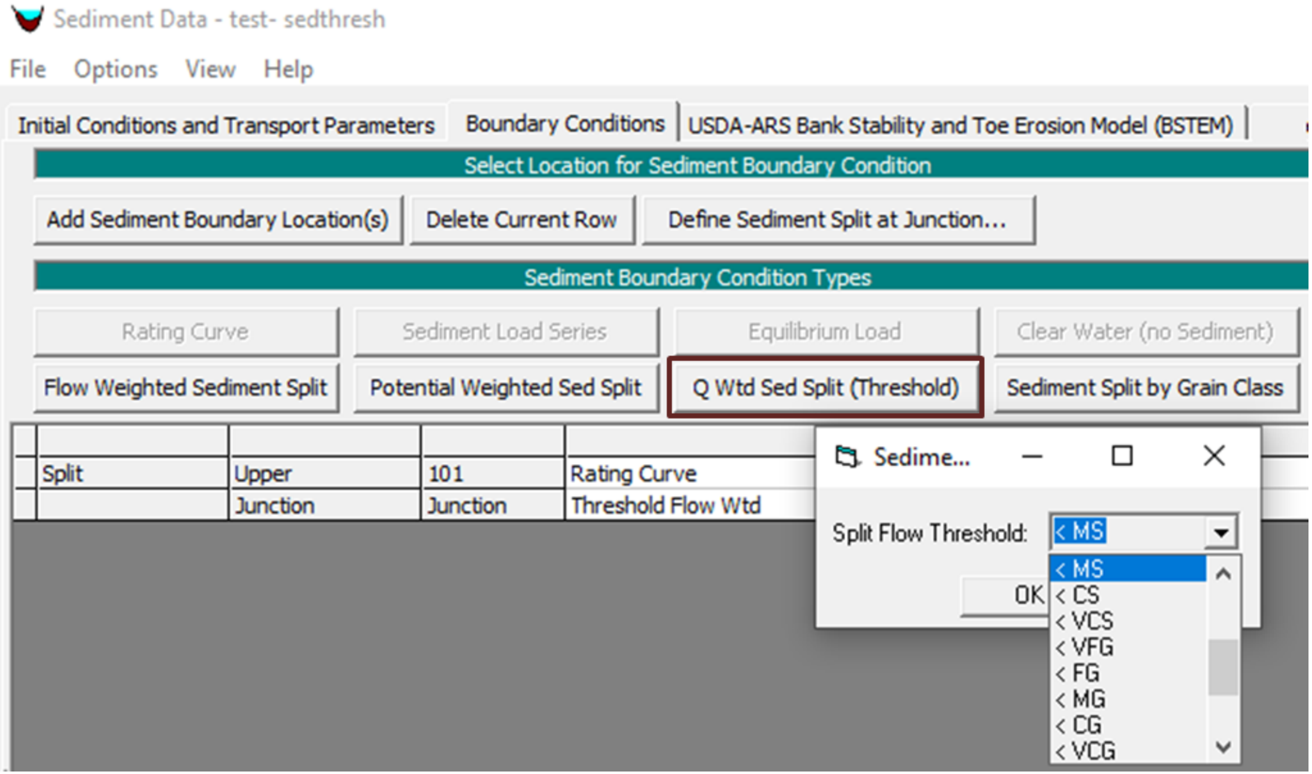
Figure 1-71: Example of a potential weighted sediment split at a junction. HEC-RAS computes the sediment potential (Gs) at each distributary, and the percentage of the total distributary potential represented by that distributary. HEC-RAS then distributes the sediment flux based on the potential, which generally sends more sediment down higher flow reaches than flow-weighting.

The potential weighted split divides sediment based on the percentage of the potential in all downstream reaches, instead of the flow.[7]

Flow Weighted Split with a Grain Class Threshold

This feature works like the grain class threshold option associated with lateral structures. This feature applies a flow weighted split for all grain classes less than a user specified threshold and sends 100% of the sediment greater than that threshold down the main reach (the reach with the same "River" name). This feature is designed to send suspended or wash load into a perched distributary while keeping bed load in the main channel.

HEC-RAS uses the "River" designation to determine the main and secondary channels. HEC-RAS will check the River names downstream of the junction. The reach that has the same river name downstream of the junction is considered the main channel. The threshold keeps the



Split	Upper	101	Rating Curve
	Junction	Junction	Threshold Flow Wtd

Split Flow Threshold: < MS

Figure 1-72: Flow weighted sediment split with a sediment split threshold. HEC-RAS will only send sediment finer than the user specified threshold to the secondary reach.

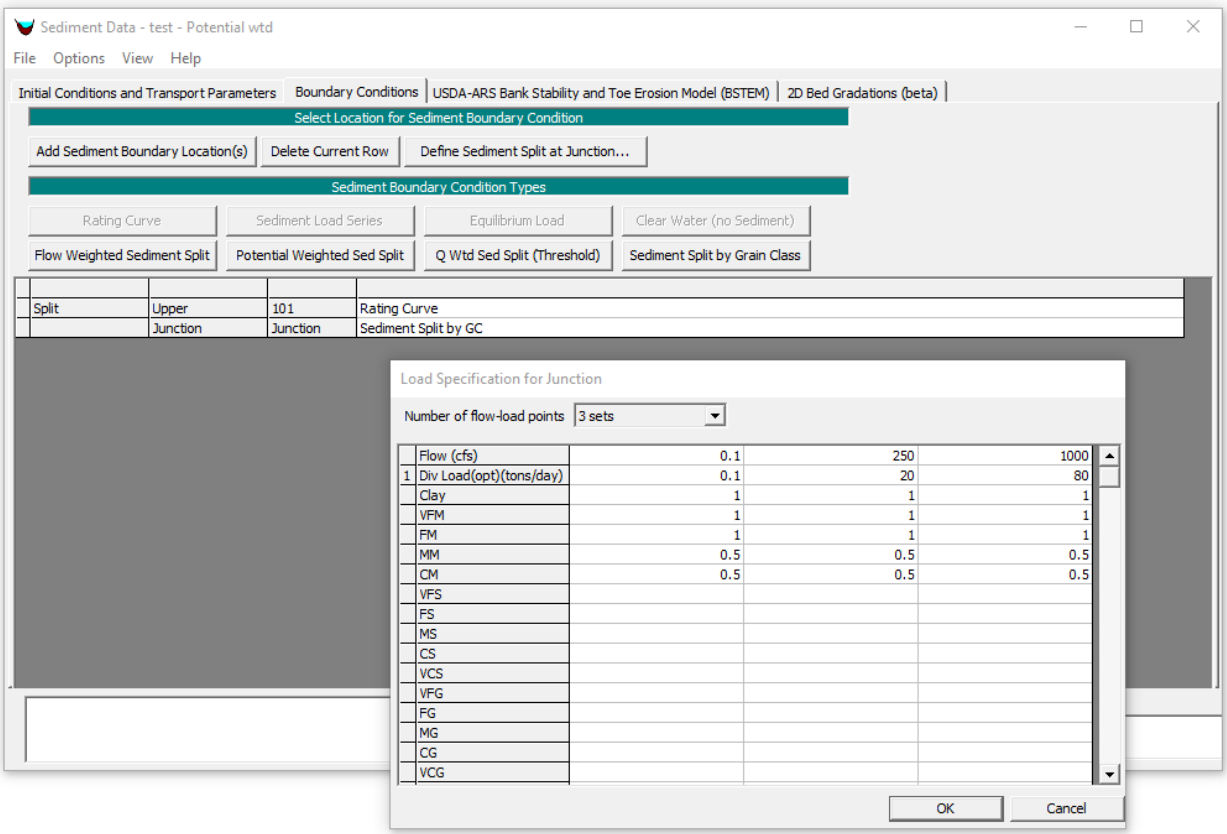
---

[7] Another feature of the non-linear transport equations also emerges from this example. The sum of the potential in the two downstream reaches is less than the potential in the upstream reach (64+4<100). This is a function of the non-linear transport equations and is one of the reasons most sediment models will deposit downstream of a flow split. The combined flow has more transport potential. But splitting the flow based on potential rather than flow can slow this process and make the model more realistic.

Sediment Splits by Grain Class

Sediment Split by Grain Class

This feature works like the diversion rating curve boundary condition. This method monitors the flow leaving the flow split. The user can choose a diverted sediment mass associated with each flow to specify the flow-load split directly. But the load split is optional. Leaving the **Div Load** row blank triggers a standard flow weighted split, and then adjusts each grain class individually from the base flow-weighted assumptions.



Split	Upper	101	Rating Curve
	Junction	Junction	Sediment Split by GC

Number of flow-load points: 3 sets

	Flow (cfs)	0.1	250	1000
1	Div Load(opt)(tons/day)	0.1	20	80
	Clay	1	1	1
	VFM	1	1	1
	FM	1	1	1
	MM	0.5	0.5	0.5
	CM	0.5	0.5	0.5
	VFS			
	FS			
	MS			
	CS			
	VCS			
	VFG			
	FG			
	MG			
	CG			
	VCG			

Figure 1-73: Sediment split efficiency ratio by grain class.

The Sediment Split by Grain Class tool then adjusts the sediment load for each grain class, from the initial value computed from the user specified or flow-weighted load. Specify a multiplier between zero and one to reduce the diverted sediment for each grain class.

For example, defining a factor of 0.5 for Very Fine Sand will half the diverted very fine sand and will send the other half in the main downstream channel. So in the example in the figure, 20 tons per day (combined for all grain classes) would be diverted to the distributary when the distributary flow is 250 cfs *if* the ratio for all grain classes was 1. Clay, very fine silt (MM), and fine silt (FM) will be diverted in their entirety. However, only half the computed medium silt (MM) and coarse silt (CM) fractions will divert, and nothing coarser than coarse silt will be diverted (because the fields are blank, entering zero in these fields would have the same result.

USDA-ARS Bank Stability and Toe Erosion Model (BSTEM)

The BSTEM model in HEC-RAS is not required for a sediment transport model. Even if the user intends to integrate BSTEM results into a mobile bed sediment transport model, it is advisable to build a robust, stable, mobile bed model without the BSTEM data or processes first, and then add the bank process complexity.

The USDA-ARS Bank Stability and Toe Erosion Model (BSTEM) capabilities are complex and have their own parameterization requirements, comparable to the sediment transport features in HEC-RAS (Gibson et al. 2015). These features are included in Chapter 5.

Sediment Properties Options

There are a number of default values used by HEC-RAS that can be changed by the user. To change the defaults, select the various options available from the **Options** menu on the Sediment Data editor. Only make changes to the default settings if it is appropriate for the specific application. A list of the options available follows.

Define Grain Classes and Sediment Properties[8]

Default and User Defined Grain Classes:

HEC-RAS defaults to twenty grain classes that follow the ψ scale (Parkers and Andrews, 1985) for which the grain class boundaries are defined by $D=2^{\psi}$, where ψ includes the integers between -8 and 11. The default grain classes are detailed in Table 1-2.

The user can define a customized set of grain classes in order to focus more detail in a particular size range or model specific grain sizes. Selecting the **User Defined Grain Classes** item on the **Options** menu allows the user to override default HEC-RAS grain classes. This menu option will open the dialog depicted in Figure 1-74. The **User Defined Grain Classes** dialog defaults to the grain classes outlined in Table 1-2, and will write a text line at the bottom of the dialog with a "**Currently Default**" message if this is the case (Figure 1-74).

HEC-RAS must have twenty grain classes, but it will only compute grain classes that exist in the model. HEC-RAS will ignore any grain classes that do not exist in the bed or the boundary conditions. Including fewer grain classes will speed up run times – particularly in the 2D sediment model.

Earlier versions of HEC-RAS required grain classes that are adjacent, increasing, and non-overlapping. Defining adjacent, increasing, non-overlapping grain classes is still usually best practice. Therefore, by default the lower bound of each grain class (except the first one) copies to the upper bound of the previous class. Users edit the grain classes in this mode by changing the upper bounds (labeled max in Figure 1-74). The editor computes

---

[8] This editor combines two different menus in version 5.0.7 and earlier. Because recent versions of HEC-RAS allow users to define sediment properties like density and unit weight by grain class, these properties are included in this editor.

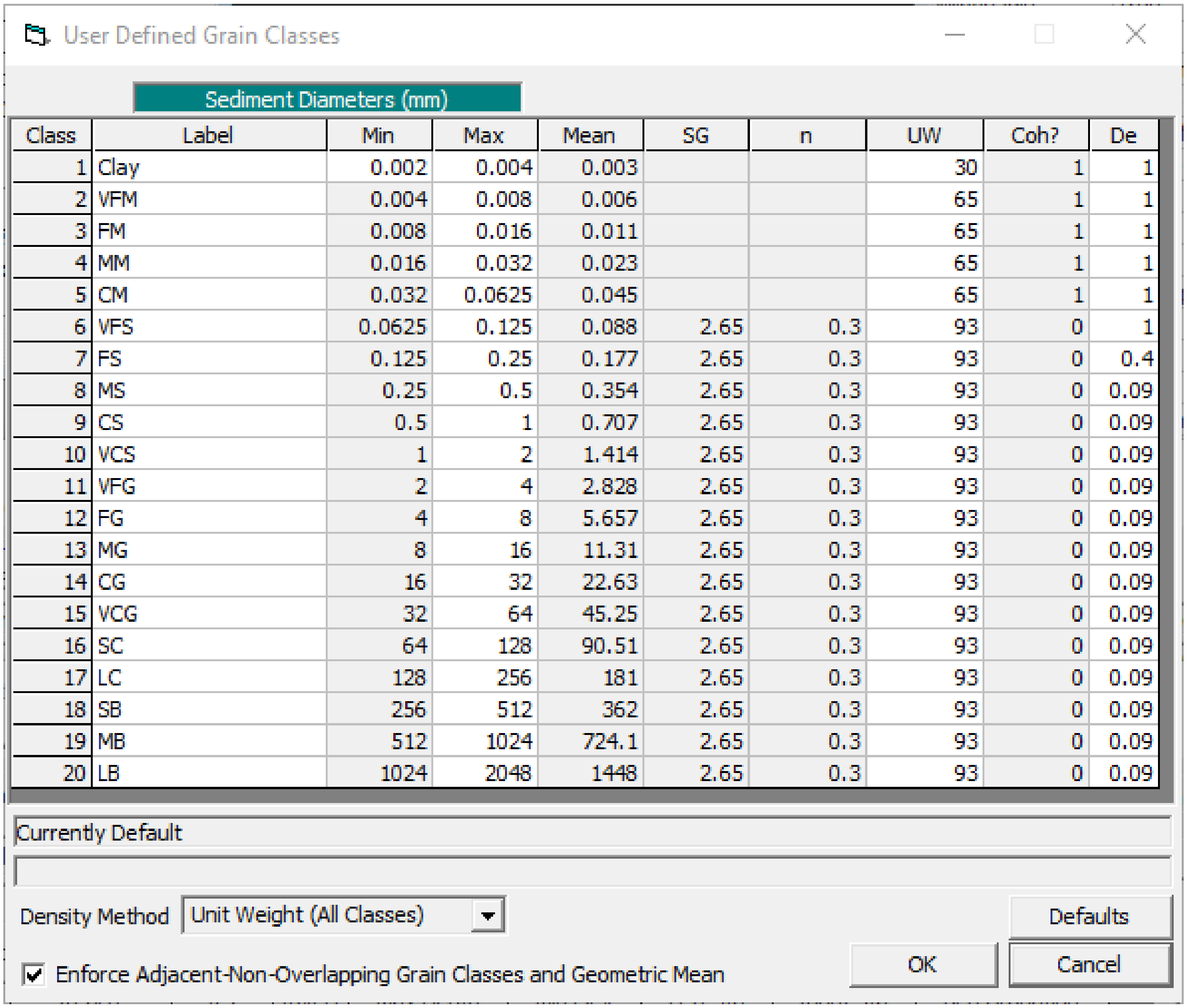
geometric[9] means (which are the actual, representative grain size HEC-RAS uses in the computation) in the **Mean**. If the user changes the grain classes, the dialog will show the "**Currently Customized**" message in the panel below the buttons. Reset to the default parameters by pressing the **Defaults** button.

Table 1-2. Default grain classes in HEC-RAS (mm).

Grain Classes		Lower Bound	Upper Bound	Mean Diameter	Geometric Mean
Clay	Clay	0.002	0.004	0.003	0.00283
Very Fine Silt	VFM	0.004	0.008	0.006	0.00566
Fine Silt	FM	0.008	0.016	0.011	0.0113
Medium Silt	MM	0.016	0.032	0.023	0.0226
Coarse Silt	CM	0.032	0.0625	0.045	0.0447
Very Fine Sand	VFS	0.0625	0.125	0.088	0.0884
Fine Sand	FS	0.125	0.25	0.177	0.177
Medium Sand	MS	0.25	0.5	0.354	0.354
Course Sand	CS	0.5	1	0.707	0.707
Very Course Sand	VCS	1	2	1.41	1.41
Very Fine Gravel	VFG	2	4	2.83	2.83
Fine Gravel	FG	4	8	5.66	5.66
Medium Gravel	MG	8	16	11.3	11.3
Coarse Gravel	CG	16	32	22.6	22.6
Very Coarse Gravel	VCG	32	64	45.3	45.3
Small Cobbles	SC	64	128	90.5	90.5
Large Cobbles	LC	128	256	181	181
Small Boulders	SB	256	512	362	362
Medium Boulders	MB	512	1024	724	724
Large Boulders	LB	1024	2048	1448	1450

---

[9] For a good discussion of why it is appropriate to use the geometric mean $\sqrt{d_{lower\ bound} d_{upper\ bound}}$ as the representative grain class, see Dr Gary Parker's chapter on Graded Sediment Analysis in ASCE Manual 110 *Sedimentation Engineering.*



Sediment Diameters (mm)

Class	Label	Min	Max	Mean	SG	n	UW	Coh?	De
1	Clay	0.002	0.004	0.003			30	1	1
2	VFM	0.004	0.008	0.006			65	1	1
3	FM	0.008	0.016	0.011			65	1	1
4	MM	0.016	0.032	0.023			65	1	1
5	CM	0.032	0.0625	0.045			65	1	1
6	VFS	0.0625	0.125	0.088	2.65	0.3	93	0	1
7	FS	0.125	0.25	0.177	2.65	0.3	93	0	0.4
8	MS	0.25	0.5	0.354	2.65	0.3	93	0	0.09
9	CS	0.5	1	0.707	2.65	0.3	93	0	0.09
10	VCS	1	2	1.414	2.65	0.3	93	0	0.09
11	VFG	2	4	2.828	2.65	0.3	93	0	0.09
12	FG	4	8	5.657	2.65	0.3	93	0	0.09
13	MG	8	16	11.31	2.65	0.3	93	0	0.09
14	CG	16	32	22.63	2.65	0.3	93	0	0.09
15	VCG	32	64	45.25	2.65	0.3	93	0	0.09
16	SC	64	128	90.51	2.65	0.3	93	0	0.09
17	LC	128	256	181	2.65	0.3	93	0	0.09
18	SB	256	512	362	2.65	0.3	93	0	0.09
19	MB	512	1024	724.1	2.65	0.3	93	0	0.09
20	LB	1024	2048	1448	2.65	0.3	93	0	0.09

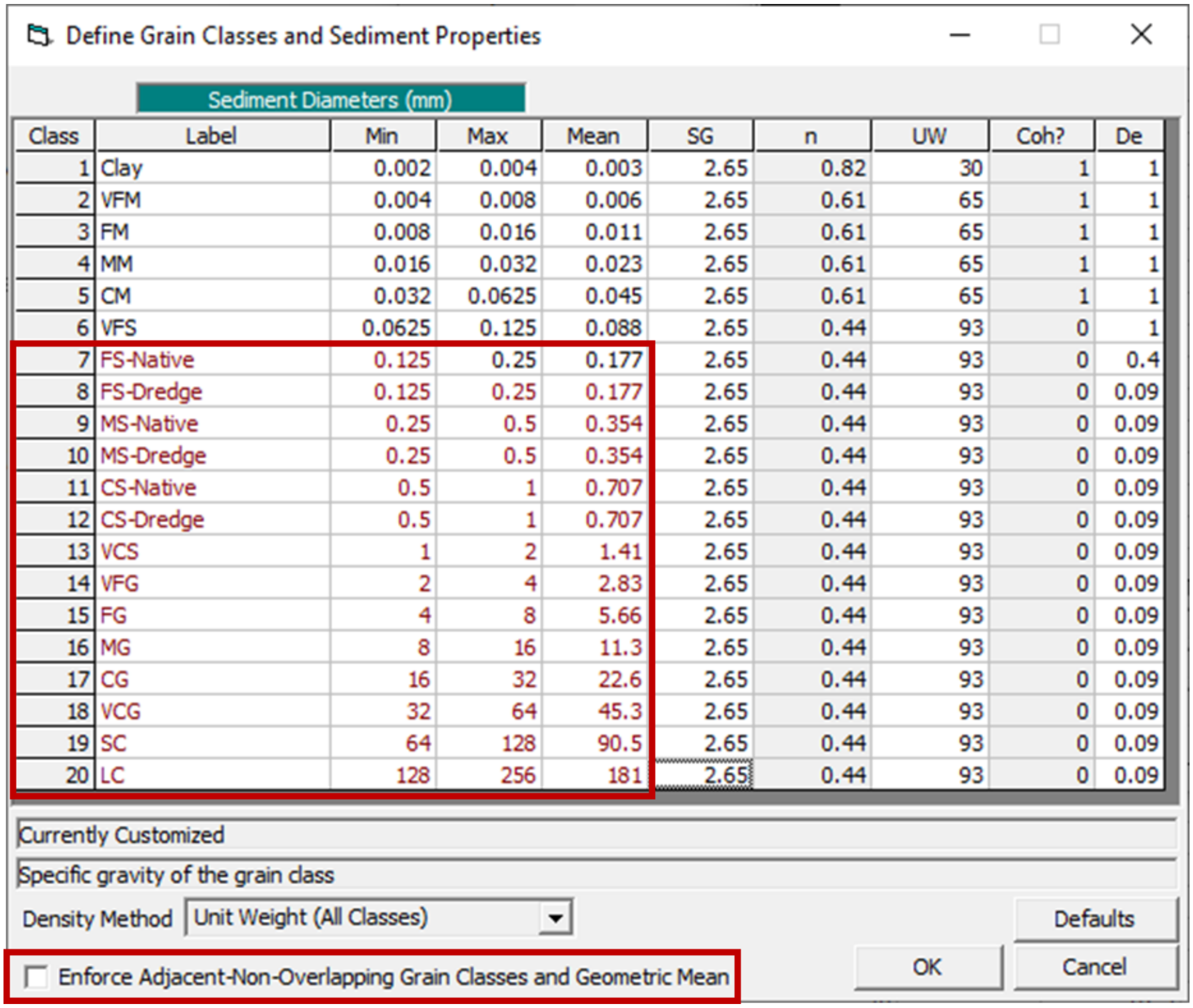
Currently Default

Density Method: Unit Weight (All Classes)

☑ Enforce Adjacent-Non-Overlapping Grain Classes and Geometric Mean

Figure 1-74. User defined grain classes dialog, default on the left and example customized grain classes, with clay and fine sand subdivided, on the right.

Current versions of HEC-RAS make the grain classes more flexible. Uncheck the **Enforce Adjacent-Non-Overlapping Grain Classes and Geometric Mean** box. This removes the interface control that enforces these constraints and allows users to edit the first four columns of this editor without limitation. In most cases, the adjacent, increasing, non-overlapping constraint is appropriate, and violating it can cause problems in the mixing algorithms (see Warning below). HEC-RAS also stops computing the geometric mean of the grain class if this feature is disengaged, so users will have to compute and enter their own representative grain class for edited grain classes. But this feature does allow users to generate duplicate grain classes of the same size class if they want to keep track of one of them.



Define Grain Classes and Sediment Properties

		Sediment Diameters (mm)							
Class	Label	Min	Max	Mean	SG	n	UW	Coh?	De
1	Clay	0.002	0.004	0.003	2.65	0.82	30	1	1
2	VFM	0.004	0.008	0.006	2.65	0.61	65	1	1
3	FM	0.008	0.016	0.011	2.65	0.61	65	1	1
4	MM	0.016	0.032	0.023	2.65	0.61	65	1	1
5	CM	0.032	0.0625	0.045	2.65	0.61	65	1	1
6	VFS	0.0625	0.125	0.088	2.65	0.44	93	0	1
7	FS-Native	0.125	0.25	0.177	2.65	0.44	93	0	0.4
8	FS-Dredge	0.125	0.25	0.177	2.65	0.44	93	0	0.09
9	MS-Native	0.25	0.5	0.354	2.65	0.44	93	0	0.09
10	MS-Dredge	0.25	0.5	0.354	2.65	0.44	93	0	0.09
11	CS-Native	0.5	1	0.707	2.65	0.44	93	0	0.09
12	CS-Dredge	0.5	1	0.707	2.65	0.44	93	0	0.09
13	VCS	1	2	1.41	2.65	0.44	93	0	0.09
14	VFG	2	4	2.83	2.65	0.44	93	0	0.09
15	FG	4	8	5.66	2.65	0.44	93	0	0.09
16	MG	8	16	11.3	2.65	0.44	93	0	0.09
17	CG	16	32	22.6	2.65	0.44	93	0	0.09
18	VCG	32	64	45.3	2.65	0.44	93	0	0.09
19	SC	64	128	90.5	2.65	0.44	93	0	0.09
20	LC	128	256	181	2.65	0.44	93	0	0.09

Currently Customized

Specific gravity of the grain class

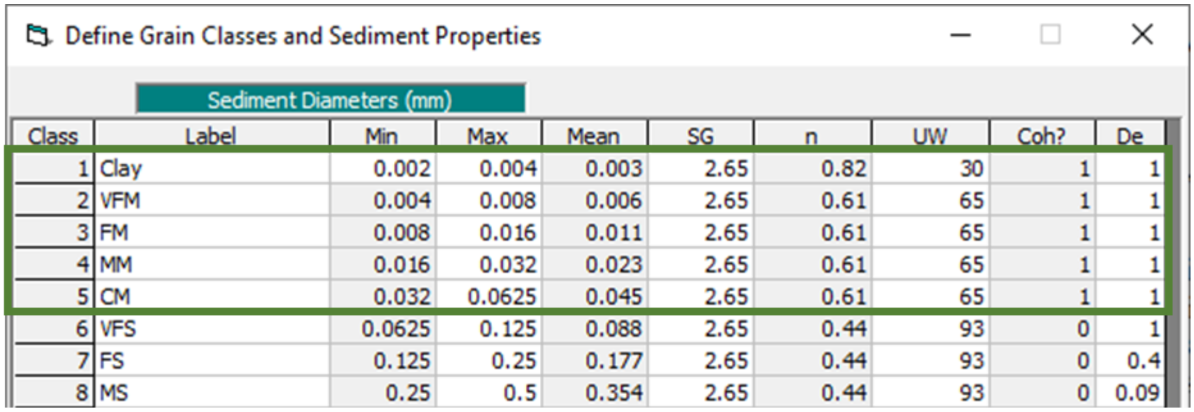
Density Method: Unit Weight (All Classes)

☐ Enforce Adjacent-Non-Overlapping Grain Classes and Geometric Mean

Figure 1-75: User defined grain classes with duplicate grain classes. Representative grain classes must be set to the new geometric mean manually. HEC-RAS does not compute these in when the enforce adjacent-non-overlapping mode is off.

Warning – Impact of Grain Class Order on Sorting Algorithms: The Thomas and Copeland sorting and mixing algorithms compute armoring based on the prevalence of coarser grain classes. These algorithms compute how much of each grain class the flow field has access to based on how much of the cover layer is composed of coarser particles. It identifies "coarser particles" as those particles in larger grain classes. Therefore, duplicate particles (or finer particles) in coarser (higher **Class** number) grain classes will artificially limit erosion in these algorithms. The representative grain size should never decrease as the grain class number increases.

Modeling Note – Limit the First Five Grain Classes to Fine Sediment: While grain classes are flexible the first five grain classes are considered 'cohesive' regardless of their size. The cohesive algorithms and parameters selected in the **Cohesive Options** will be applied to these grain classes. The **Unit Weight** and **Densities** in the **Sediment Properties Editor** tie unit weight to these grain classes. Additionally, mixing and armoring algorithms in both the main sediment model and BSTEM compute a "% cohesive" and take different approaches based on the percentage of the bed material in the first five grain classes. Therefore, when defining new grain classes, reserve the first five for materials that behave like cohesives and constrain cohesive materials (e.g. that will deposit and scour according to Krone and Partheniades methods) to these first five grain classes. (Note: Future versions will use the **Coh?** Column to control this behavior, but current and past versions assume these grain classes – and only these grain classes – are cohesive).



Class	Label	Min	Max	Mean	SG	n	UW	Coh?	De
1	Clay	0.002	0.004	0.003	2.65	0.82	30	1	1
2	VFM	0.004	0.008	0.006	2.65	0.61	65	1	1
3	FM	0.008	0.016	0.011	2.65	0.61	65	1	1
4	MM	0.016	0.032	0.023	2.65	0.61	65	1	1
5	CM	0.032	0.0625	0.045	2.65	0.61	65	1	1
6	VFS	0.0625	0.125	0.088	2.65	0.44	93	0	1
7	FS	0.125	0.25	0.177	2.65	0.44	93	0	0.4
8	MS	0.25	0.5	0.354	2.65	0.44	93	0	0.09

First five grain classes are always "cohesive" (e.g. they use the cohesive algorithms regardless of user specified grain size)

Specific Gravity, Porosity, and Unit Weight

Specific Gravity: The default specific gravity for all sediment particles is 2.65. While generally appropriate, this assumption is not universally valid. Users can change this value, but the current version of HEC-RAS only applies one specific gravity to all grain classes throughout the model. The grain class-specific specific gravity option is included for 2D sediment transport which has variable density algorithms.

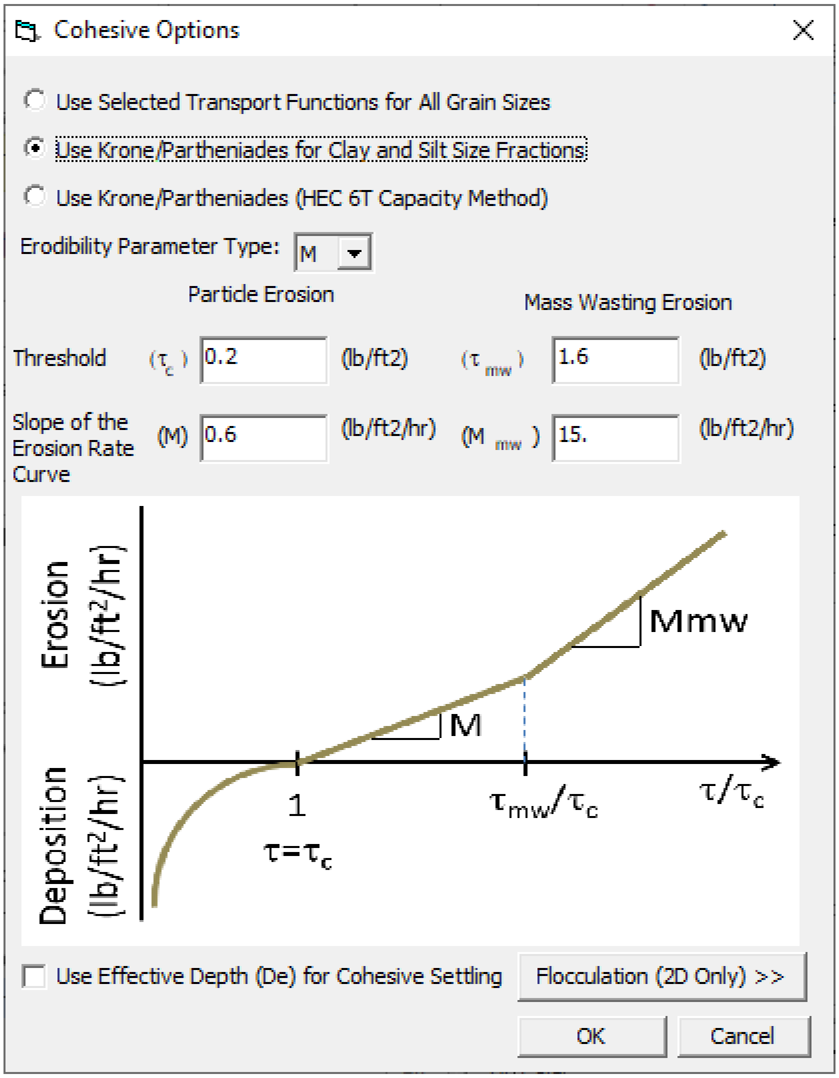
Unit Weight/Density: Sediment unit weights or densities are used to convert deposited or eroded masses into volumes that translate into bed elevation changes. This is one of the only parameters that is different for SI and US customary units. US customary is defined in terms of unit weights (lb/ft^3) while SI is defined in terms of density (kg/m^3). HEC-RAS converts between density and unit weight internally. Clay (grain class 1), silt (grain classes 2-5) and sand/gravel (grain classes 6-20) each have distinct, default grain classes.

Modeling Note – Cohesive unit weight/density: Cohesive unit weight can vary substantially between systems and even within the same reservoir (e.g. deeper consolidated clays are often consolidated and much denser than surficial deposits). HEC-RAS adopted defaults from HEC 6 but are on the low end of the range, representing 'fluffy,' reservoir deposits. When calibrating a depositional cohesive model to volume change computed from repeated cross sections, cohesive density will be a very sensitive parameter. If you are over-predicting cohesive deposition, consider the applicability of this parameter.

Cohesive Options

Cohesive methods and parameters can be specified by selecting **Set Cohesive Options** under the Options Menu. The method selected will be applied to the first five grain classes (GC 1-5) which are silts and clays in the default grain classes (but will apply to the first five grain classes regardless of size if the user edits them).

HEC-RAS can either compute fine particle transport with the standard transport capacity approach - using the selected transport function to extrapolate transport potential for the silt and clay grain classes outside of the developed range of these equations, or with the Krone and Partheniades equations.



Cohesive Options

○ Use Selected Transport Functions for All Grain Sizes

● Use Krone/Partheniades for Clay and Silt Size Fractions

○ Use Krone/Partheniades (HEC 6T Capacity Method)

Erodibility Parameter Type: M

	Particle Erosion			Mass Wasting Erosion	
Threshold	(τ_c)	0.2	(lb/ft2)	(τ_{mw})	1.6	(lb/ft2)
Slope of the Erosion Rate Curve	(M)	0.6	(lb/ft2/hr)	(M_{mw})	15.	(lb/ft2/hr)

☐ Use Effective Depth (De) for Cohesive Settling

Figure 1-76. Cohesive options editor.

HEC-RAS includes two versions of the Krone and Parthinades equations, the HEC-RAS method from previous versions and the HEC 6T method. See the Technical Reference Manual for formulations of Krone and Partheniades as well as a description of the difference between HEC-RAS and HEC 6T methods. Both use the thresholds and slopes, computing erosion rates in the same way. However, once erosion rates are computed, the methods apply them to the multi-grain class bed materials differently. The methods have several differences, but mostly the HEC-RAS method distributes the erosion rate over all grain classes while the HEC 6T applies it to each (after reducing it based on inflowing load). The HEC 6T method generally computes more erosion.

Method

HEC-RAS includes three methods for modeling cohesive transport. Modelers should be aware that ***The Default Method is Not Recommended***. Cohesive transport should be parameterized using the Krone and Partheniades approaches, especially if the system erodes cohesive materials.

Modeling Note – Parameterizing Cohesive Transport: Cohesive transport parameters can be difficult or expensive to collect, but are also highly variable (spanning at least five orders of magnitude) and site specific. They should either be measured with a SedFlume (Briaud, 2008; USACE, 2012) or similar apparatus or jet tests in the field or should be the primary calibration parameter. SEDFLUME analyses are available at the US Army Corps of Engineers Engineering Research and Development Center (ERDC-CHL, formerly WES) or at a handful of universities. ERDC-CHL can also conduct jet tests as well as the USDA-Agricultural Research Station and several universities, districts and contractors. See the Cohesive Parameter Estimation section of the Technical Reference Manual for more information on this and some example data.

Modeling Note – Bed-Material Load Modeling Option: If the fine sediment in your model is just washload, and is not interacting with the bed, it may be appropriate to ignore it, and remove it from the model. Removing wash load from your model avoids the uncertainty and numerical artifacts of transporting fine sediment with transport functions developed for cohesionless sediment and avoids the requirement to

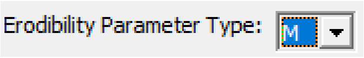
Alternately, setting the erosion threshold low enough that wash load remains in suspension is another approach to keeping wash load in your model, without detailed cohesive sediment data. However, if the objective of the model includes cohesive erosion, these parameters must be measured and/or calibrated.

Erodibility Parameter Type:

There are two forms of the excess shear equation: the dimensional equation (*Kd*) and dimensionless equation (*M*). The erodibility parameters in these equations are not equivalent and have different units. They are related to each other by the critical shear stress:

$$M = K_d \tau_c$$

See the *M-Kd* Section of the Technical reference manual for more discussion of these two equations. But the critical consideration is that users must make sure they understand which form their data are in. Selecting the appropriate Erodibility Parameter Type:



Erodibility Parameter Type: M

Will change the units in the interface and align your data with the correct form of the equation.

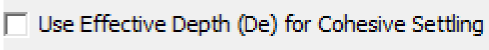
Modeling Note – Linear Erosion Model: HEC-RAS requires all four parameters, even if your erodibility data suggests a linear model (e.g. only one Erodibility slope). To simulate a linear shear-erosion rate relationship, make the two erosion rates the same and/or set the mass wasting threshold stress much higher than the shear stresses in the simulation.

Modeling Note – Reservoir Cohesive Deposition: Despite the volume default effects described in the previous note, HEC-RAS under predicts cohesive deposition – particularly in reservoirs - more often. There are several reasons for this.

1. The Continuity (Exner) equation is just a mass balance model and does not track longitudinal transport physically, like the Advection-Diffusion approach. If the control volume depth is large relative to the distance between cross sections (e.g. the sediment Courant condition is <<1), the Exner equation will not compute enough residence time to compute appropriate deposition with fall velocity-based approaches. Always use the **Limit to Water Velocity** method, (**Sediment Data→Options →Transport Methods: 1D Routing Method**) when simulating reservoirs or other low Velocity depositional zones:

   
   1D Routing Method: Limit to Water Velocity

2. HEC-RAS fully mixes sediment vertically at the beginning of every time step, forcing the sediment to settle out of the whole water column. In a reservoir with high residence time, the center of mass of the cohesives may drop below the center of mass of the water over time (and space). HEC-RAS 6.0 gives users some opportunity to influence the vertical mixing of each cohesive grain class vertically, by extending the effective depth to the cohesive deposition equation ☐ Use Effective Depth (De) for Cohesive Settling, but it is still a limitation of the model.

3. Aggregates and flocculation – Cohesive sediment often transports in aggregates or flocs – which are clusters of combined cohesive particles. These behave like larger particles, with higher fall velocities, and deposit more quickly (giving reservoirs higher trap efficiencies for aggregate cohesives or estuaries higher trap efficiencies for flocs)

Therefore, it is often appropriate to “coarse” the fines in the boundary load gradation to offset these biases and calculate more cohesive deposition during the calibration process if HEC-RAS is under predicting compared to the prototype.

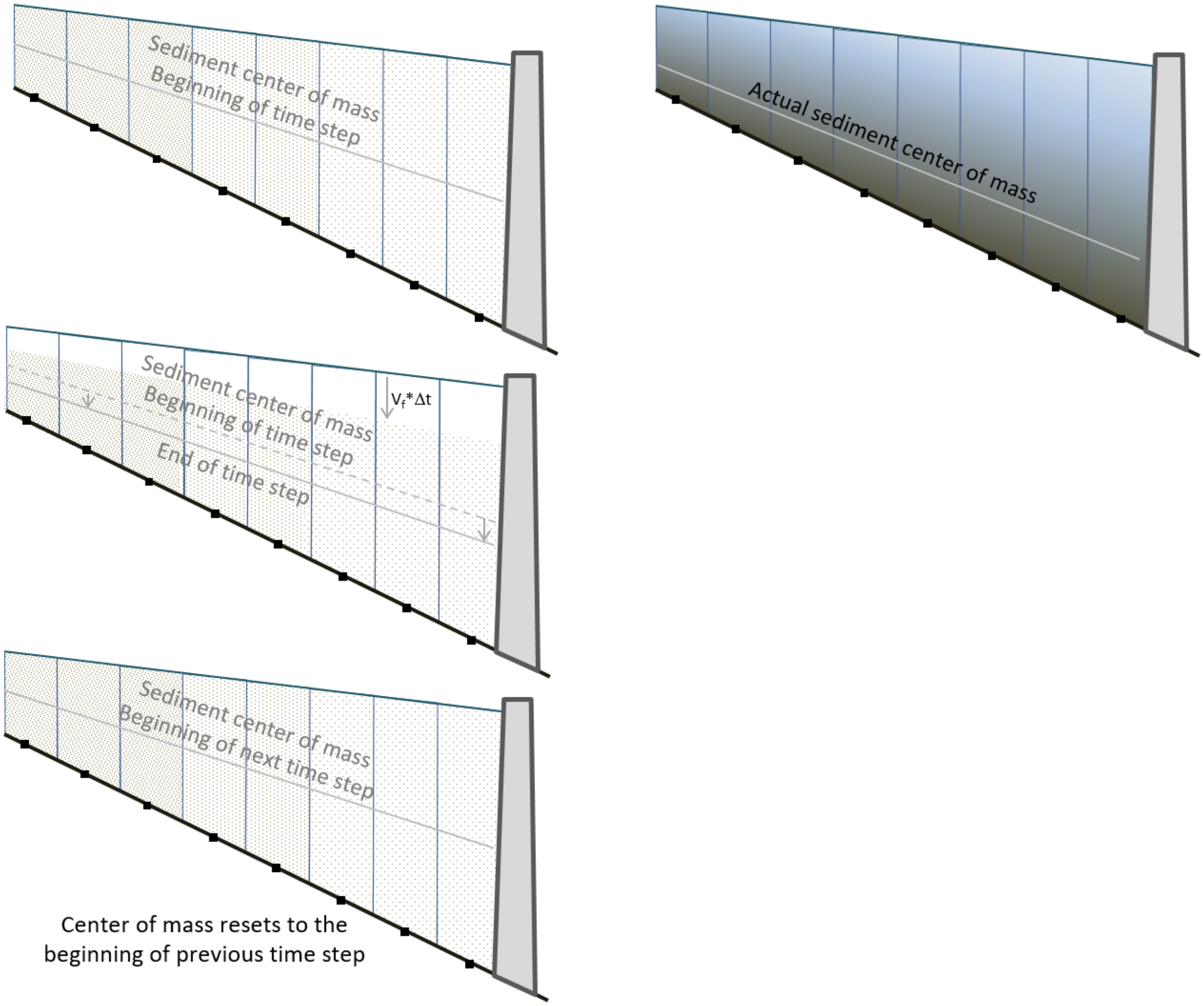
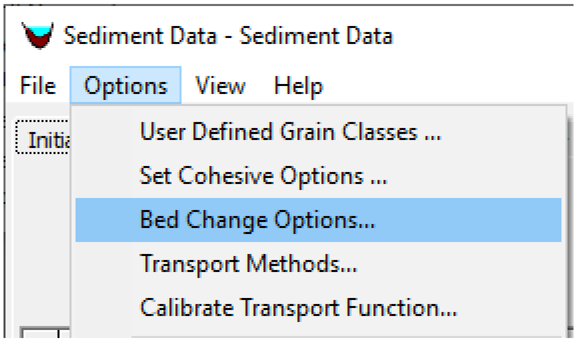


Figure 1-77: Vertically mixing the cohesive distribution each time step can cause the model to under predict deposition because the sediment has to fall farther than the prototype, where the center of mass of the sediment falls over time (and longitudinally). From Gibson et al, 2020 (Supplemental Materials).

Bed Change Options

The **Bed Change** interface in 1D sediment transport changed substantially in version 6.0. Earlier versions had three, global, options. Current versions allow users to select the bed change process for erosion and deposition for the channel and floodplain respectively. To select **Bed Change Options** select the **Options→Bed Change Options** menu in the **Sediment Data** editor.

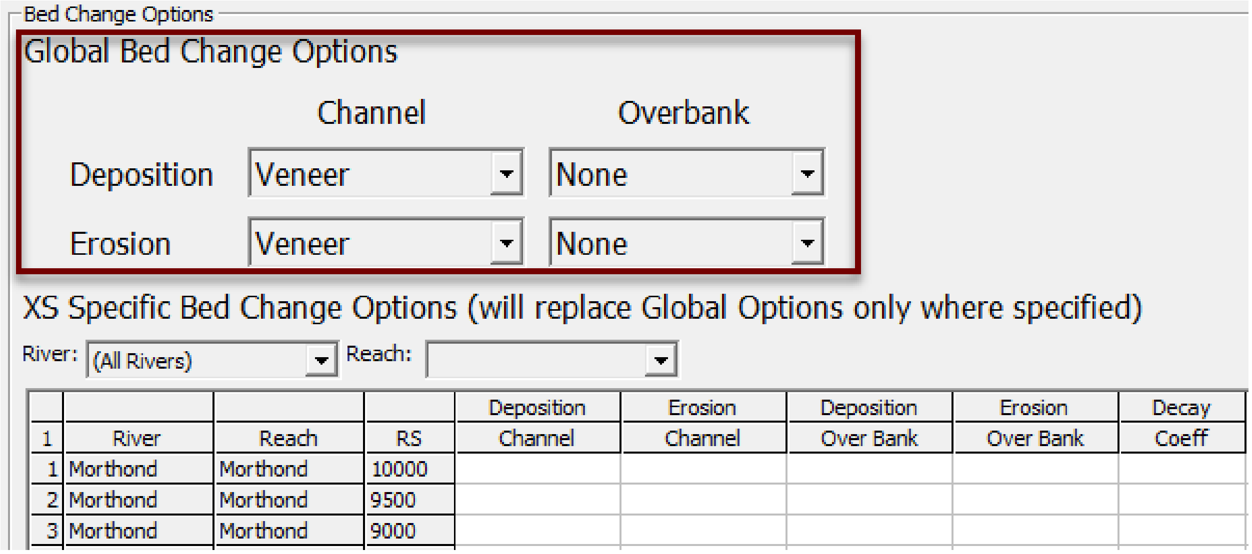
The 1D bed change methods are relatively simple. They are easy to understand. However, selecting the right bed change approach can be one of the most sensitive and difficult parts of 1D sediment modeling. The 1D bed change algorithms often attempt to simplify laterally heterogeneous processes into cross-section averaged behavior. These assumptions can lead to numerical artifacts and unintended consequence. Modelers must select their bed change model carefully and experiment with their sensitivity, to select the one that introduces the least error.



Selecting a Modular, Global Bed Change Method

The default approach to bed change in 1D sediment transport is always the "veneer method." The veneer method adjusts each wet, movable node the same vertical distance to deposit or erode the computed mass at each cross section.[10] But the new editor gives users more flexibility to mix-and-match appropriate bed change methods in the channel and floodplains.

The **Global Bed Change Editor** allows user to select a bed change method in a 2X2 matrix, making selections by process (erosion or deposition) and location (channel and overbank).



Global Bed Change Options

	Channel	Overbank
Deposition	Veneer	None
Erosion	Veneer	None

XS Specific Bed Change Options (will replace Global Options only where specified)

River: (All Rivers) Reach:

				Deposition	Erosion	Deposition	Erosion	Decay
1	River	Reach	RS	Channel	Channel	Over Bank	Over Bank	Coeff
1	Morthond	Morthond	10000					
2	Morthond	Morthond	9500					
3	Morthond	Morthond	9000					

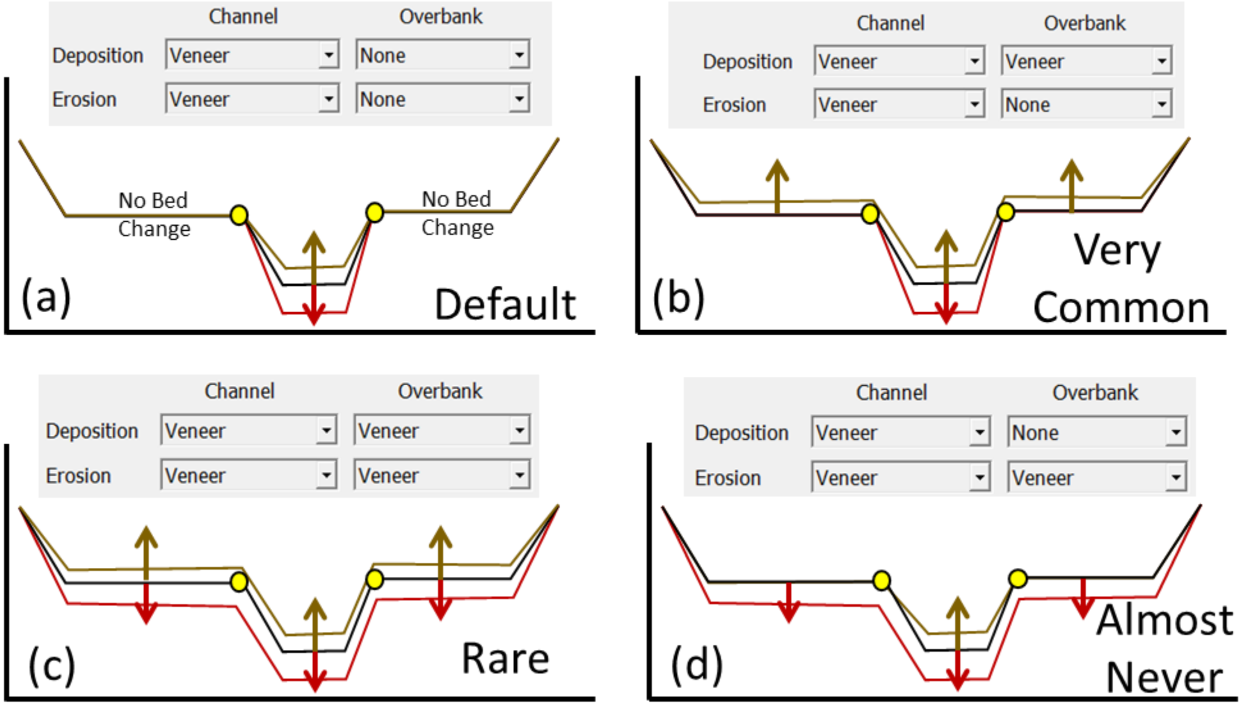
Warning – Bed Change Channel and Overbank based on Movable Bed Limits: "Channel" and "Overbank" in these methods are determined by ***Movable Bed Limits*** NOT Bank Stations. In most places in HEC-RAS, the bank stations mark the transition between the channel and the overbank of floodplain. That is also true in the sediment model, where transport capacity is based on the results from the *hydraulic* channel (the portion of the model between the hydraulic bank

---

[10] The veneer method is sometimes - colloquially - called the "peanut butter method" because it is like trying to spread a uniform layer of sediment across all of the movable cross-section points.

stations). But in the bed change options, the channel and the overbanks transition at the *Movable Bed Limits*.

HEC-RAS requires erosion and deposition in the channel. But users can select erosion and/or deposition in the overbank. This gives users four possible permutations of channel-overbank processes. These four options are illustrated in the figure below (in order of how often they are used).



	Channel	Overbank
Deposition	Veneer	None
Erosion	Veneer	None

	Channel	Overbank
Deposition	Veneer	Veneer
Erosion	Veneer	None

	Channel	Overbank
Deposition	Veneer	Veneer
Erosion	Veneer	Veneer

	Channel	Overbank
Deposition	Veneer	None
Erosion	Veneer	Veneer

Figure 1-78: The four possible permutations of erosion and deposition in the channel and overbanks or floodplains.

These permutations include:

a) Deposition and Erosion in the Channel and no bed change in the overbanks. This is the default approach. The name of the "movable bed limits" suggests this approach. The channel can move within the movable bed limits but not outside of them. However, if the prototype deposits significant sediment outside of the channel, this method can overpredict channel deposition. It can even lead to the Unrealistic Vertical Adjustment or "Channel Filled with Sediment" Errors, that can crash the sediment model. It can also lead to a perched channel or an inverted channel (as depicted in the figure below). Therefore, option (b) in the figure above (and described below) is very common.

b) If the modeled system deposits in the floodplain, it can be useful for the model to deposit in the floodplain. Floodplain flows can carry (usually fine) sediment and deposit, but rarely scour across the cross section. So the most common alternative **Bed Change Method** is option (b) in the figure above, allowing deposition in the overbank, but not erosion. This approach may, actually, be the appropriate method in more models than the default.

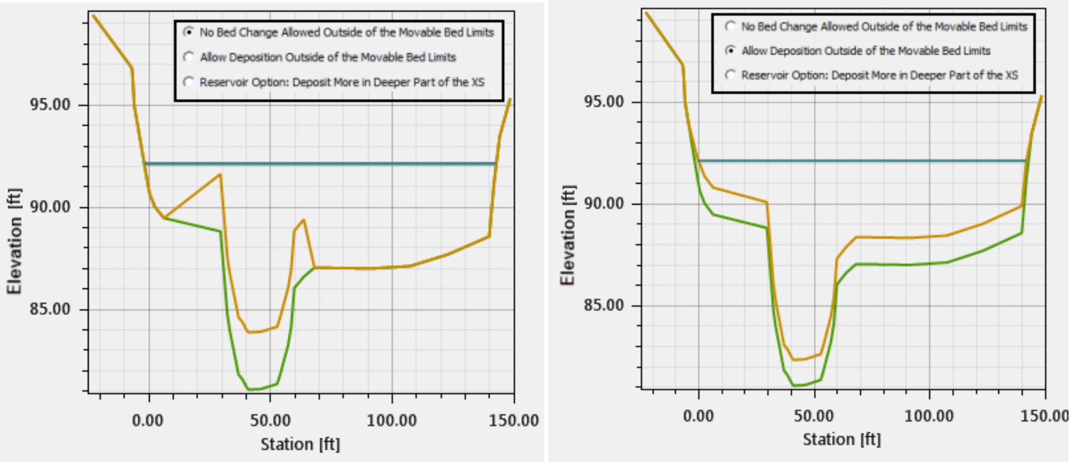


Figure 1-79: Deposition with the default method, which confines deposition to movable bed limits (Left) and the method that allows deposition outside the movable bed limits (right).

Modeling Note: The Overbank Deposition method tends to over-predict overbank deposition: While method (a) over predicts channel deposition and under predicts floodplain deposition. Method (b) tends to over-predict overbank deposition (which can lead to artificial channel erosion). There are a couple reasons that the overbank deposition algorithms over predict floodplain deposition. First, method (b) does not account for floodplain scour mechanism. Second, if the time step is too large, the algorithms do not account for the loss of floodplain conveyance quickly enough (see next Modeling Note).

But, by far the most important reason that the 1D model overpredicts overbank deposition is the 1D gradation assumption. HEC-RAS extends the active layer gradation to the entire mobile, wet, portion of the bed the material it erodes or deposits in the channel has the same gradation as the floodplain. Therefore, the 1D assumptions tend to deposit coarser sediment in the numerical flood plain than the prototype.

HEC is working on algorithms that limit overbank deposition to the finer grain classes that actually reach the floodplain. But a 2D model is often a more appropriate tool to quantify floodplain sediment dynamics.[11] However, if the study only needs to approximate floodplain deposition as a sediment sink for a reginal model, modelers have two options. They can test the sensitivity of methods (a) and (b) above and determine if the under-prediction of method (a) or the overprediction of method (b) introduce more error. Or, they can compute floodplain deposition externally, truncate the cross section or select method (a) above, and remove the floodplain deposits in the appropriate grain classes with a *negative* load boundary condition.

c) The current version of HEC-RAS allows deposition and erosion in the overbanks as well. This would be similar setting – in some ways[12] – to setting the movable bed

---

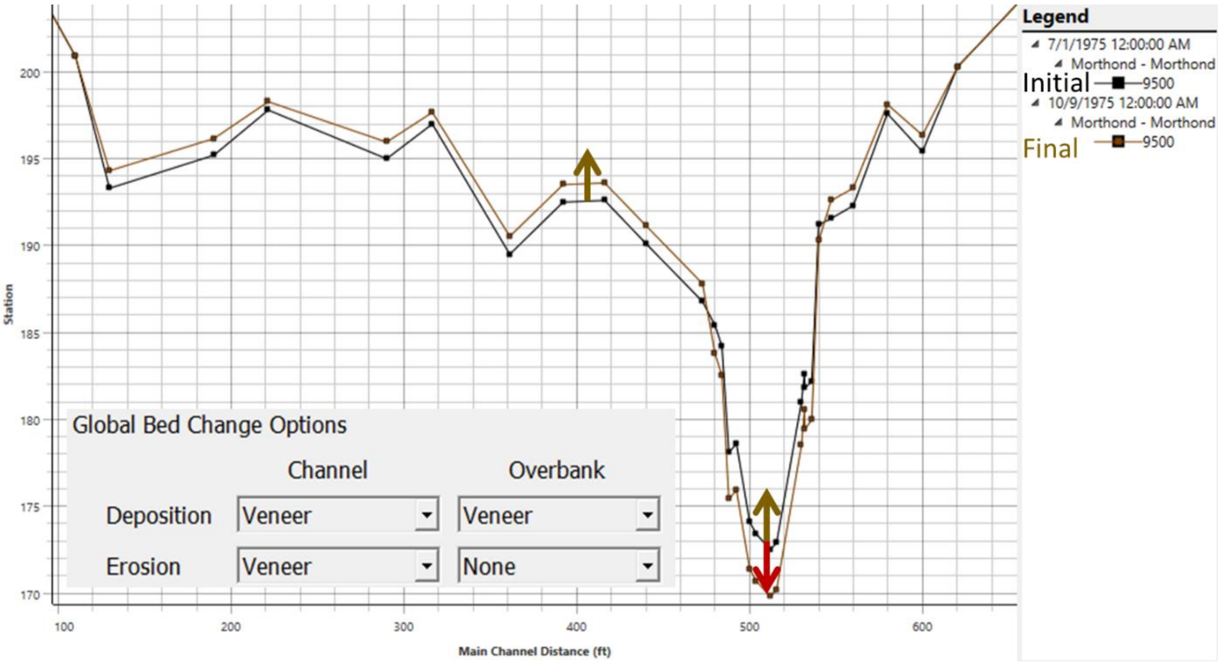
[11] Though 2D models also can have trouble differentiating between grain classes that should transfer to floodplain cells or nodes in most schemes. Carefully assess 2D floodplain deposition results.

[12] Several transport functions multiply unit transport (e.g. flux/width) times a channel width ("B") which is the wet top width within the movable bed limits. So allowing deposition and erosion outside

limits to the edge of the cross section. Floodplain erosion – where it happens – is usually localized or channelized. The veneer method is rarely an appropriate modeling approach. So this method should be used with caution, and should be carefully justified with field observations in the model documentation.

d) The modular approach to bed change allows users to select floodplain erosion and exclude floodplain deposition. This is not a standard morphological process and is almost never appropriate.

The figure below includes results from the overbank deposition method.



Global Bed Change Options

	Channel	Overbank
Deposition	Veneer	Veneer
Erosion	Veneer	None

Figure 1-80: Sample data set with the two most common modeling approaches.

Modeling Note – Floodplain Deposition-Channel Erosion: Even though the 1D model assumes cross-sectional average bed change, the veneer method sometimes computes different bed change trends in different parts of the cross section. The most common example of this is depicted in the overbank deposition example above. If the flow-load relationship makes high flows depositional and low flows erosional, HEC-RAS can compute channel erosion and overbank deposition. Gibson and Nelson (2010)[13] explain how this works. This phenomenon can be a numerical artifact. But it is also an observed process in some systems. **Error! Reference source not found.** (USACE, 2012) includes an example where both the 1D model and the prototype deposited in the floodplain and eroded in the channel.

---

the movable bed limits would maintain this transportable width for the transport function, while changing the bed at all active, wet, nodes. Modelers must carefully weigh these options to decide which is the most appropriate.

[13] Gibson, S. and Nelson, A. (2016) Modeling differential lateral bed change with a simple veneer method in a one-dimensional sediment transport model, River Flow 2016, International Conference on Fluvial Hydraulics.

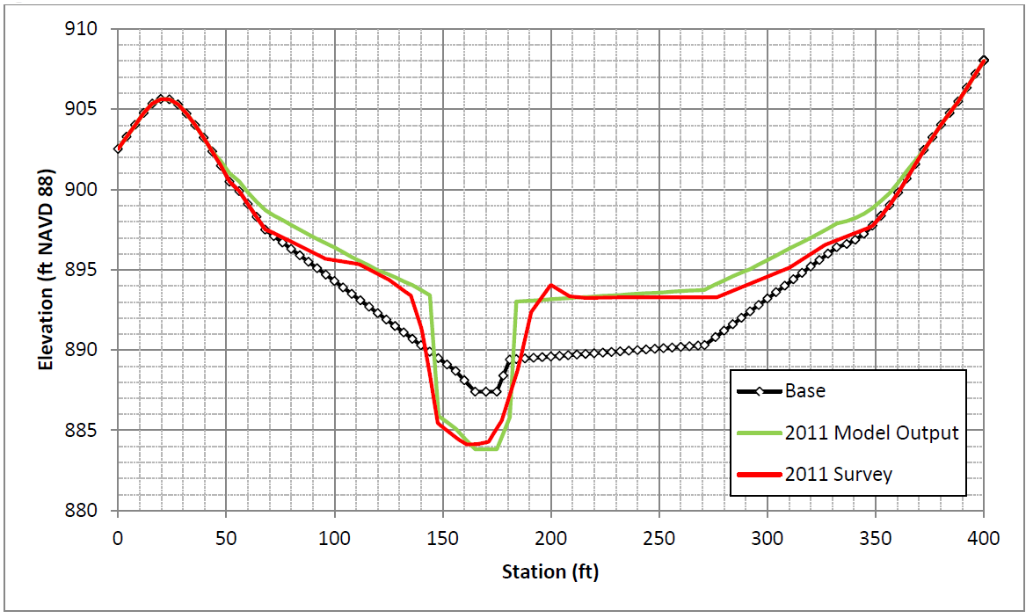
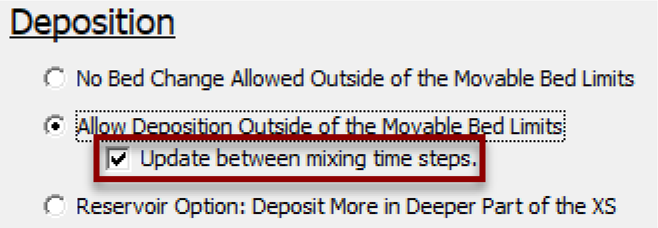


Figure 1-81: Starting and final cross sections in the field and in HEC-RAS model of the Fargo diversion. The model allowed deposition in the overbanks, scouring at low flows, depositing at high flows, simulating overbank deposition and channel erosion with the 1D veneer method (USACE, 2012).

Modeling Note: Optional Overbank Deposition Method in version 5.0.7 is mandatory in 6.0 and later: Versions of HEC-RAS late in the 5.0.x series added a new way to compute overbank deposition, that calculated deposition during each mixing time step, rather than once for the entire computation increment. This method improved results with no known liabilities. Therefore, HEC not only made this method default in version 6.0 but made it mandatory. This may change model results but will improve model performance.



Deposition

○ No Bed Change Allowed Outside of the Movable Bed Limits

● Allow Deposition Outside of the Movable Bed Limits

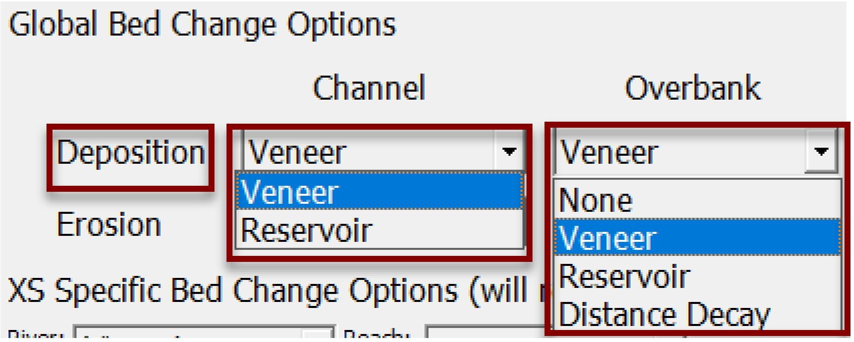
☑ Update between mixing time steps.

○ Reservoir Option: Deposit More in Deeper Part of the XS

Figure 1-82: Overbank deposition option in HEC-RAS 5.0.7 that became default and mandatory in subsequent versions.

Alternate Channel Deposition Methods

By default, HEC-RAS changes cross sections with the veneer method. However, there are two other deposition methods users can select for appropriate applications, the **Reservoir** (Depth Dependent Deposition) **Method** (channel or floodplain) and the **Distance Decay** method (floodplain only).



The Reservoir Deposition Method (Depth Dependent Deposition)

Some depositional systems, particularly prograding reservoir deltas, depart from the veneer assumption, depositing more in the deeper parts of the channel. **The Reservoir Option: Deposit More in the Deeper Parts of the XS** method adjusts bed change proportional to water depth. The Reservoir deposition method is available in the channel and overbank, but it is designed to fill the channel in backwater situations.

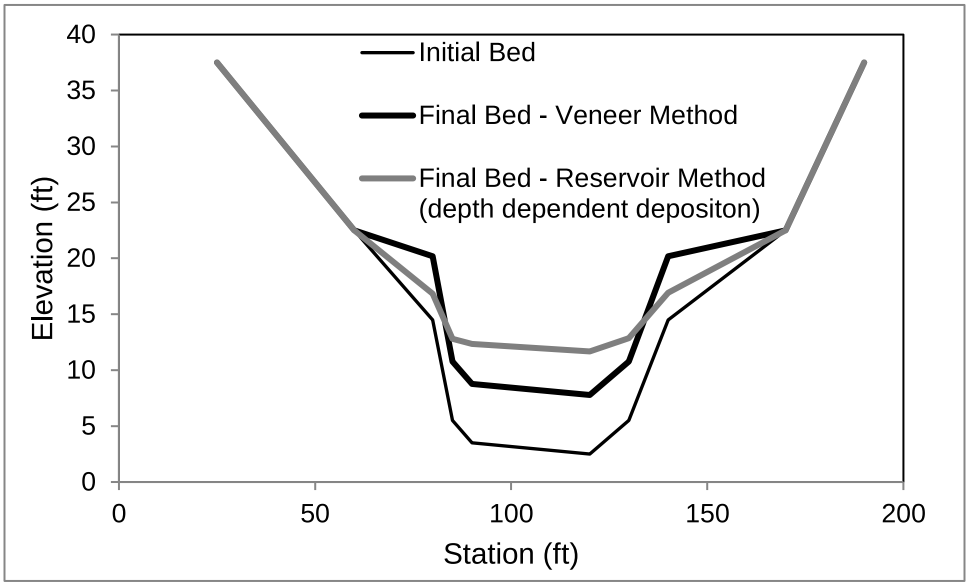


Figure 1-83: Results from the differential depth method and the basic veneer method.

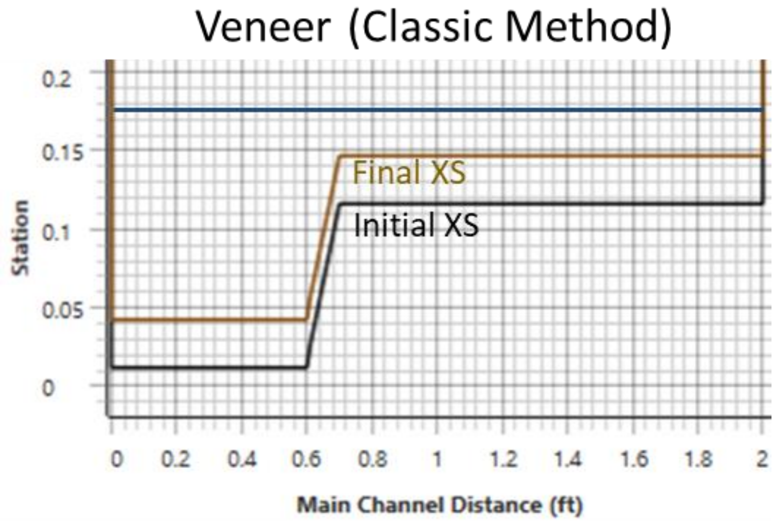
Modeling Note: Differential deposition vs Veneer in a Reservoir: Differential deposition based on depth is a function of length of reservoir, longitudinal location, and gradation of inflowing material (i.e. fall velocity). In the upstream portion of the reservoir, where coarser materials fill the valley, the channel will fill. The depth dependent method is appropriate here. However, fine materials that settle out in the reservoir pool, tend to blanket the flooded valley with a fine uniform veneer, often maintaining the pre-reservoir cross section shape through decades of deposition.

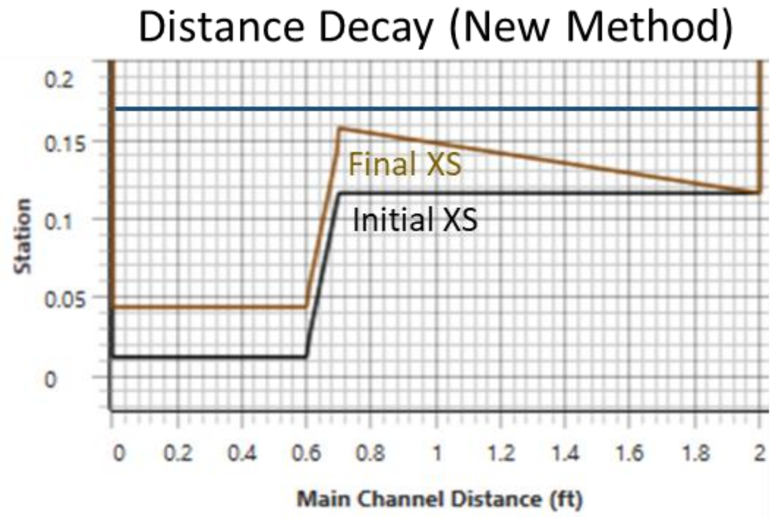
Modeling Note: Differential Deposition will Generate Flat Cross-Sections in non-Monotonic Bed Change Regimes**:** Depth dependent deposition may seem like an attractive alternative to the veneer method in non-reservoir, riverine settings. However, it is often unstable in systems that alternately deposit and erode. Depth dependent deposition cross sections converge on flat channels and can presently lose the channel shape during deposition events. This method performs best in settings of monotonic channel deposition

Distance Decay Floodplain Deposition Method

When sediment deposits in floodplains, it is not always evenly distributed. More sediment tends to settle out closer to the channel than in the father reaches of the floodplain. Walling and He (1998) and others have demonstrated that distance-decay models can estimate this distance-dependence of floodplain deposits. Therefore, HEC has included a distance-decay floodplain deposition model in HEC-RAS.

HEC is working on more sophisticated versions of these distance-decay models, but the current version of HEC-RAS has a simple, linear decay model. The linear decay model deposits the full "veneer" deposition thickness at the movable bed limits and reduces the bed change proportionally along the distance between the movable bed limit and the water surface extent. The figure below includes results from a simplified model of a floodplain deposition flume (Branß et al., 2018).[14]

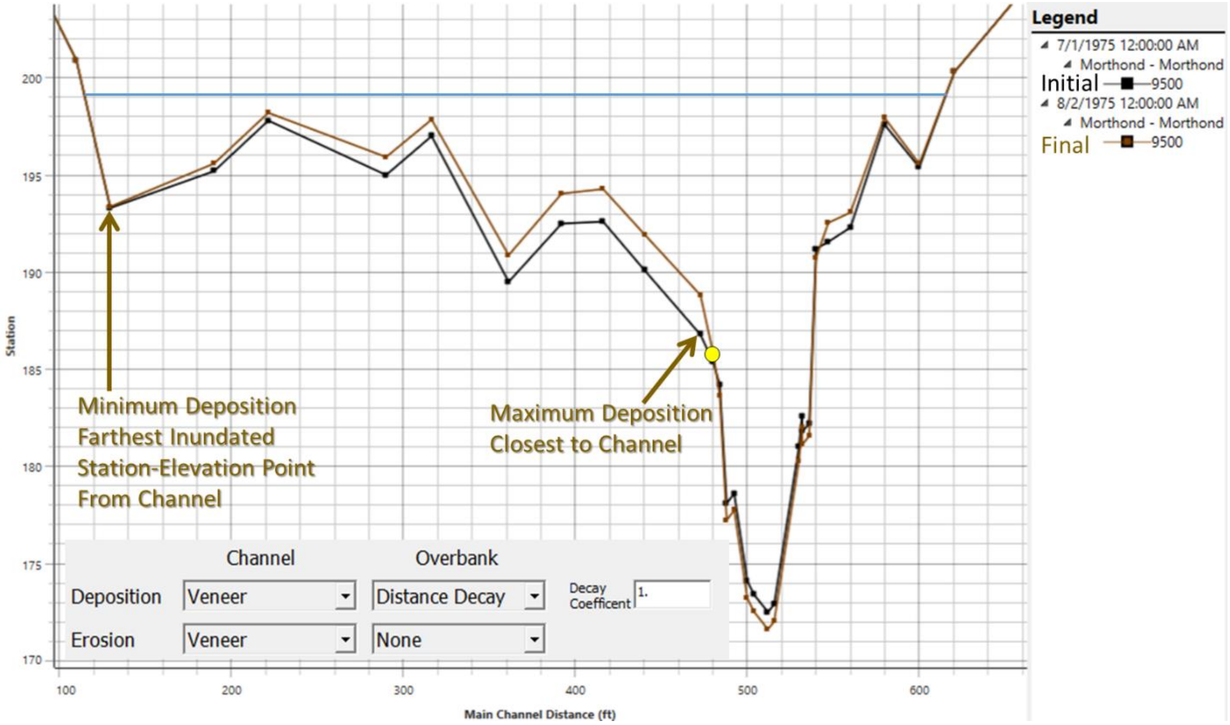




---

[14] Also Branß, T., Dittrich, A., Gonzalez, N., (2018) "Reproducing natural levee formation in an experimental flume," The International Conference On Fluvial Hydraulics (River Flow 2016).

The two figures below include an example of a more complicated cross section with depth-decay floodplain deposition and the calculation of bed change at a particular node).



	Channel	Overbank	
Deposition	Veneer	Distance Decay	Decay Coefficent 1.
Erosion	Veneer	None	

Figure 1-84: Example of the Distance Decay floodplain deposition model. The floodplain deposit thickness decreases with the distance from the channel.

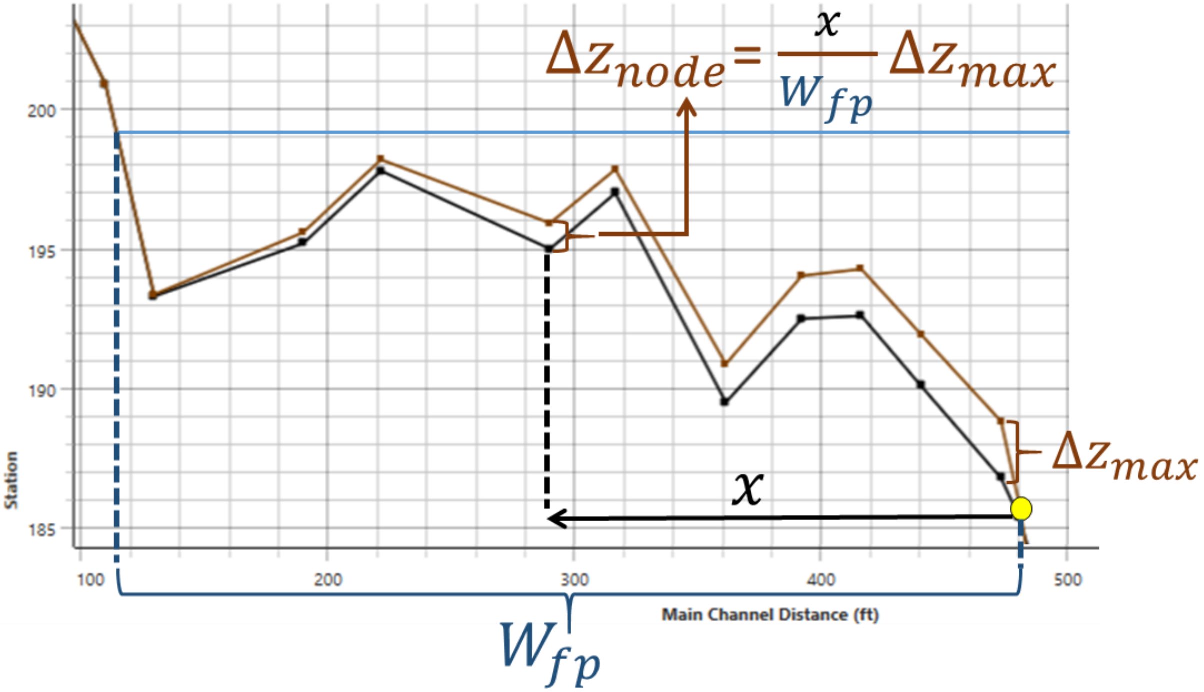


Figure 1-85: Example of deposition calculation in the linear distance-decay method.

Alternate Erosion Method: Simplified Channel Evolution Model (CEM)

The veneer method is the default method for channel erosion and is available (though rarely appropriate) for floodplain erosion. HEC-RAS includes one additional channel erosion method: the **Simplified CEM** method. The Simplified Channel Evolution Model is also designed for reservoir applications, in particular dam removals and reservoir flushing models.

The veneer method can under predict erosion in reservoir deposits. When a river scours reservoir deposits, following either a dam removal (Echevarria, 2012) or a reservoir flushing drawdown, it does not remove sediment uniformly from the flat reservoir deposits. Rivers tend to form one or more distinct channel through reservoir deposits during drawdowns or dam removals. The shear and hydraulic radius of a developing channel will erode more sediment than removing an even veneer from the top of a reservoir deposit. But these channels will also reach an equilibrium slope faster than a veneer approach and leave sediment embankments behind. The Simplified CEM model approximates these processes by eroding sediment in a defined, expanding, channel rather than a uniform veneer.

HEC-RAS translates parameters from the **Erosion Bed Change Option** into a simplified channel evolution model, eroding sediment in the shape of a trapezoidal channel (Figure 1-86) with the specified parameters (after Cui et al., 2005 and Cantelli et al., 2004).

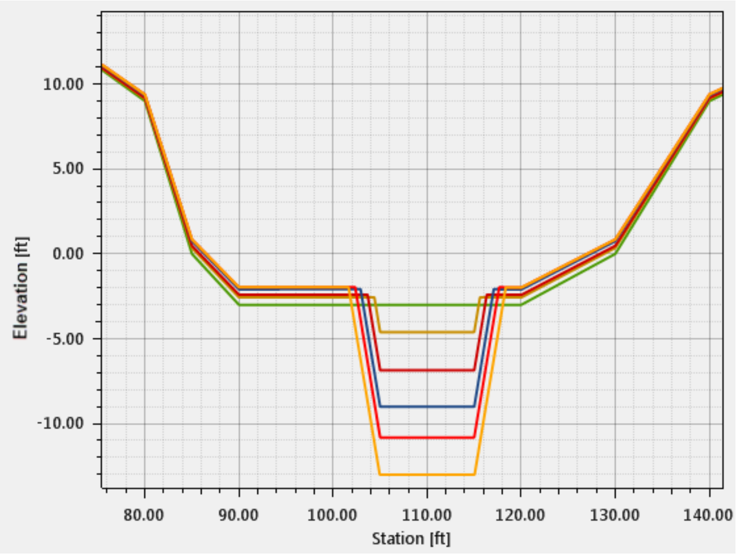


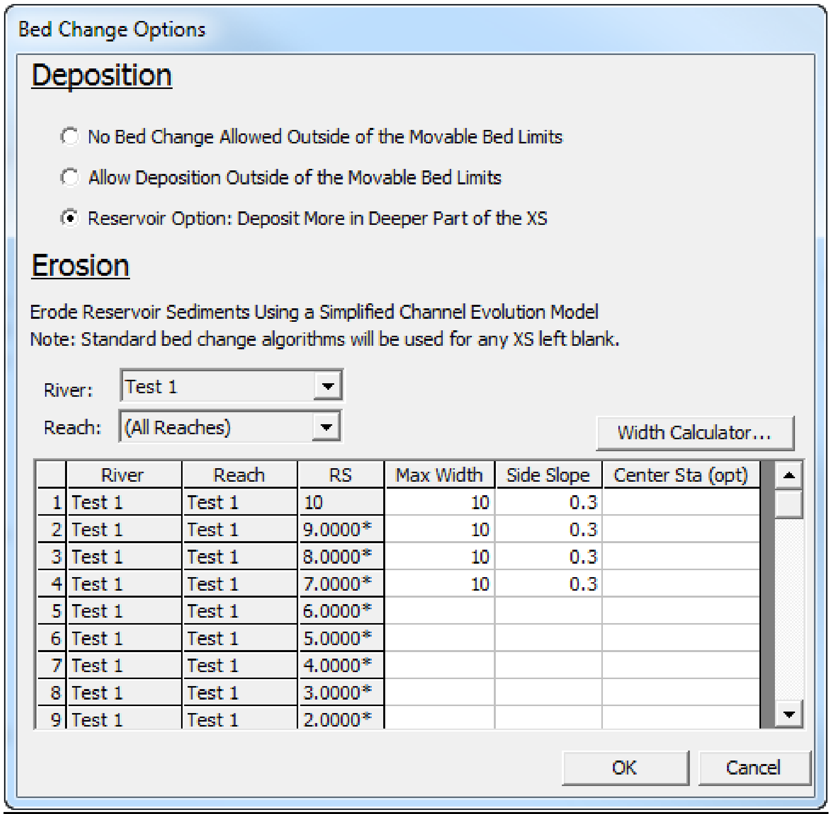
Figure 1-86: Simplified channel evolution progression.

HEC will only apply this method to cross sections with **Max Width** and **Side Slope** data. The program will erode all other cross sections with the veneer method. Therefore, in a dam removal or reservoir flushing model, users can specify these variables for the cross sections with reservoir deposits to cut through and leave the rest to respond with the veneer method.

<u>Max Width</u>: The Simplified Channel Evolution Model assumes that the channel will expand until it reaches a maximum width (after Morris et al., 2008). Once it scours to the **Max Width** it incises, maintaining that trapezoidal bottom width, until it reaches the bottom of the sediment volume (**Max Depth** or **Min Elevation** from the **Initial Conditions and Transport Parameters** Tab). If the river still has capacity to erode when the channel reaches the bottom of the sediment control volume, the trapezoidal

channel will expand laterally, maintaining the bottom elevation and side slopes, but increasing the bottom width.

Selecting a maximum bottom width is difficult and uncertain. Quantitative tools can help estimate this variable. Dimensionless analysis (Parker, 2008), regime theory, and other empirical geomorphic equations can guide bottom with estimates. Adkinson (1996) fit a regression to the bottom widths of channels scoured during several reservoir flushing events, and the equation is included in HEC-RAS (press the **Width Calculator…** button). However, all of these relationships have a lot of scatter. Selecting a bottom width requires good, regional, soil specific, geomorphic intuition. Even the best estimates are still uncertain and are candidates for calibration parameters or sensitivity analysis (Echevarria, 2012).



Bed Change Options

Deposition

○ No Bed Change Allowed Outside of the Movable Bed Limits

○ Allow Deposition Outside of the Movable Bed Limits

● Reservoir Option: Deposit More in Deeper Part of the XS

Erosion

Erode Reservoir Sediments Using a Simplified Channel Evolution Model
Note: Standard bed change algorithms will be used for any XS left blank.

River: Test 1

Reach: (All Reaches)

	River	Reach	RS	Max Width	Side Slope	Center Sta (opt)
1	Test 1	Test 1	10	10	0.3	
2	Test 1	Test 1	9.0000*	10	0.3	
3	Test 1	Test 1	8.0000*	10	0.3	
4	Test 1	Test 1	7.0000*	10	0.3	
5	Test 1	Test 1	6.0000*			
6	Test 1	Test 1	5.0000*			
7	Test 1	Test 1	4.0000*			
8	Test 1	Test 1	3.0000*			
9	Test 1	Test 1	2.0000*			

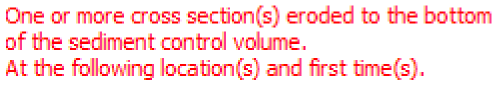
Figure 1-87: Specifying parameters for the simplified channel evolution model in select reservoir cross sections.

Side Slope: The side slopes define the shape of the trapezoidal channel. While empirical equations can guide **Max Width** estimation, there is little guidance for **Side Slope** selection. Angle of repose is a good place to start, but sensitivity analysis should also quantify the impact of this uncertain parameter.

Center Station (opt): HEC-RAS centers the trapezoidal channel between the movable bed limits. Because channels often form randomly in reservoir sediment and, often, a single channel is a numerical surrogate for multiple developing channels, this assumption is often good enough, given the other uncertainties. However, reservoirs that are flushed regularly, often form channels in the general location. If it is advantageous to capture that lateral channel position either computationally or, simply visually, specify the channel center station here.

Modeling Note - Eroding Valley Walls: The Simplified Channel Evolution Model removes sediment from the cross section at the specified side slope without considering physical limits of channel morphology. For example, if the side slope extends through a bedrock cliff or reinforced valley walls, the algorithm will still clip the cross section at the specified slope, 'eroding' the bluff or bank. Monitor the method carefully to assure physically reasonable results.

Modeling Note – Eroding to Bedrock: The Channel Evolution Model will often erode to the bottom of the sediment control volume, particularly if the reservoir was built on a previously bed-rock channel, or if the model is designed to return the channel to the historic grade (e.g. if there is a coarse, historic, cobble layer buried underneath the reservoir silt deposits, and the modelers decide to limit scour to that historic control). Previous versions of the **Simplified CEM** model would oscillate once HEC-RAS scoured to the bottom of the sediment control volume, because there was no bed sediment available to compute capacity. Recent versions of HEC-RAS partition capacity based on the initial bed gradation if the cross section erodes to the **Max Depth** or **Min Elev** (by either the CEM or the Veneer Method). HEC-RAS will also throw a runtime error, if the model scours to the bottom of the control volume:



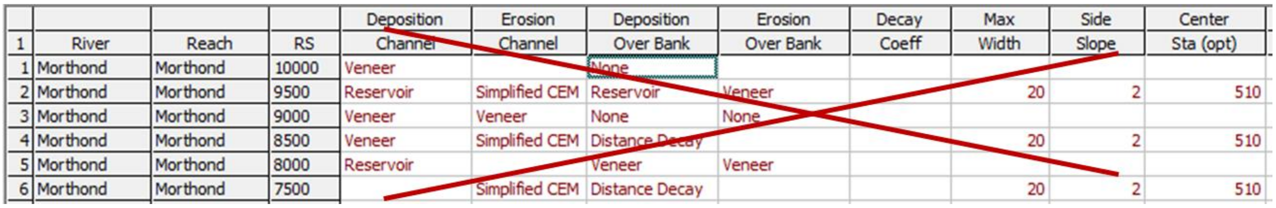
One or more cross section(s) eroded to the bottom
of the sediment control volume.
At the following location(s) and first time(s).

This is often a sign that the model is eroding too aggressively (because the bed is too fine or the transport function to powerful) or that the alluvial control volume was too small. But in cases where the model is expected to erode to a known vertical control, this error is expected and acceptable.

Local (Reach) Bed Change Methods

The most recent version of HEC-RAS also includes an option to override the Global Bed Change Options by specifying a different method at a cross section or – more appropriately – a group of cross sections.

Modeling Note – Bed Change Methods Should Apply to Morphologically Similar Reaches, not to Individual Cross Sections: Just because HEC-RAS allows users to define different bed change methods for each cross section, does not mean they should. This method should not change from cross section-to-cross section. If you do choose to override the default method, it should be for a particular reason over a coherent morphological setting, usually comprising a set of consecutive cross sections.



				Deposition	Erosion	Deposition	Erosion	Decay	Max	Side	Center
1	River	Reach	RS	Channel	Channel	Over Bank	Over Bank	Coeff	Width	Slope	Sta (opt)
1	Morthond	Morthond	10000	Veneer		None					
2	Morthond	Morthond	9500	Reservoir	Simplified CEM	Reservoir	Veneer		20	2	510
3	Morthond	Morthond	9000	Veneer	Veneer	None	None				
4	Morthond	Morthond	8500	Veneer	Simplified CEM	Distance Decay			20	2	510
5	Morthond	Morthond	8000	Reservoir		Veneer	Veneer				
6	Morthond	Morthond	7500		Simplified CEM	Distance Decay			20	2	510

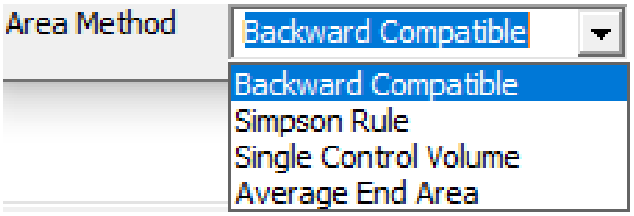
Examples of appropriate application of these local bed change methods would be:

- Choosing the **Reservoir** method for channel deposition along the topset slope of a reservoir delta while the **Veneer** method is the default elsewhere.

- Using the **Simplified CEM** method to compute erosion for a dam removal through the reservoir deposits, but default to the **Veneer** method for erosion downstream of the dam.

Area Method

The Area-Volume conversion method selects the algorithm that HEC-RAS uses to compute a water volume from cross sections. These options are new since version 6.0 and the recommended methods are a departure from the approach in 5.0.7. See the section of the technical reference manual on Volume-Area conversions for technical detail on these methods.



- Backwards compatible - uses Simpson for bed sorting, rectangle for bed change
- Average end area - uses HEC-6 method for bed sorting and bed change
- Simpson - uses Simpson for bed sorting and bed change (recommended)
- Single CV - uses rectangle for bed sorting and bed change

Transport Method

HEC-RAS routes sediment with the Exner equation, modeling sediment mass with the continuity equation. This approach includes no physical limitation on sediment velocity and, depending on cross section spacing and time step, often moves sediment faster than the water velocity.

HEC-RAS includes an option that limits sediment velocity to the water velocity, only releasing sediment from each control volume that the water passing through that control volume can carry. To activate this option, select **Sediment Routing Method** from the **Options** menu and pick **Limit to Water Velocity** from the drop down list.

Wish List: 1D Advection-Diffusion - We would like to improve on this simplification, offering the Advection-Diffusion equation to route sediment according to more physical processes and user specified coefficients.

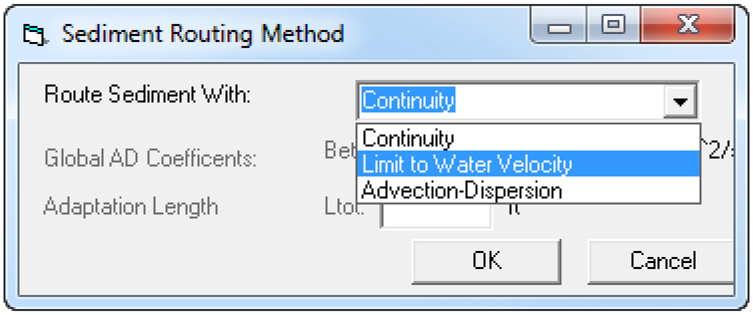
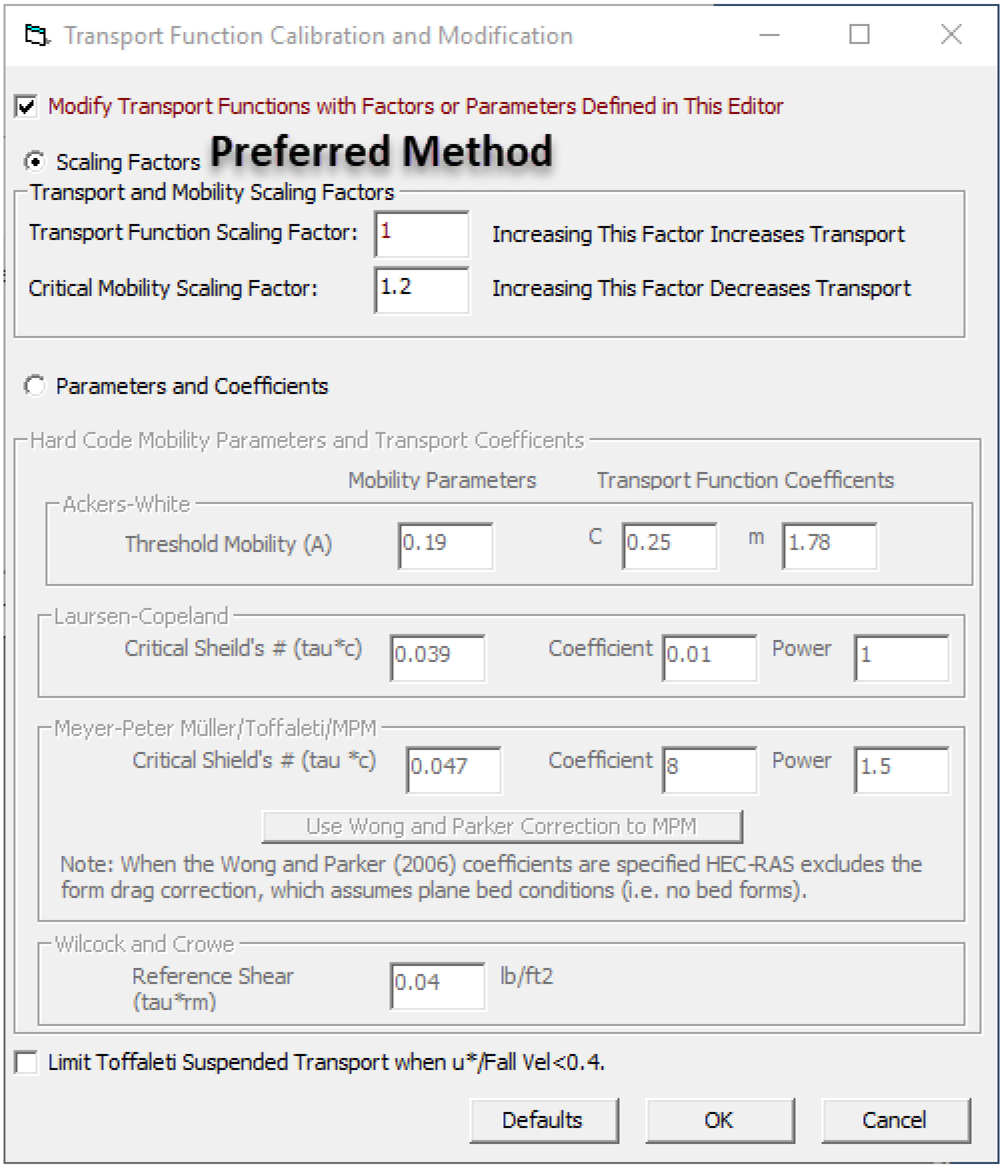


Figure 1-88: Routing Method Editor.

Transport Function and Calibration

The sediment transport functions are, to varying degrees, combinations of theoretical and empirical science. Even the most theoretically detailed equations were fit to data using empirical coefficients. These coefficients represent the central tendencies of the data considered but will not likely reflect the transport of a specific site precisely, even if an appropriate transport function is selected. Therefore, HEC-RAS provides opportunities to "Calibrate" the transport function. This should be the last stop in calibration, after the user has selected the most appropriate (theoretically and based on initial performance) transport function, carefully checked all data and parameters, and considered calibrating by adjusting data within the observed range. To use calibration parameters first click the box labeled **Modify Transport Functions with Factors or Parameters Defined in This Editor.** If the box is not checked, variables can be edited and changed but they will not be used for transport calculations.



☑ Modify Transport Functions with Factors or Parameters Defined in This Editor

● Scaling Factors **Preferred Method**

Transport and Mobility Scaling Factors

Transport Function Scaling Factor: 1 Increasing This Factor Increases Transport

Critical Mobility Scaling Factor: 1.2 Increasing This Factor Decreases Transport

○ Parameters and Coefficients

Hard Code Mobility Parameters and Transport Coefficents

	Mobility Parameters		Transport Function Coefficents		
Ackers-White: Threshold Mobility (A)	0.19	C	0.25	m	1.78
Laursen-Copeland: Critical Sheild's # (tau*c)	0.039	Coefficient	0.01	Power	1
Meyer-Peter Müller/Toffaleti/MPM: Critical Shield's # (tau *c)	0.047	Coefficient	8	Power	1.5
Wilcock and Crowe: Reference Shear (tau*rm)	0.04 lb/ft2				

Note: When the Wong and Parker (2006) coefficients are specified HEC-RAS excludes the form drag correction, which assumes plane bed conditions (i.e. no bed forms).

☐ Limit Toffaleti Suspended Transport when u*/Fall Vel<0.4.

Figure 1-89: Transport Function Calibration and Modification Editor.

Scaling Factors:

Scaling Factors are (new in 5.1) are the preferred method for calibrating transport equations. Most transport functions are built around an excess shear or stream power function, where the shear or stream power is compared to a critical mobility factor (τ_c, SV_c) raised to some power. So a simplified version of the MPM equation is often written:

$$q_b^* = 8(\tau^* - \tau_c^*)^{3/2}$$

where q_b^* is a dimensionless measure of transport (the Einstein number), τ^* is the dimensionless shear stress (the Shields number) and τ^*_c is the critical dimensionless shear.

The **Scaling Factor** calibration method provides users two opportunities to scale results. So, the simplified MPM function could be re-written with the two scaling factors:

$$q_b^* = \propto \cdot\, 8(\tau^* - \varepsilon \cdot \tau_c^*)^{3/2}$$

where α is the **Transport Function Scaling Factor** and ε is the **Critical Mobility Scaling Factor**.

The transport function scaling factor is a simple linear multiplier on the capacity equation (e.g. 1.1 increases capacity 10% and 0.9 decreases capacity by 10%). The **Critical Mobility Factor** is a little more complicated, but also easier to justify physically. The **Critical Mobility Scaling Factor affects** the *competence* (the minimum flow at which water can move a grain class) as well as the *capacity*. It is inversely related to flow (a factor of 1.1 will make the sediment less mobile and will *decrease* transport). Additionally, because it is usually inside of the power, the effects are non-linear. Finally, not all transport functions use an excess shear/power/mobility form, so some (Engelund Hansen and Toffaleti) do not have a Critical Mobility Scaling Factor.

However, Buffington and Montgomery (1997) - among others - point out that the original critical shear data from Shields research had significant scatter and studies that have back-calculated critical Shields' parameters have found a wide range of values. So some modelers find mobility to be an appropriate, and more physically defensible parameter to adjust.

Table 1-3: List of the critical mobility factor adjusted with the scaling factor in each transport function (where applicable).

	Transport Scaling Factor	Critical Mobility Scaling Factor
Ackers-White	X	A
Engelund-Hansen	X	
Laursen (Copeland)	X	τ_c^*
Meyer-Peter Muller	X	τ_c^*
Toffaleti	X	
MPM-Toffaleti	X	τ_c^* in MPM

Yang	X	SV_c
Wilcock-Crowe	X	τ_m^*

Warning – Be Careful Calibrating the Transport Function: These variables should only be adjusted within reasonable ranges in response to a hypothesis based on observed physical processes. Only change the critical shields parameter within a reasonable range, with physical justification. Changing coefficients no longer honors the form of the transport function.

Define Transport Function Parameters and Coefficients:

The second calibration option exposes parameters in four of the HEC-RAS transport functions. ***This feature is not recommended.*** The scaling factors are preferred, and the second method is mainly maintained for backward compatibility.

Each of the four transport functions has a variable that quantifies the force or energy required to mobilize the particle. In Laursen-Copeland and MPM it is the critical shear stress, τ_c^* (also known as the Shields number), in Ackers-White it is the Threshold Mobility (A) and in Wilcock it is the reference Shear Stress τ_{rm}^*. When calibrating a sediment transport function using this feature, these mobility factors should be the main parameters adjusted, since they can be related to physical phenomena. For example, imbricated or vegetated particles will be harder to move than the critical Shields parameter would suggest, so a physical case could be made for a higher τ_c^*, which would decrease transport. Conversely, the presence of substantial fine particles could make it easier for the flow field to entrain coarser particles, resulting in a lower τ_c^*.

Consider, again, the simplified form of MPM:

$$q_b^* = 8(\tau^* - \tau_c^*)^{3/2} \quad , \quad \tau_c^* = 0.047$$

where q_b^* is a dimensionless measure of transport (the Einstein number), τ^* is the dimensionless shear stress (the Shields number) and τ^*_c is the critical dimensionless shear. 8 and 3/2 are coefficients fit to the simple excess shear relationship in the original formulation. Exposing the critical shear stress, the coefficient and the power of the MPM relationship turns it into a generic excess shear formula that can be used to customize a site-specific excess shear, power function. In fact, Wong and Parker (2006) recently reanalyzed the data set initially used to develop the MPM equation and found that the relationship

$$q_b^* = 4.93\,(\tau^* - \tau_c^*)^{1.6} \quad , \quad \tau_c^* = 0.047$$

fit the original MPM data better than the MPM equation. Pressing the **Use Wong and Parker Correction to MPM** button, will automatically set the coefficient and power to the corrected values.

The transport function calibration menu offers the opportunity to use the Wong and Parker correction to the MPM equation, based on their 2006 paper. This reduces the MPM coefficient from 8 to 4.93, maintains the critical Shield's number of 0.047, and increases the power (MPM exponent) from 1.5 to 1.6. Wong and Parker's function was developed based only on reanalysis of data sets used by MPM *without* bed forms. Wong and Parker (2006) argued that the form drag correction embedded in many versions of MPM (including the one used in HEC-RAS) is not justified for lower-regime plane-bed conditions, and that MPM over-predicts bed load transport without it. Therefore, if the Wong Parker coefficients (a=4.93, $\tau^*_c=0.047$, b=1.6) are used with MPM, whether entered manually or selected with the interface button, HEC-RAS will set the form drag correction to 1, which implies plane-bed conditions (i.e. no bed forms).

Warning – Be Careful Overwriting Dynamic Parameters: Several of the parameters exposed in this editor are actually functions that can have different values in different hydrodynamic and sediment settings. You may notice that selecting this method but leaving the parameters default may change the result because the default does not reflect the model conditions. This is why the scaling factors calibration method should be preferred (the direct parameterization may disappear in future versions). For example, the critical mobility scaling factor can adjust the reference shear in Wilcock and Crowe - as recommend–d - (Wilcock, personal communication) without over-writing the sand dependency built into the reference shear that is the main feature of the transport function.

Toffaleti Limiter

Yaw et al., (2019)[15] demonstrated that the Toffaleti equation (and the combined Toffaleti-MPM equation) include a discontinuity in high energy conditions for high energy conditions. This can lead to unrealistic transport under certain conditions. The issue emerges when the suspended zone equations try to compute transport for materials that are not suspended.

The Toffaleti Limiter (which is included in the Transport Function Calibration editor) uses a shear velocity-to-fall velocity ratio ($u^*/\omega \le 0.4$) to determine if the grain class is likely to be suspended by the hydraulics. The feature limits suspended transport to grain classes under that threshold and only includes the larger particles in the bed load (near bed) portion of the equation.

☑ Limit Toffaleti Suspended Transport when u*/Fall Vel<0.4.

2D Options

These options are described in the 2D sediment manuals.

BSTEM Options

These options are only applicable to models with bank failure and toe erosion, using the USDA-ARS Bank Stability and Toe Erosion Model (BSTEM). BSTEM has a separate manual and these options are described there.

---

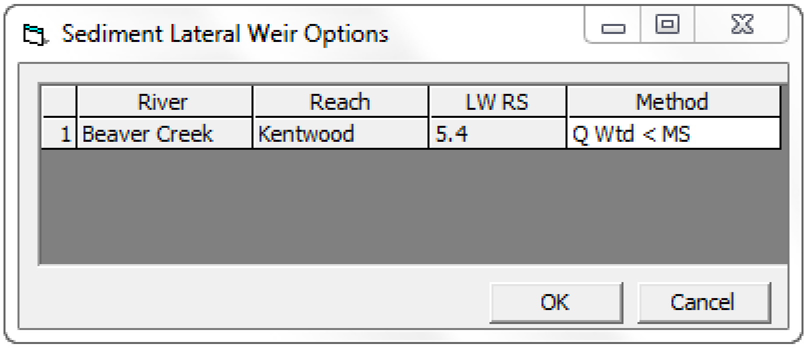
[15] Yaw, M., Pizzi, D., AuBuchon, J., Gronewold, R., Gibson, S. (2019) Middle Rio Grande and Tributaries Numerical Sediment Routing Study, Cochiti Dam to Elephant Butte Reservoir, Proceedings, SedHyd Interagency Sediment Conference.

Lateral Structure

HEC-RAS can simulate sediment transport with Lateral Structures in both quasi-unsteady and unsteady modes. Like flow splits, Lateral structures use the default assumption that sediment is diverted in proportion to the diverted flow (i.e. if 10% of flow leaves over a Lateral Structure, 10% of the transporting sediment will also divert, with the same gradation as the transporting sediment).

However, diverted sediment is usually substantially finer than sediment transporting in the main channel, especially if the diversion structure is perched higher than the bed load transport zone, or even the vertical center of mass of grain classes with low Rouse numbers. The **Lateral Weir Options** provide a "screen option" that prevents coarse grain classes from diverting.

Select the **Lateral Weir Options** to set Lateral Structure **Diversion Thresholds**. The editor will list all the Lateral Structures in the project and the **Flow Weighted** method will populate for each by default. HEC-RAS will compute the percentage of flow diverted, and then will divert that percentage of sediment, but will exclude the grain class selected and all coarser. For example, in Figure 1-90, only the grain classes *finer* than medium sand will be diverted (producing the plot on the right in Figure 1-91). Because screened grain classes are excluded after the original sediment diversion computation, the diverted sediment mass will be *less than* proportional to flow (which is why the total sediment diverted drops as the filter is applied in Figure 1-91).



	River	Reach	LW RS	Method
1	Beaver Creek	Kentwood	5.4	Q Wtd < MS

Figure 1-90: Setting a Diversion Threshold in the Lateral Weir Editor.

See the SedRuleLat.prj files in the example data sets for an example Lateral Structure application. This data set also illustrates how to leverage native Lateral Structure features for sediment studies, using operational rules to monitor sediment variables and operate gates in response to them.

HEC-RAS storage areas are not connected to the sediment transport mode, either in their classical or 2D incarnations. If sediment is routed to a storage area with a Lateral Structure, it disappears from the model. However, if a user sets the downstream

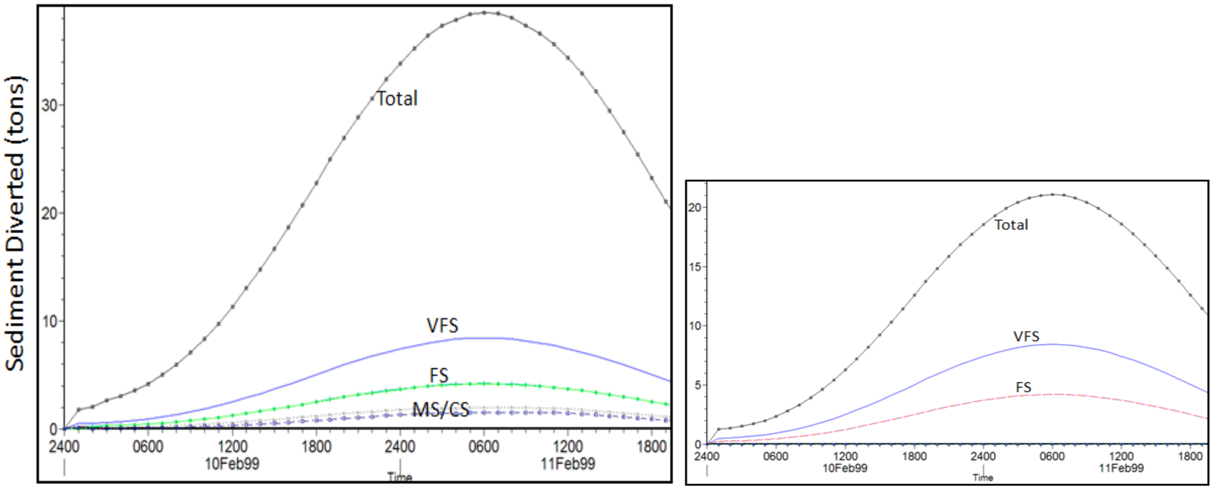
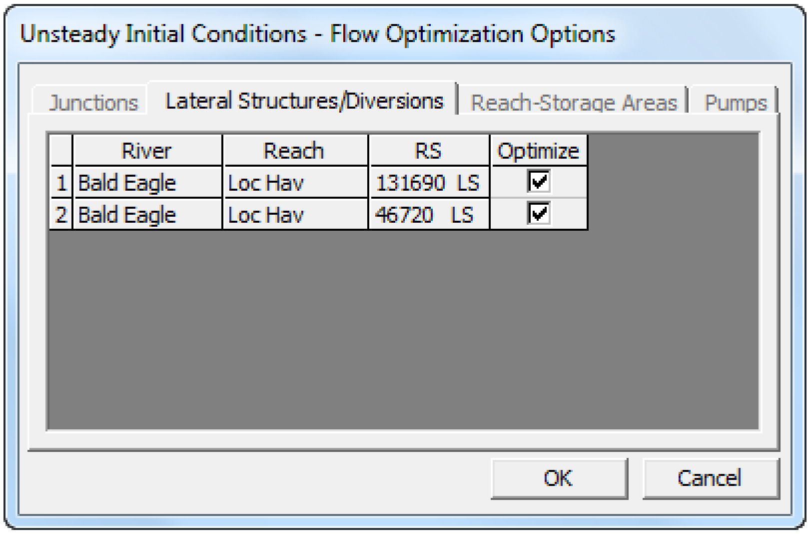


Figure 1-91: Sediment time series diverted over a Lateral Structure with (left) default assumption and (right) the diversion filter applied in the previous figure.

Modeling Note – Quasi-Unsteady Lateral Structures: A note of caution on Lateral Structures and quasi-unsteady flow: flow over lateral structures is principally an unsteady phenomenon. As flow is diverted by a lateral weir, water levels drop, which leads to less flow over the weir. In unsteady flow, these feedbacks are accounted for implicitly. This is not the case with steady flow. An iterative approach can be employed in HEC-RAS to account for the feedbacks between flow diversion and the water level and converge on a solution. This option is not the default and has to be selected by going to the **Options→Flow Optimization** menu in the **Sediment Transport Analysis** editor and selecting the **Lateral Structures/Diversions** tab.



	River	Reach	RS	Optimize
1	Bald Eagle	Loc Hav	131690 LS	☑
2	Bald Eagle	Loc Hav	46720 LS	☑

Figure 1-92: Lateral structure optimization option.

Quasi-unsteady hydrodynamics are a series of steady flow analyses, so Lateral Structure flows are not accounted for implicitly. In order to account for feedbacks between diverted flows and water levels in quasi-unsteady flow optimize flow. However, this will increase run times dramatically, because the iteration required every time step by the optimization routines is computationally expensive. The alternatives are to move to an unsteady sediment transport model or compute a time series of flow diversion externally (e.g. with an unsteady flow run), add them as negative flows in the quasi-unsteady editor, and use the rating curve method (method 4 above) to compute sediment loads in the diversion.

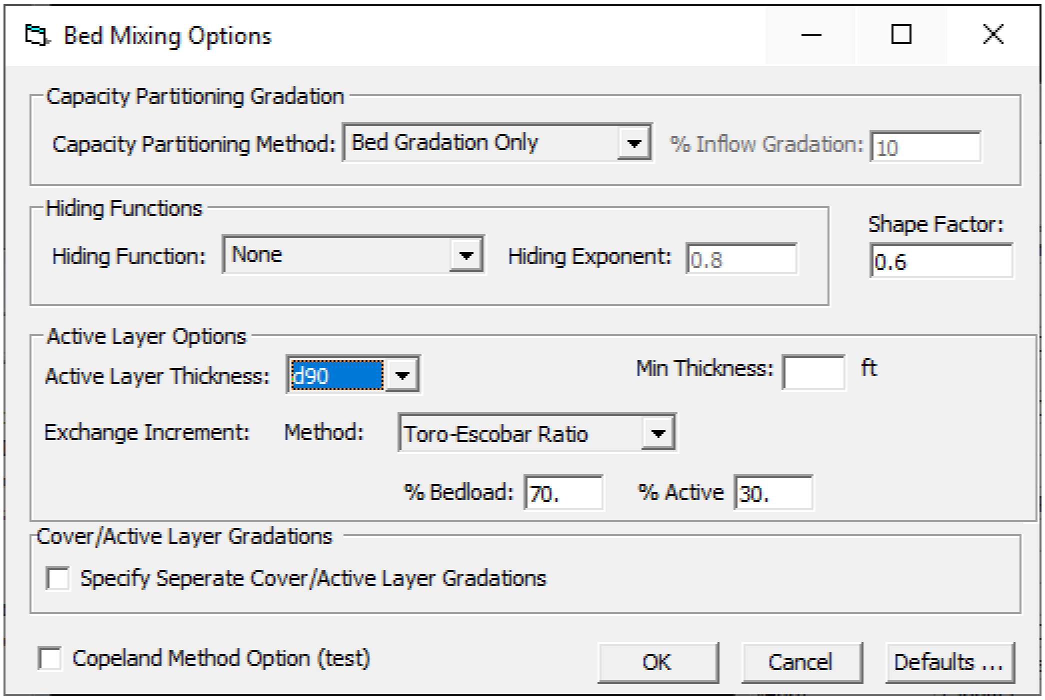
Modeling Note – Lateral Structure Output: HEC-RAS does not provide sediment output by lateral structure. Instead, each cross section has a **Lateral Diversion** output variable, which sediment diverted from that cross-section's control volume by Lateral Structures or user specified diversions in the Rating Curve Boundary condition. Therefore, since lateral structures can span several cross sections, the total diverted sediment must be summed over all contributing cross sections.

Bed Mixing Options

Bed mixing options are associated with the fractionation of the transport capacity partitioning, hiding, and the bed mixing (sorting and armoring) algorithms, including the Active Layer, Thomas, and Copeland Methods. Sediment transport models can be very sensitive to the

Capacity Partitioning

HEC-RAS follows the fundamental assumption most multiple-grain class sediment transport models employ, partitioning transport capacity by the relative grain class fraction in the bed. The Technical Reference Manual includes more detail on this capacity partitioning approach (Einstein, 1960)


Bed Mixing Options

Capacity Partitioning Gradation

Capacity Partitioning Method: Bed Gradation Only

% Inflow Gradation: 10

Hiding Functions

Hiding Function: None

Hiding Exponent: 0.8

Shape Factor: 0.6

Active Layer Options

Active Layer Thickness: d90

Min Thickness: ft

Exchange Increment: Method: Toro-Escobar Ratio

% Bedload: 70.

% Active 30.

Cover/Active Layer Gradations

☐ Specify Seperate Cover/Active Layer Gradations

☐ Copeland Method Option (test)

Figure 1-93: Options for Bed Mixing

Shape Factor

The shape factor is the ratio of b-axis to the a-axis of a particle, the length of the intermediate axis, perpendicular to the longest axis divided by the length of the longest axis. A spherical particle has a shape factor of 1 while a particle with a long axis that is two twice as long as the smallest axis has a shape factor of 0.5. HEC-RAS only uses the shape factor in the **Report 12** fall velocity method.

Active Layer Options

The three-layer mixing methods (e.g. Thomas and Copeland) regulate their layer thickness parameters automatically, based on their equilibrium depth and cover layer algorithms. The two-layer **Active Layer** method is a simpler alternative. It does not have the sophisticated cover layer dynamics of the three-layer methods, but it is more intuitive.

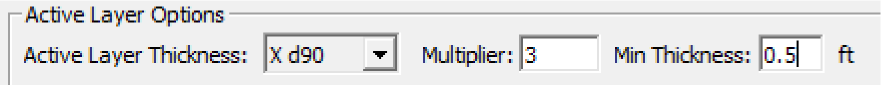
Therefore, HEC-RAS exposes key parameters of the active layer method, allowing the users to adjust them for their system. Ruark et al. (2011)[16] demonstrated that simple, active-layer sediment models can be very sensitive to the Active Layer Thickness.

The default Active Layer thickness is set to one-d90 of the active layer material. So HEC-RAS computes the 90th percentile particle size in the active layer mixture for each time step, and makes the active layer that thickness. The algorithm will either pull sediment up from the inactive layer or push extra sediment down into the inactive layer to achieve that thickness.

While the active layer is a conceptual simplification (Parker) that is not, entirely, self-defining,[17] experimental and laboratory observations suggest that ***gravel beds*** transport in a layer that is approximately equivalent to the thickness of one-to-three diameters of the largest particles in the mixture (e.g. d_{84}, d_{90}, d_{100}). However, the active layer thickness for a ***sand bed*** usually scales to the bedform amplitude so a sand bed active layer is usually one-to-two orders of magnitude larger than the d_{90}.

HEC-RAS allows users to define the active layer thickness in multiples of the d_{90}. This is usually between 1 and 5 for gravel beds, and over 10 for sand beds.

To adjust the active layer thickness (from the default of 1d_{90}) select the **Options→Bed Mixing Options** menu from the Sediment Editor and click on the dropdown box next to **Active Layer Thickness**, selecting **Xd90**. This will make a **Multiplier** box visible. Define the active layer thickness in multiples of the d_{90}.



Active Layer Options

Active Layer Thickness: X d90 Multiplier: 3 Min Thickness: 0.5 ft

Defining the active layer thickness in terms of a d90 is very common for rivers with gravel and cobble armor layers. However, it is vulnerable to numerical artifacts if the load suddenly fines. A fine pulse (e.g. from a dam removal or reservoir flush) can suddenly make the active layer much finer, dropping the active layer thickness to a few millimeters or – in extreme cases – fractions of a millimeter.

---

[16] Ruark, M.D., Niemann, J.D., Greimann, B.P. and Arabi, M. (2011) Method for Assessing Impacts of Parameter Uncertainty in Sediment Transport Modeling Applications, ASCE Journal of Hydraulic Engineering, 137(6).

[17] Church, M. and Haschenburger, J.K. (2016) What is the "active layer"? *Review of Geophysics*.

The **Min Thickness** option makes the active layer more resilient to gradational disequilibrium. If the default **d90** or the user-specified **Xd90** are larger than the minimum active layer thickness (half a foot in the figure), HEC-RAS will compute the active layer thickness dynamically, based on that parameter. However, if the dynamic active layer falls below this **Min Thickness** HEC-RAS will default to this minimum thickness.

Modeling Note: Select an Active Layer thickness that will not run out of sediment - Users should size their active layer to avoid running out of sediment during any time step. If HEC-RAS scours all of the sediment from the active layer in a bed mixing time step (SPI) it will not replenish the layer. This will artificially limit scour and make the model artificially resistant to scour. Users can increase the number of Bed Mixing Time steps per computational increment or increase the size of the active layer to avoid active layer exhaustion. HEC-RAS versions 6.0 and later generates runtime errors if the active layer runs out of sediment. See the section on selecting the active layer thickness in the Technical Reference Manual.

Modeling Note: Xd90 is *much* larger for sand bed rivers – The default Active Layer method is parameterized for bimodal beds with significant gravel or cobble components. The active layer concept is different for sand bed rivers. In order to avoid active layer exhaustion – and to adhere to the theoretical definition of the active layer – sand bed rivers require many multiples of the d_{90}. The Copeland method was designed for sand bed rivers and is often appropriate. However, when modelers apply the Active Layer method to sand bed rivers, **Xd90**s of 30, 100 or more are often appropriate, and defining a **Min Thickness** is a best practice to avoid active layer exhaustion.

Modeling Note: Active Layer Parameters will not affect Thomas or Copeland methods – The Thomas and Copeland methods do have “active layer” components. However, they conceptualize the active layer differently and compute it automatically. Therefore, adjusting these parameters will only affect the simulation if the **Active Layer Sorting Method** is selected.

Cover/Active Layer Gradations

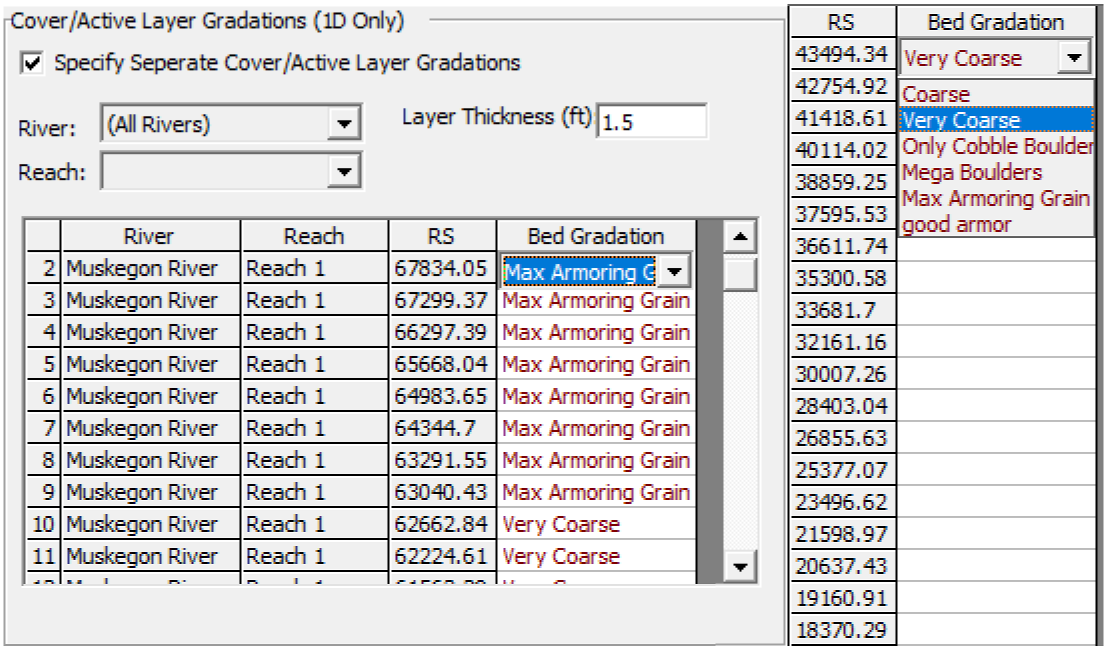
Rivers with significant gravel or cobble components often form coarse cover or armor layers. But the default sediment editor only assigns one gradation per cross section. In settings with coarse cover layers and finer sub-surface layers, this single gradation will either underestimate the gradation of the cover layer or overestimate the gradation of the subsurface layer.

This feature allows users to define a separate cover layer gradation for armored cross sections. Defining a bed gradation in this editor will initialize the cover layer in the Thomas or Copeland Sorting Methods and the active layer in the Active Layer Mixing method with the gradation defined in this editor. The bed gradation defined in the main sediment editor will initialize the sub-surface layer. Any cross section left blank in this editor will initialize the cross section with a single gradation defined in the main manual.

To define separate active or cover layer gradations click on the **Specify Separate Cover/Active Layer Gradations** check box. This will expand the editor to show a list of cross sections in the model. Click on the **Bed Gradation** box to select the cover or active layer gradation for the cross section from a drop down of all the gradations specified.

This drop-down list of gradations will include all of the bed gradations specified in the **Bed Gradation** editor. Create a **Bed Gradation Template** for each gradation you would like to select in either the main sediment editor or this cover gradation editor.

This method also requires an initial **Layer Thickness** to initialize these layers. The cover or active layers with the specified gradations will have an initial layer thickness defined in the **Layer Thickness** field. Running a warm-up period or using a hotstart are alternate ways of developing coarse cover layer gradations without eroding the bed.



Cover/Active Layer Gradations (1D Only)

☑ Specify Seperate Cover/Active Layer Gradations

River: (All Rivers)

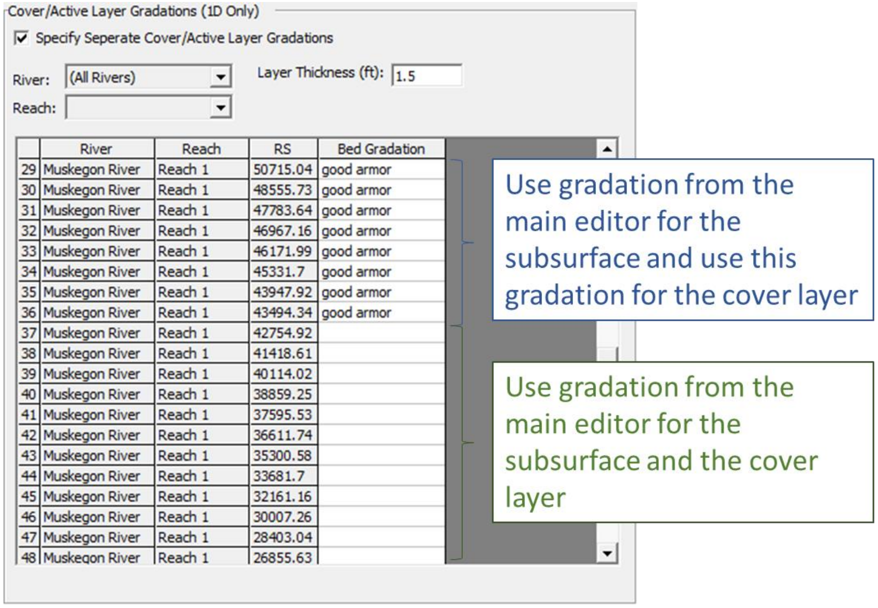
Reach:

Layer Thickness (ft) 1.5

	River	Reach	RS	Bed Gradation
2	Muskegon River	Reach 1	67834.05	Max Armoring G
3	Muskegon River	Reach 1	67299.37	Max Armoring Grain
4	Muskegon River	Reach 1	66297.39	Max Armoring Grain
5	Muskegon River	Reach 1	65668.04	Max Armoring Grain
6	Muskegon River	Reach 1	64983.65	Max Armoring Grain
7	Muskegon River	Reach 1	64344.7	Max Armoring Grain
8	Muskegon River	Reach 1	63291.55	Max Armoring Grain
9	Muskegon River	Reach 1	63040.43	Max Armoring Grain
10	Muskegon River	Reach 1	62662.84	Very Coarse
11	Muskegon River	Reach 1	62224.61	Very Coarse

RS	Bed Gradation
43494.34	Very Coarse
42754.92	
41418.61	
40114.02	
38859.25	
37595.53	
36611.74	
35300.58	
33681.7	
32161.16	
30007.26	
28403.04	
26855.63	
25377.07	
23496.62	
21598.97	
20637.43	
19160.91	
18370.29	

If this cover field is left blank, HEC-RAS will use a homogeneous bed gradation from the main sediment editor for the entire cross section.



Cover/Active Layer Gradations (1D Only)

☑ Specify Seperate Cover/Active Layer Gradations

River: (All Rivers)

Reach:

Layer Thickness (ft): 1.5

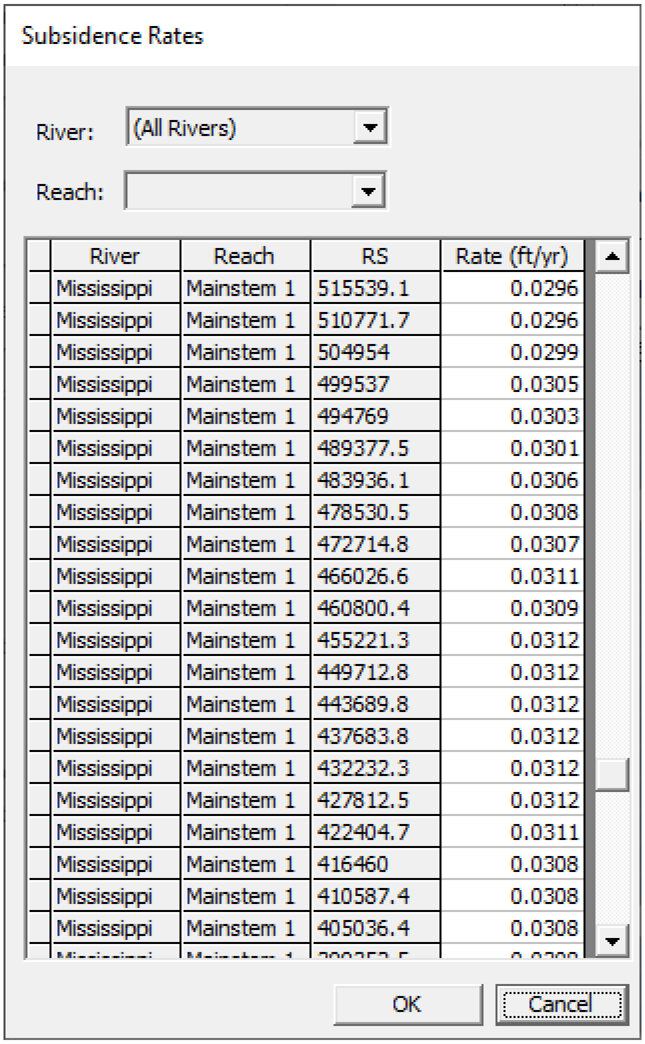
	River	Reach	RS	Bed Gradation
29	Muskegon River	Reach 1	50715.04	good armor
30	Muskegon River	Reach 1	48555.73	good armor
31	Muskegon River	Reach 1	47783.64	good armor
32	Muskegon River	Reach 1	46967.16	good armor
33	Muskegon River	Reach 1	46171.99	good armor
34	Muskegon River	Reach 1	45331.7	good armor
35	Muskegon River	Reach 1	43947.92	good armor
36	Muskegon River	Reach 1	43494.34	good armor
37	Muskegon River	Reach 1	42754.92	
38	Muskegon River	Reach 1	41418.61	
39	Muskegon River	Reach 1	40114.02	
40	Muskegon River	Reach 1	38859.25	
41	Muskegon River	Reach 1	37595.53	
42	Muskegon River	Reach 1	36611.74	
43	Muskegon River	Reach 1	35300.58	
44	Muskegon River	Reach 1	33681.7	
45	Muskegon River	Reach 1	32161.16	
46	Muskegon River	Reach 1	30007.26	
47	Muskegon River	Reach 1	28403.04	
48	Muskegon River	Reach 1	26855.63	

Use gradation from the main editor for the subsurface and use this gradation for the cover layer

Use gradation from the main editor for the subsurface and the cover layer

Subsidence

In some locations, regional subsidence drops the land elevation relative to sea level. Regional subsidence can complicate mobile bed calculations for systems where the river datum is changing relative to the tail water. Therefore, HEC-RAS includes a **Subsidence** feature. Users can define constant subsidence rates for each cross section. HEC-RAS will lower all the cross-section nodes (inside and outside of the movable bed limits) at this rate over the duration of the simulation.


Subsidence Rates

River: (All Rivers)

Reach:

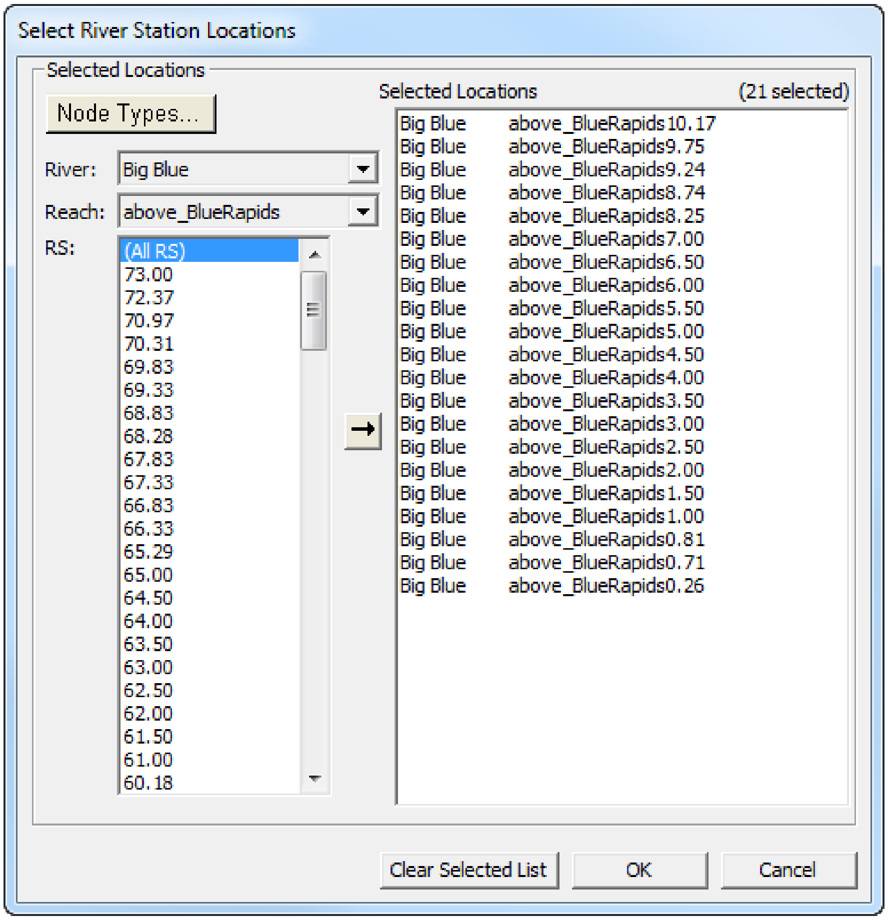
River	Reach	RS	Rate (ft/yr)
Mississippi	Mainstem 1	515539.1	0.0296
Mississippi	Mainstem 1	510771.7	0.0296
Mississippi	Mainstem 1	504954	0.0299
Mississippi	Mainstem 1	499537	0.0305
Mississippi	Mainstem 1	494769	0.0303
Mississippi	Mainstem 1	489377.5	0.0301
Mississippi	Mainstem 1	483936.1	0.0306
Mississippi	Mainstem 1	478530.5	0.0308
Mississippi	Mainstem 1	472714.8	0.0307
Mississippi	Mainstem 1	466026.6	0.0311
Mississippi	Mainstem 1	460800.4	0.0309
Mississippi	Mainstem 1	455221.3	0.0312
Mississippi	Mainstem 1	449712.8	0.0312
Mississippi	Mainstem 1	443689.8	0.0312
Mississippi	Mainstem 1	437683.8	0.0312
Mississippi	Mainstem 1	432232.3	0.0312
Mississippi	Mainstem 1	427812.5	0.0312
Mississippi	Mainstem 1	422404.7	0.0311
Mississippi	Mainstem 1	416460	0.0308
Mississippi	Mainstem 1	410587.4	0.0308
Mississippi	Mainstem 1	405036.4	0.0308

Modeling Note: Using Subsidence with fixed bed models – HEC-RAS only includes subsidence in the sediment model. But users sometime want to apply subsidence for fixed-bed hydraulic models. Modelers can apply subsidence to a hydraulic model by creating a "dummy" sediment file with simple, synthetic, sediment data, and then set all the cross sections to Pass Through Nodes (see next section). This will signal that HEC-RAS should adjust cross sections due to subsidence but not erosion or deposition.

Set Pass Through Nodes

Classic Pass Through Nodes

Pass through nodes remain fixed throughout the sediment simulation. Sediment that enters the cross- section control volume associated with that cross section leaves that control volume. Capacity for the node is set equal to supply. The cross section will not deposit or erode. This feature was designed for channel bends where multi-dimensional channel dynamics keep sediment from depositing but the one-dimensional transport approach computes deposition. To use this option the user simply selects the river station locations in which they would like all sediment to pass through (i.e. no deposition or erosion)



Select River Station Locations

Selected Locations

River: Big Blue

Reach: above_BlueRapids

RS:
(All RS)
73.00
72.37
70.97
70.31
69.83
69.33
68.83
68.28
67.83
67.33
66.83
66.33
65.29
65.00
64.50
64.00
63.50
63.00
62.50
62.00
61.50
61.00
60.18

Selected Locations (21 selected)

Big Blue	above_BlueRapids10.17
Big Blue	above_BlueRapids9.75
Big Blue	above_BlueRapids9.24
Big Blue	above_BlueRapids8.74
Big Blue	above_BlueRapids8.25
Big Blue	above_BlueRapids7.00
Big Blue	above_BlueRapids6.50
Big Blue	above_BlueRapids6.00
Big Blue	above_BlueRapids5.50
Big Blue	above_BlueRapids5.00
Big Blue	above_BlueRapids4.50
Big Blue	above_BlueRapids4.00
Big Blue	above_BlueRapids3.50
Big Blue	above_BlueRapids3.00
Big Blue	above_BlueRapids2.50
Big Blue	above_BlueRapids2.00
Big Blue	above_BlueRapids1.50
Big Blue	above_BlueRapids1.00
Big Blue	above_BlueRapids0.81
Big Blue	above_BlueRapids0.71
Big Blue	above_BlueRapids0.26

Figure 1-94: Selecting pass through nodes.

Modeling Note – Using Pass Through Nodes to Troubleshoot Models: Pass through nodes can stabilize an unsteady sediment model, focusing bed change on the region of interest, running the rest of the model as flow only. They can also help add complexity incrementally, getting a stable hydraulic model first, then bringing sediment cross sections (upstream to downstream) online incrementally. Additionally, pass through nodes only limit vertical bed change. They do not prevent BSTEM bank failure or toe scour. Therefore, users sometimes use them to isolate bank processes from bed processes.

Pool Pass Through Nodes

Pools are one of the primary applications of pass through nodes. Pools are fundamentally three-dimensional features. One-dimensional morphodynamic models do not simulate helical currents and mobility inversions that maintain pools.[18] Because 1D models do not simulate these multidimensional pool maintenance processes, cross-section averaged models convert the larger cross-section area of pool cross sections to low velocity transport nodes. Therefore, 1D models tend to deposit in pools. These deposits become artificial, numerical, sediment sinks, removing sediment load from the model, and inducing erosion in other cross sections.

Pass-through nodes are one way to mitigate artificial pool deposition in HEC-RAS. Making pools pass-through nodes keeps them "open." Pass through nodes do not erode or deposit. Turning bed change off can seem like an aggressive solution to a numerical artifact, but in most cases, forcing a pool to no-change leads to a more realistic local- and reach-scale model than depositing with the standard morphodynamic equations.

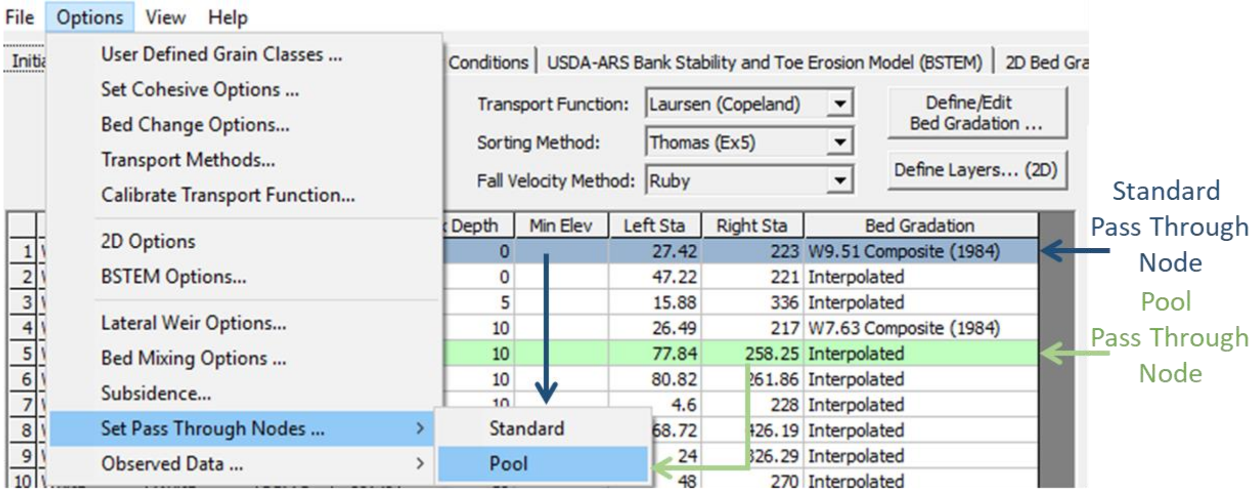
However, if the base-level change of the reach is changing over time, making pools pass-through will fix their elevation, while the rest of the reach rises or falls together. HEC developed the **Pool Pass Through Node** option as an intermediate tool, that allows the pools to adjust with the neighboring cross sections, without over-depositing based on the 1D assumptions.

The **Pool Pass Through Node** applies the transport capacity of the bounding cross section(s) to the specified node. If the modeler selects multiple, consecutive, **Pool Pass Through Nodes**, HEC-RAS will assign the transport capacity of the non-pass through cross section(s) next to the pool pass through cluster. Assigning pool nodes the transport capacity from a "representative" bounding cross section, will allow the pool nodes to erode or deposit at a similar rate as the upstream run or crossing reach, without artificially depositing in a pool that the river keeps open.

Define **Pool Pass Through Node(s)** by selecting the **Options** Menu, and then selecting Set **Pass Through Nodes→Pool**. This will launch a cross section selection dialogue. Select designated Pool Pass Through Cross Sections. The HEC-RAS Sediment Data interface will highlight standard and pool pass through nodes in blue and green respectively to help modelers keep track.

---

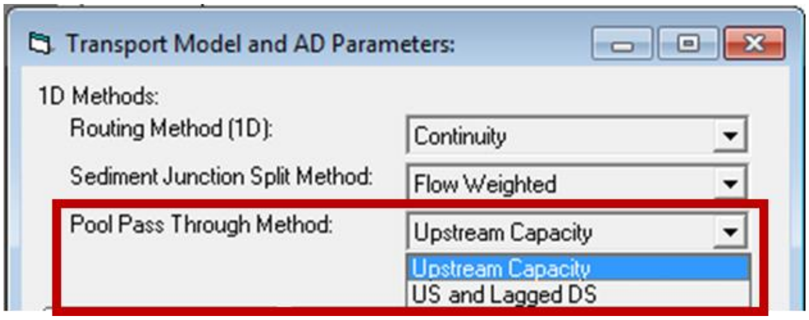
[18] Incidentally, 2D models do not simulate some of these processes either. Three-dimensional modelers in the USACE have found that even 3D models tend to under-represent these process. At this point, most numerical models require some form of empiricism or simplification to simulate transport through pools.



Transport Function: Laursen (Copeland)
Sorting Method: Thomas (Ex5)
Fall Velocity Method: Ruby

	Depth	Min Elev	Left Sta	Right Sta	Bed Gradation
1	0		27.42	223	W9.51 Composite (1984)
2	0		47.22	221	Interpolated
3	5		15.88	336	Interpolated
4	10		26.49	217	W7.63 Composite (1984)
5	10		77.84	258.25	Interpolated
6	10		80.82	261.86	Interpolated
7	10		4.6	228	Interpolated
8			68.72	26.19	Interpolated
9			24	326.29	Interpolated
10			48	270	Interpolated

Because HEC-RAS computes sediment transport from upstream-to-downstream and transport capacity is dynamic based on bed gradation, the **Pool Pass Through Node** option cannot average the upstream and downstream transport capacities during the same time step. So the **1D Methods** under the **Options→Transport Methods** menu offers two different approaches to compute the capacity of **Pool Pass Through Nodes**.



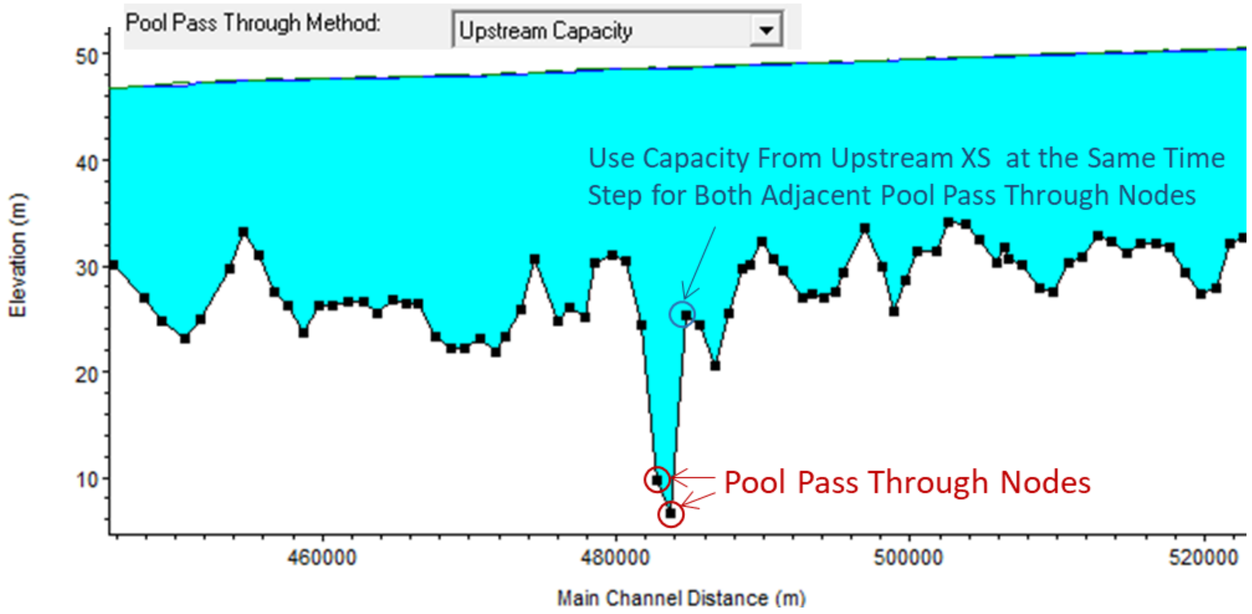
1D Methods:
Routing Method (1D): Continuity
Sediment Junction Split Method: Flow Weighted
Pool Pass Through Method: Upstream Capacity

Figure 1-95: Two computational options for the pool pass through nodes.

Method 1: Upstream Capacity – The **Pool Pass Through Node(s)** adopt the transport capacity of the next upstream cross section that is not a pass through node (from the same time step). See the schematic of this approach below.[19]

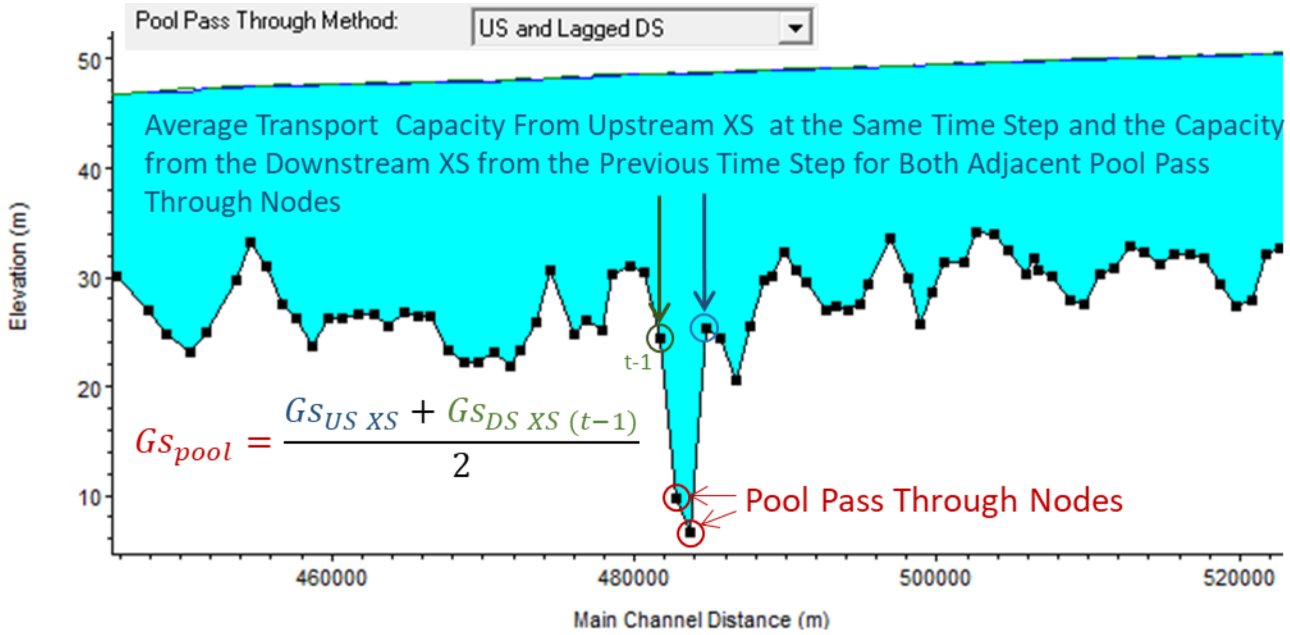
---

[19] This is one of the large bluff-associated pools (#3 in Figures 5 and 8) on the Madeira river documented in Gibson et al (2019) "Two pool-to-pool spacing periods on large sand-bed rivers: Mega-pools on the Madeira and Mississippi," *Geomorphology*, 328, 196-210.



Pool Pass Through Method: Upstream Capacity

Method 2: US and Lagged DS – HEC-RAS averages the transport capacity of the upstream cross section (from the same times step) and the capacity of the downstream cross section at the previous time step. The **Pool Pass Through Node(s)** adopt the averaged of the synchronous upstream capacity and the lagged downstream capacity.



Pool Pass Through Method: US and Lagged DS

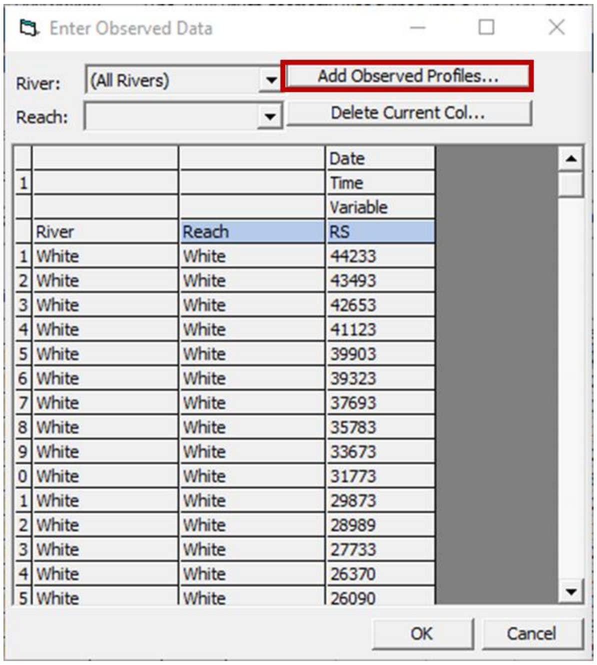
$$Gs_{pool} = \frac{Gs_{US\ XS} + Gs_{DS\ XS\ (t-1)}}{2}$$

Observed Data

The observed sediment data changed substantially in HEC-RAS version 6.0. Previous versions only included one generic observed profile. Current versions allow multiple profiles which can persist throughout the simulation or be associated with particular dates and can be associated with standard HEC-RAS, sediment output variables (to plot with computed results of the same kind) or novel observations that will show up in the sediment results under their own heading.

Observed Profile Data

Select **Observed Profile** data by selecting **Options→Observed Data→Profile**. This will launch the dialogue below. Press the **Add Observed Profiles** button to add observed data. To designate observed data as one of the standard HEC-RAS sediment output variable types (so it shows up just below the computed results with an _obs tag) select one of the variables from the list by double clicking or pressing the arrow. The date and time are optional. Leaving the date and time blank, will generate a persistent observed profile, which will write the observed data to every time step at the specified cross section. Adding a date and time will only write the observed data at the closest output time step to the date and time entered.

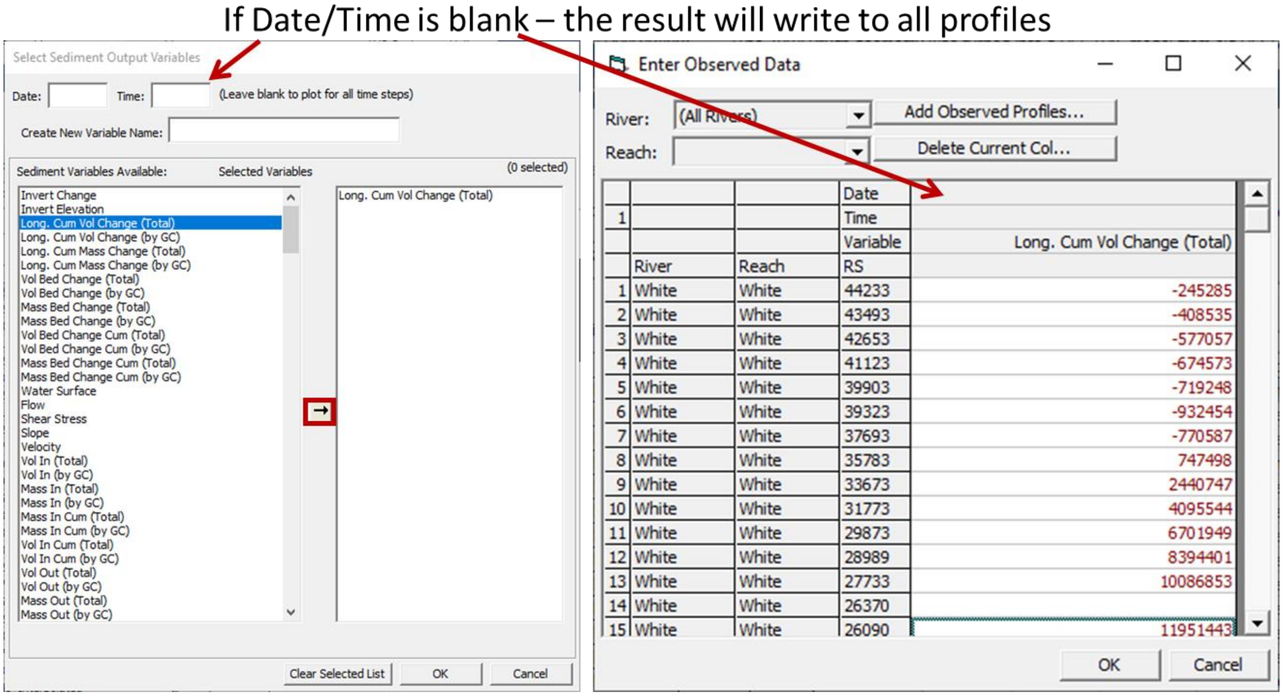


River: (All Rivers)

Reach:

			Date
1			Time
			Variable
	River	Reach	RS
1	White	White	44233
2	White	White	43493
3	White	White	42653
4	White	White	41123
5	White	White	39903
6	White	White	39323
7	White	White	37693
8	White	White	35783
9	White	White	33673
0	White	White	31773
1	White	White	29873
2	White	White	28989
3	White	White	27733
4	White	White	26370
5	White	White	26090

Figure 1-96: Add Observed Profiles.



If Date/Time is blank – the result will write to all profiles

Select Sediment Output Variables

Date: Time: (Leave blank to plot for all time steps)

Create New Variable Name:

Selected Variables (0 selected): Long. Cum Vol Change (Total)

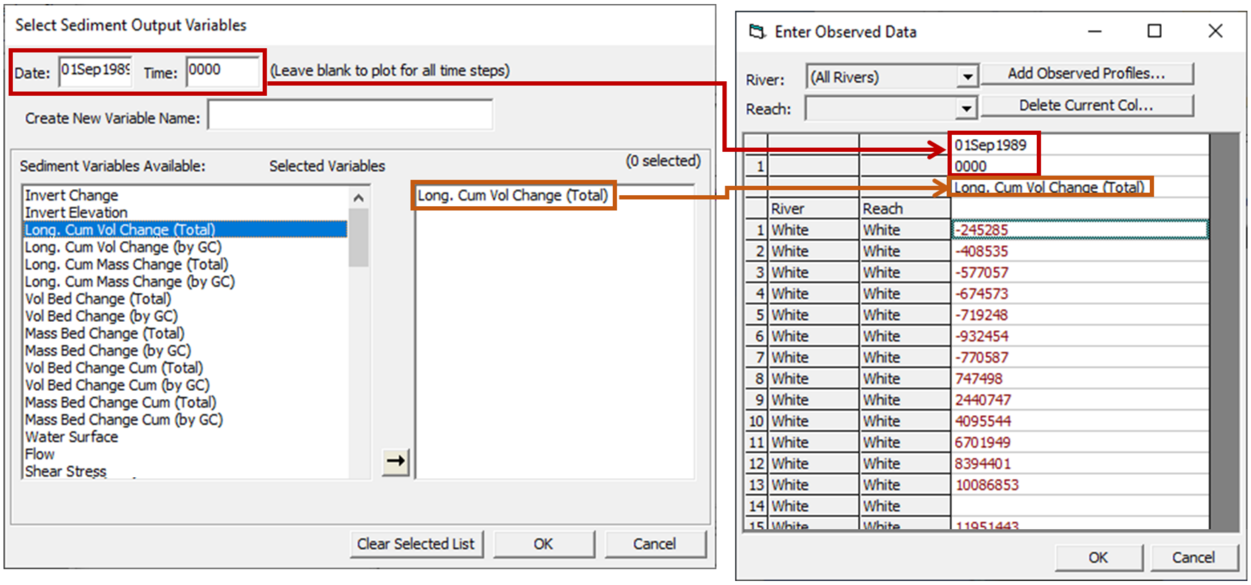
River: (All Rivers)

Reach:

			Date	
1			Time	
			Variable	Long. Cum Vol Change (Total)
	River	Reach	RS	
1	White	White	44233	-245285
2	White	White	43493	-408535
3	White	White	42653	-577057
4	White	White	41123	-674573
5	White	White	39903	-719248
6	White	White	39323	-932454
7	White	White	37693	-770587
8	White	White	35783	747498
9	White	White	33673	2440747
10	White	White	31773	4095544
11	White	White	29873	6701949
12	White	White	28989	8394401
13	White	White	27733	10086853
14	White	White	26370	
15	White	White	26090	11951443

Figure 1-97: Select standard sediment variables to associate observed data with. Leave the date and time blank for these data to show up with all profiles.

Finally, modelers can define a profile (either persistent throughout time or at a particular date) with a customized label. This can be useful if modelers want to coordinate some other system process with flow or sediment results. Type in the new variable name in the **Create New Variable** Name text box instead of selecting a sediment variable, add a date if appropriate, and press **OK.** The figure below adds observations from a hypothetical muskrat survey that will then write to the sediment results file and can be viewed with the other data.



Select Sediment Output Variables

Date: 01Sep198ǃ Time: 0000 (Leave blank to plot for all time steps)

Create New Variable Name:

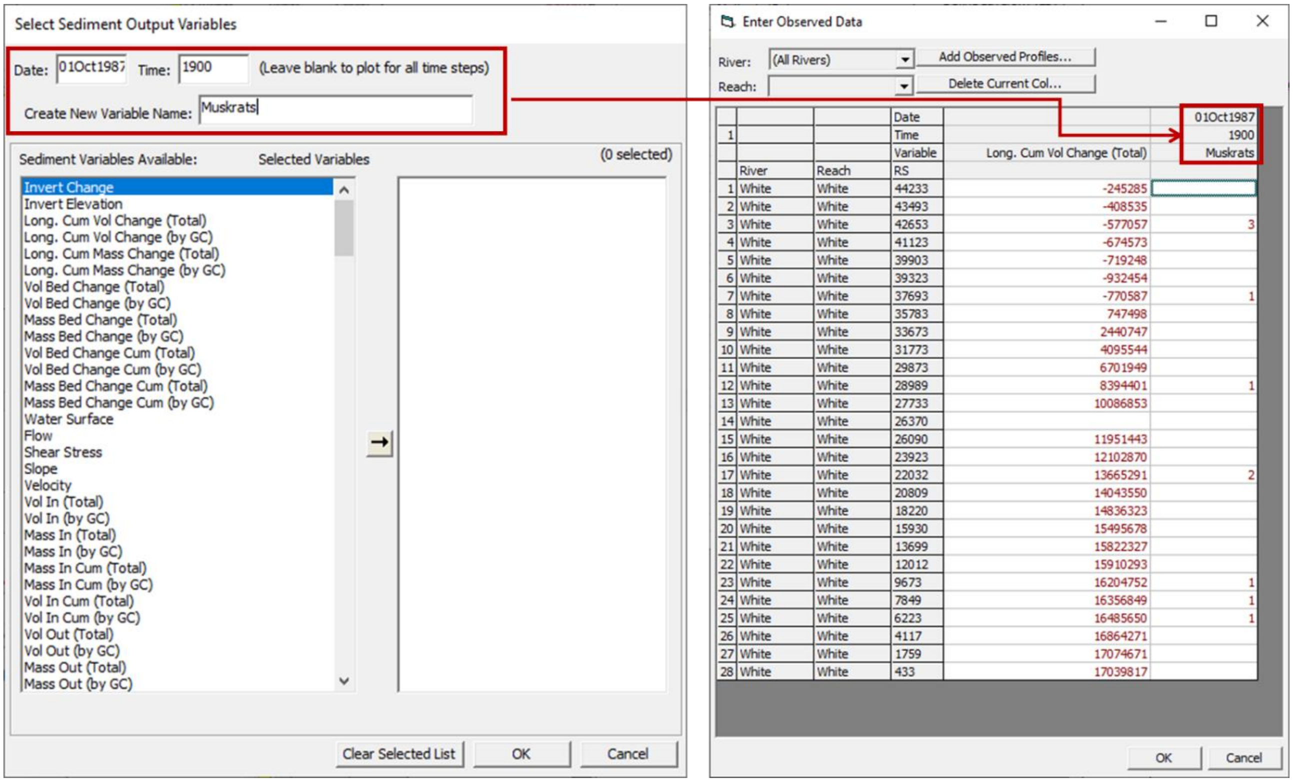
Selected Variables (0 selected): Long. Cum Vol Change (Total)

River: (All Rivers)

Reach:

			01Sep1989
1			0000
			Long. Cum Vol Change (Total)
	River	Reach	
1	White	White	-245285
2	White	White	-408535
3	White	White	-577057
4	White	White	-674573
5	White	White	-719248
6	White	White	-932454
7	White	White	-770587
8	White	White	747498
9	White	White	2440747
10	White	White	4095544
11	White	White	6701949
12	White	White	8394401
13	White	White	10086853
14	White	White	
15	White	White	11951443

Figure 1-98: Define a date and time for profiles for them to show up with the simulated results closest to the date and time.



Select Sediment Output Variables

Date: 01Oct1987 Time: 1900 (Leave blank to plot for all time steps)

Create New Variable Name: Muskrats

Enter Observed Data

River: (All Rivers)

Reach:

			Date		01Oct1987
1			Time		1900
			Variable	Long. Cum Vol Change (Total)	Muskrats
	River	Reach	RS		
1	White	White	44233	-245285	
2	White	White	43493	-408535	
3	White	White	42653	-577057	3
4	White	White	41123	-674573	
5	White	White	39903	-719248	
6	White	White	39323	-932454	
7	White	White	37693	-770587	1
8	White	White	35783	747498	
9	White	White	33673	2440747	
10	White	White	31773	4095544	
11	White	White	29873	6701949	
12	White	White	28989	8394401	1
13	White	White	27733	10086853	
14	White	White	26370		
15	White	White	26090	11951443	
16	White	White	23923	12102870	
17	White	White	22032	13665291	2
18	White	White	20809	14043550	
19	White	White	18220	14836323	
20	White	White	15930	15495678	
21	White	White	13699	15822327	
22	White	White	12012	15910293	
23	White	White	9673	16204752	1
24	White	White	7849	16356849	1
25	White	White	6223	16485650	1
26	White	White	4117	16864271	
27	White	White	1759	17074671	
28	White	White	433	17039817	

*Figure 1-99: Fill in the **Create New Variable Name** to add observations in a profile that is not associated with an HEC-RAS output variable*

Geometric Considerations for a Sediment Transport Model

One of the advantages of using HEC-RAS for a sediment transport simulation is that many systems have existing, fixed bed, HEC-RAS hydraulic models. Because the sediment transport model uses the same geometry file, building the sediment file from an existing sediment model includes some efficiencies. However, there are some considerations with

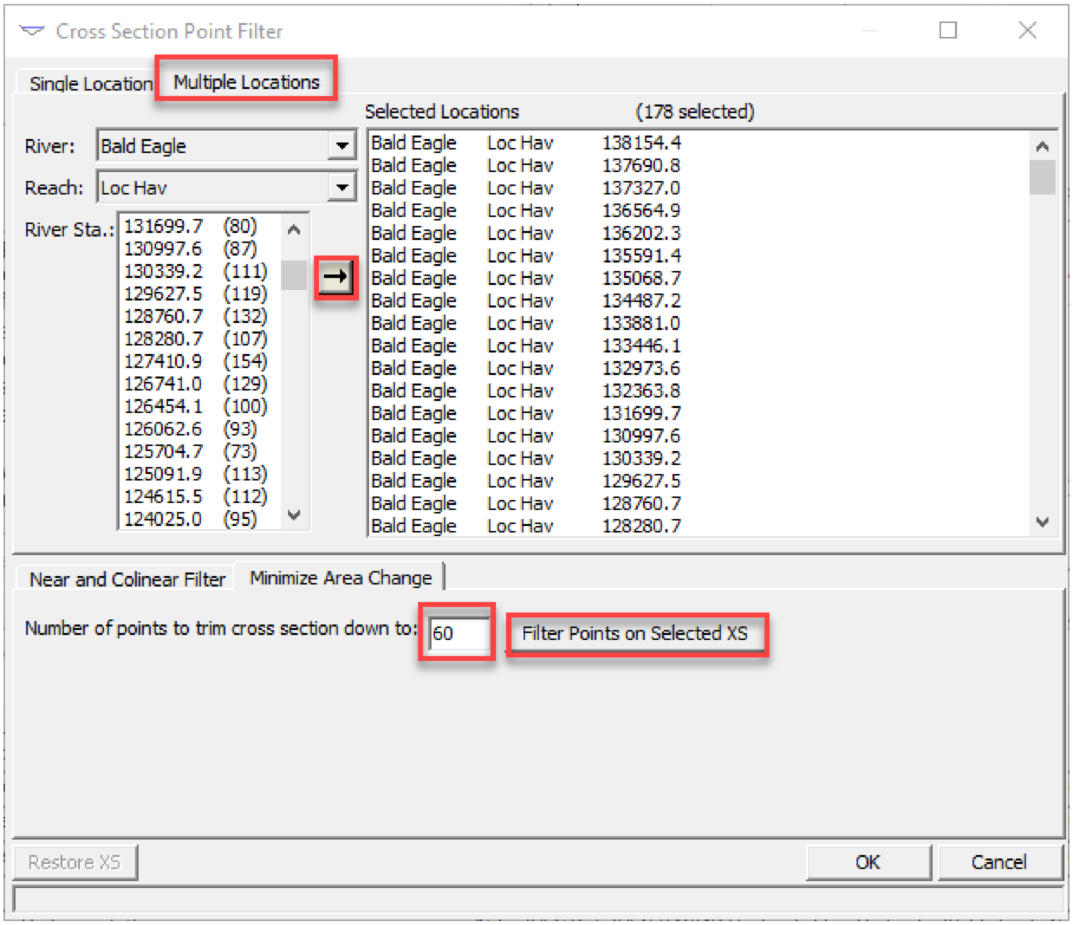
Historic Geometry for a Calibration

Most fixed bed, hydraulic studies in HEC-RAS start with the best, most recent, cross section information available. Sediment studies, however, often start with historic cross sections, and calibrate by running the period of record between these historic cross sections and a contemporary bathymetry. After the model is calibrated, then future projections often start with the best, most recent bathymetry available. But a good set of historic cross sections is one of the most valuable assets a sediment transport study can have.

Filter the Cross Section Points

HEC-RAS limits cross sections to 500 station-elevation points. But 500 points is almost always far more than required to adequately represent the shape of the cross section. In hydraulic modeling, too many station-elevation points can affect run time (which is exacerbated in sediment which runs the steady flow computations every time step) but is mostly innocuous. Dense station-elevation points can cause several issues in a 1D sediment transport model including bed inversion and node stranding.

Almost any cross section can be reasonably represented with 100 station-elevation curves and sediment models often perform best when cross sections are limited to 60 station-elevation points or less. To optimize the shape representation with the fewest station elevation points use the point filter in HEC-RAS. In the geometry file, select **Tools→ Cross Section Point Filter**. See the main HEC-RAS user manual to learn about the different options and how to evaluate the quality of the filter methods, but the simplest method to reduce the cross section point density is to select the **Multiple Location** and **Minimize Area Change** tables (Figure 1-100), and define the maximum station-elevation points. Then press the → button to select all cross sections. Press the **Filter Points on Selected XS** button to filter. Filter Points on Selected XS



River: Bald Eagle

Reach: Loc Hav

River Sta.:

131699.7	(80)
130997.6	(87)
130339.2	(111)
129627.5	(119)
128760.7	(132)
128280.7	(107)
127410.9	(154)
126741.0	(129)
126454.1	(100)
126062.6	(93)
125704.7	(73)
125091.9	(113)
124615.5	(112)
124025.0	(95)

Selected Locations (178 selected)

Bald Eagle	Loc Hav	138154.4
Bald Eagle	Loc Hav	137690.8
Bald Eagle	Loc Hav	137327.0
Bald Eagle	Loc Hav	136564.9
Bald Eagle	Loc Hav	136202.3
Bald Eagle	Loc Hav	135591.4
Bald Eagle	Loc Hav	135068.7
Bald Eagle	Loc Hav	134487.2
Bald Eagle	Loc Hav	133881.0
Bald Eagle	Loc Hav	133446.1
Bald Eagle	Loc Hav	132973.6
Bald Eagle	Loc Hav	132363.8
Bald Eagle	Loc Hav	131699.7
Bald Eagle	Loc Hav	130997.6
Bald Eagle	Loc Hav	130339.2
Bald Eagle	Loc Hav	129627.5
Bald Eagle	Loc Hav	128760.7
Bald Eagle	Loc Hav	128280.7

Number of points to trim cross section down to: 60

Figure 1-100: HEC-RAS cross section point filter editor, with the global tool that minimizes area error with a user-specified cross section limit depicted.

After you filter the cross sections, you can return to the **Single Location** tab and evaluate the filter, making sure it retains the shape of the cross section, and press **Restore XS** if it went poorly.

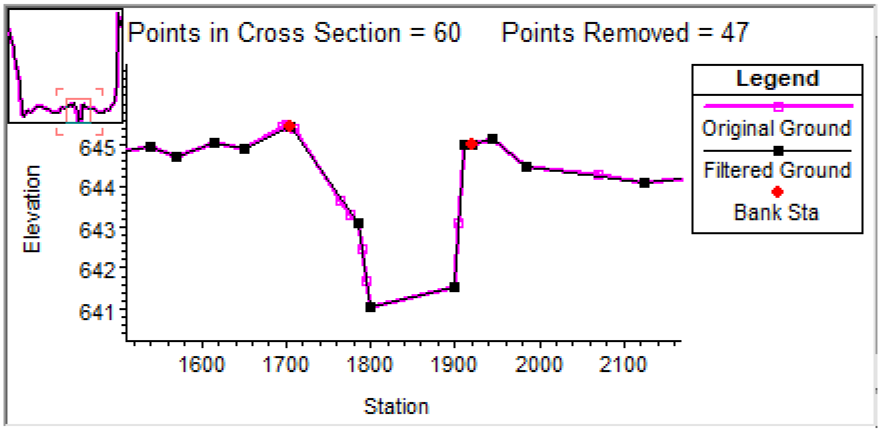


Figure 1-101: Evaluating a filtered XS for shape changes. Pink nodes have been removed.

Modeling Bridges in a Sediment Simulation

The HEC-RAS bridge modeling approaches (particularly Pressure-Weir) can cause instabilities in HEC-RAS sediment models. Bridge cross sections tend to be much closer together than standard cross section spacing. Additionally, the upstream and downstream bridge face cross sections replicate themselves just inside the bridge, which usually generates four tightly spaced cross sections, much closer together than the cross section spacing throughout the rest of the model. This cross section spacing can cause model instabilities and erratic scour patters around structures. There are three main options for dealing with problematic bridges in HEC-RAS.

Option 1: Delete the Bridge:

If the bridge does not affect upstream hydraulics significantly, consider the impact of deleting it. It is common to remove high chord bridges from sediment models. If the bridge does induce upstream backwater effects that affect transport, there are two other common modeling approaches.

Option 2: Bound the Bridge with Pass Through Nodes:

Setting the upstream and downstream cross sections to Pass-Through Nodes will also make the bridge "pass through". Making the bridge a pass through element, converts the bridge into a fixed-bed feature. The model will use the standard HEC-RAS hydraulics to compute backwater effects and bridge influences on hydraulics, without scouring (or depositing) in the bridge itself. This approach leverages the bridge hydraulics capabilities that are useful in a reach-scale model (e.g. backwater effects, not contraction scour) without computing localized sediment effects at the structure, which the 1D, mobile bed model cannot resolve. The pass through bridge approach does make one major assumption. It does not allow reach-wide base level change. If the whole reach incises 1m, the pass through bridge will not, and will create a numerical check dam.

Option 3: Model the Bridge as a Lidded Cross Section:

If bridges cause instabilities in the sediment model but cannot be removed without affecting the hydraulics, consider modeling the bridge with a **Lidded Cross Section** (see discussion of Lidded Cross Sections in the main HEC-RAS manual). Define the bridge as a cross section, including piers as elevated station-elevation points (Figure 1-102). Then, in the cross section editor, select **Options → Add Lid to XS…** to model the bridge deck as a lid. Lidded cross sections do not provide full bridge hydraulics computations. HEC-RAS will not compute pressure flow or momentum loss at lidded cross section. But lidded cross sections (with piers represented in station elevation data) will account for bridge area and wetted perimeter, solving the energy equation.

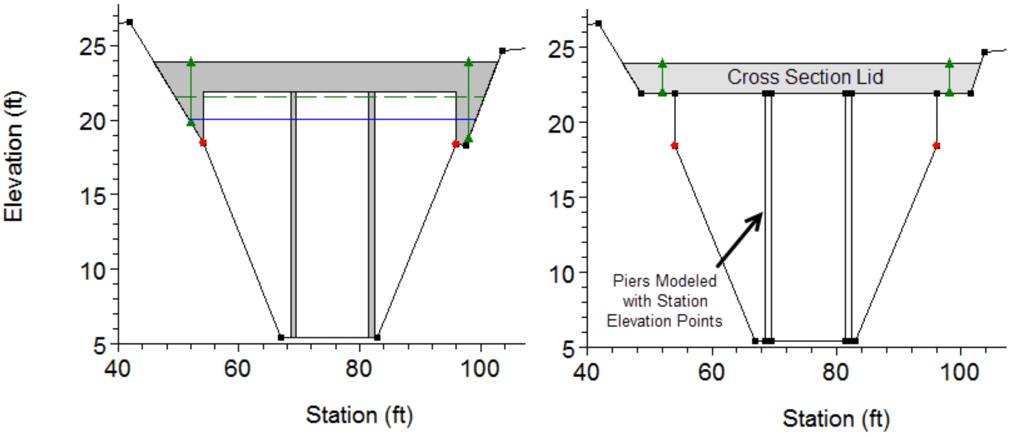


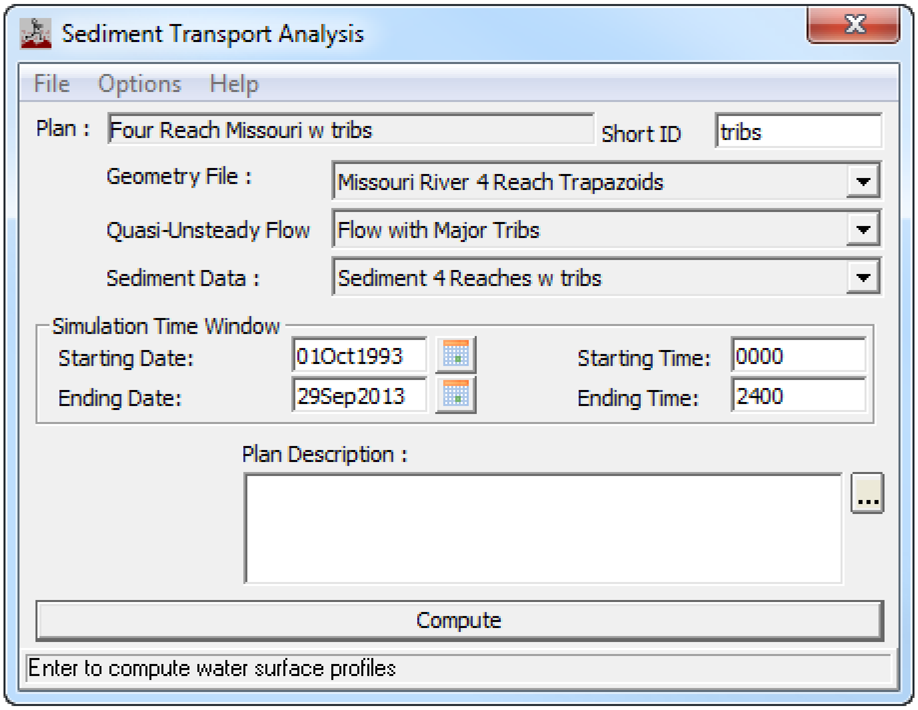
Figure 1-102: HEC-RAS bridge (left) modeled as a lidded cross section (right).

Simulating Sediment Transport

Creating a Plan

For sediment transport computations, the user is required to create a Plan file. A sediment plan includes a geometry file (.gxx), a sediment file (.zxx), a flow file (quasi-unsteady: .qxx), and some plan level options data. To create and simulate a quasi-unsteady sediment model, open **Sediment Analysis** under the **Run** menu on the main HEC-RAS dialog or press the **Sediment Analysis** button. When this option is selected, the Sediment Transport Analysis window will appear as shown in Figure 1-103.

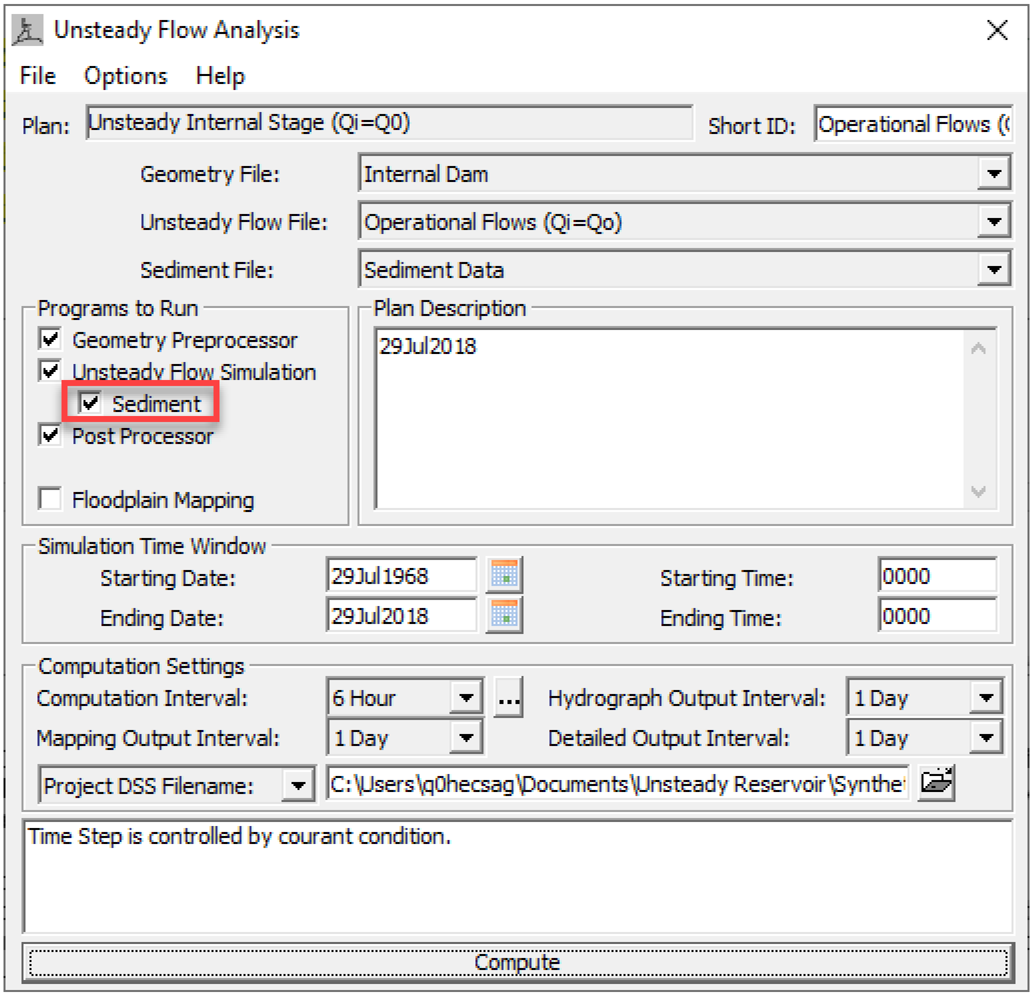
As with Unsteady Flow, a time window must also be specified for the sediment analysis. This requires start and end dates (in DDMMMYYYY format) as well as start and end times (2400 clock) in the **Simulation Time Window** (Figure 1-103).



Plan : Four Reach Missouri w tribs
Short ID tribs
Geometry File : Missouri River 4 Reach Trapazoids
Quasi-Unsteady Flow Flow with Major Tribs
Sediment Data : Sediment 4 Reaches w tribs
Simulation Time Window
Starting Date: 01Oct1993
Ending Date: 29Sep2013
Starting Time: 0000
Ending Time: 2400
Plan Description :
Enter to compute water surface profiles

Figure 1-103: Sediment analysis window.

To create and simulate an unsteady sediment plan, open the **Unsteady Flow Analysis** editor by selecting it from the **Run** menu or pressing the **Unsteady Analysis** button.



Plan: Unsteady Internal Stage (Qi=Q0) Short ID: Operational Flows (

Geometry File: Internal Dam

Unsteady Flow File: Operational Flows (Qi=Qo)

Sediment File: Sediment Data

Programs to Run

☑ Geometry Preprocessor
☑ Unsteady Flow Simulation
  ☑ Sediment
☑ Post Processor

☐ Floodplain Mapping

Plan Description: 29Jul2018

Simulation Time Window

Starting Date: 29Jul1968 Starting Time: 0000
Ending Date: 29Jul2018 Ending Time: 0000

Computation Settings

Computation Interval: 6 Hour Hydrograph Output Interval: 1 Day
Mapping Output Interval: 1 Day Detailed Output Interval: 1 Day

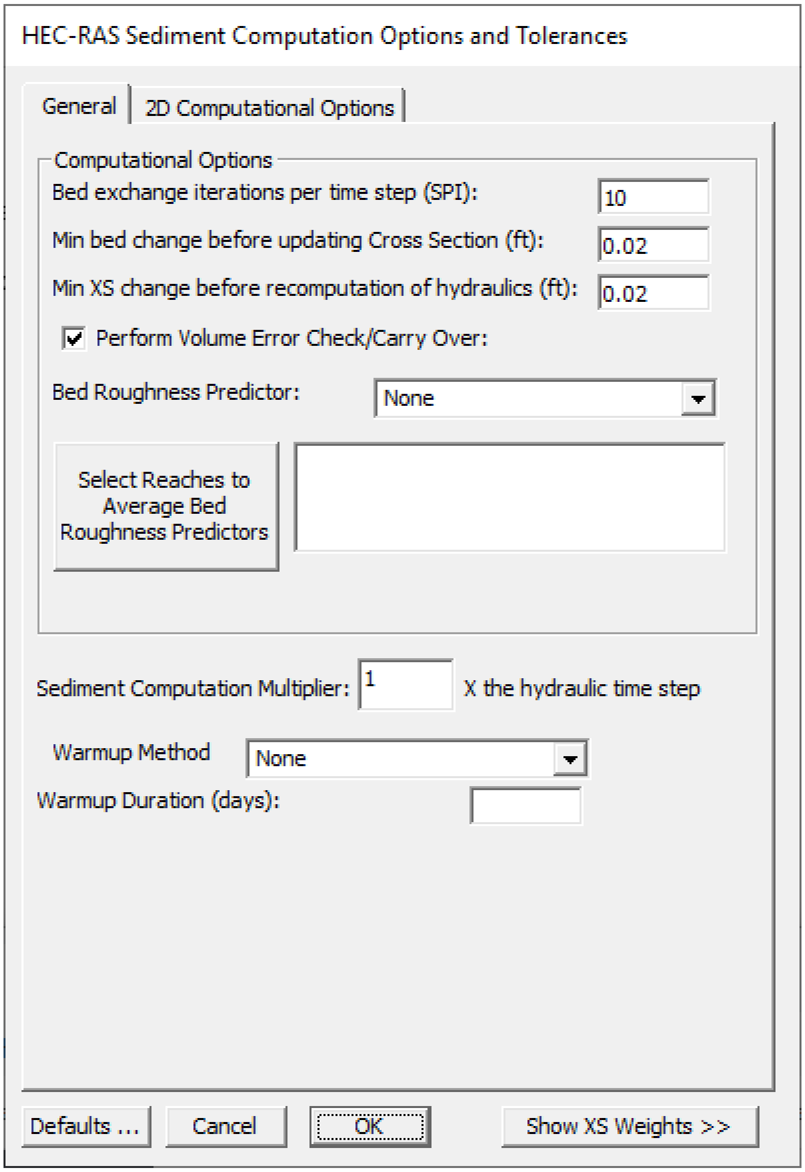
Project DSS Filename: C:\Users\q0hecsag\Documents\Unsteady Reservoir\Synthe

Time Step is controlled by courant condition.

Figure 1-104: Unsteady flow analysis.

Sediment Computation Options and Tolerances

HEC-RAS includes several settings and model coefficients under the **Options** menu of the Sediment Analysis dialog. Many of these **Options** are identical to those in the Steady Flow Analysis dialog and are documented in The Steady Flow manual. However, there are four **Options** specific to **Sediment Transport Analyses**. Sediment specific options include the **Sediment Computation Options and Tolerances, Transport Energy Slope**, and **Sediment Output Options** menu items available from the **Options** menu of the Sediment Transport Analysis window. When this option is selected, a window will appear as shown in Figure 1-105.



Bed exchange iterations per time step (SPI): 10
Min bed change before updating Cross Section (ft): 0.02
Min XS change before recomputation of hydraulics (ft): 0.02
☑ Perform Volume Error Check/Carry Over:
Bed Roughness Predictor: None
Sediment Computation Multiplier: 1 X the hydraulic time step
Warmup Method: None
Warmup Duration (days):

Figure 1-105: Sediment Computations Options and Tolerances Menu.

Bed Exchange Iterations:

The mixing and armoring algorithms update several times per computational interval. HEC-RAS subdivides the computational increments into mixing time steps or **Bed Exchange Iterations**. Set the **Bed Exchange Iterations** (SPI factor in HEC-6) to control the mixing updates per computation increment. For example, if **Bed Exchange Increments** variable is 10 (default) HEC-RAS will update the mass and gradation of the bed layers every 10% of the computation increment, updating bed layer gradations and exchange increments ten time between backwater and bed change computations. Sorting and armoring iterations are important to track supply limitation in order to keep the model from over predicting erosion. However, they also affect run times. The recommended range for this parameter is 1 to 50. Start with a high **Bed Exchange Iteration Per Time Step** value and drop it as much as possible without changing the results. (Figure 1-105)

Minimum Bed Change Before Updating Cross Section:

HEC-RAS does not update the cross sections every computational increment. Instead it tracks erosion or deposition at a cross section until a minimum bed change is achieved. When this threshold is exceeded at one of the cross sections the bathymetry is re-computed. The default is 0.02 feet which will generally be exceeded in streams with relatively active beds. This tolerance can be increased to lower run times or decreased to make the model more sensitive to bed change.

Modeling Note – Min Bed Change and Stability: The hydraulic and bed change thresholds are legacy features. They do not often improve run times dramatically and can introduce instabilities, particularly in simplified channels. Test the sensitivity of these parameters. If they do not improve run times, consider setting them to 0.

Minimum Cross Section Change Before Hydraulic Update:

Similarly, hydraulic parameters are not automatically computed after each computational increment unless one of the cross sections has undergone appreciable change. This conserves computational resources since the frequency with which hydraulic computations are performed drives run times. This parameter is, by default, set equal to the **Minimum Bed Change Before Updating Cross Section** parameter so that every time the cross sections change, the hydraulics are recomputed but can be edited separately.

Volume Change Method: HEC-RAS computes deposition or erosion in mass. Then it coverts mass to a uniform vertical bed change, applied to all wetted nodes in the movable bed limits. This computation requires iteration to converge on a precise solution, which is computationally expensive. Instead, HEC-RAS converts the computed bed change into mass change (by computing the area change between the original and updated cross sections), compares it to the computed mass change, and carries remainders over into the next time step. HEC-RAS selects this option by default. It is recommended unless results are being compared with HEC-6 which does not use this option.

Modeling Note – Volume Check and BSTEM: HEC-RAS will not apply the volume check for cross sections selected for USDA-ARS Bank Stability and Toe Erosion (BSTEM) modeling (even if it is checked), because volume change in that module is incompatible with this feature.

Bed Roughness Predictors

HEC-RAS includes multiple methods to vary channel roughness spatially or temporally. HEC-RAS can vary manning n value as a function of flow, stage, lateral station, or season. Calibrating one-dimensional hydraulic models often requires process dependent roughness parameters. Use these features to calibrate a steady or unsteady flow hydraulic model *before* adding sediment data.

However, bed roughness can also vary based on sediment dynamics. These are discussed in detail in the Technical Reference Manual.

Limerinos:

The Limerinos method is a relatively simple equation based on the d_{84} and hydraulic radius, with no consideration for bed form mechanics. Therefore, it should be applied mainly to coarse, gravel and cobble systems where the grain roughness is the primary source of channel roughness.

Brownlie:

Brownlie (1983) computed bed roughness based on bed form mechanics in large rivers. In particular, he tried to capture the non-linear drop in roughness when bed form dominated transport shifts from lower to higher regimes (EM 4000). Brownlie, evaluates the bed form regime based on hydraulic parameters, grain size, and the gradational distribution, then applies separate equations for low and high regime transport.

Van Rijn:

Van Rijn (1984) is based on flume and field data. Van Rijn computes bed form dimensions from flow and sediment parameters and converts these into equivalent bed roughness. This method was designed to compute bed roughness in both dune and plane bed regimes.

Modeling Note – Check Roughness Predictors: 1D modelers have had mixed success with automated n-value equations. It can be valuable to calculate a dynamic n-value based on evolving hydrodynamic and sediment conditions, but n-value is a very sensitive parameter in sediment models, and is should be calibrated during the hydraulic modeling. Check the n-values computed by these equations against those selected during the hydraulic calibration. Or run a sediment model without bed-change (by making all the nodes pass-through) to see the range of computed n-values for the hydraulic simulation alone. If the equations are not computing n-values that calibrate the hydraulic model, they are not appropriate for a sediment model.

Reach Averaging Bed Roughness Predictors:

Bed roughness predictors can be noisy. Calculating separate roughness parameters for each cross section based on dynamic hydraulic and sediment parameters can make roughness vary erratically both in space and time, sometimes switching regimes from cross section to cross section or time step to time step. The reach average tool smooths these effects.

Group sequential cross sections with similar morphological setting (e.g. flow, slope, gradation) into a ‘bed roughness averaging reach’ by pushing the button: **Select Reach to Average Bed Roughness Predictors.** HEC-RAS will average the hydraulic and sediment parameters for the cross sections included in each reach and use the average values to compute a single bed roughness for all included cross sections. This tends to smooth the results in space and time. Any cross section not included in a reach will compute bed roughness locally, based on its own parameters.

Sediment Computation Run Time Multiplier

The **Sediment Computation Time Multiplier** allows users to decouple the time step for unsteady hydraulics and sediment transport. For stability, the unsteady hydraulic computations in HEC-RAS often require smaller time steps than the sediment model requires. But the sediment computations are a significant portion of the run time.

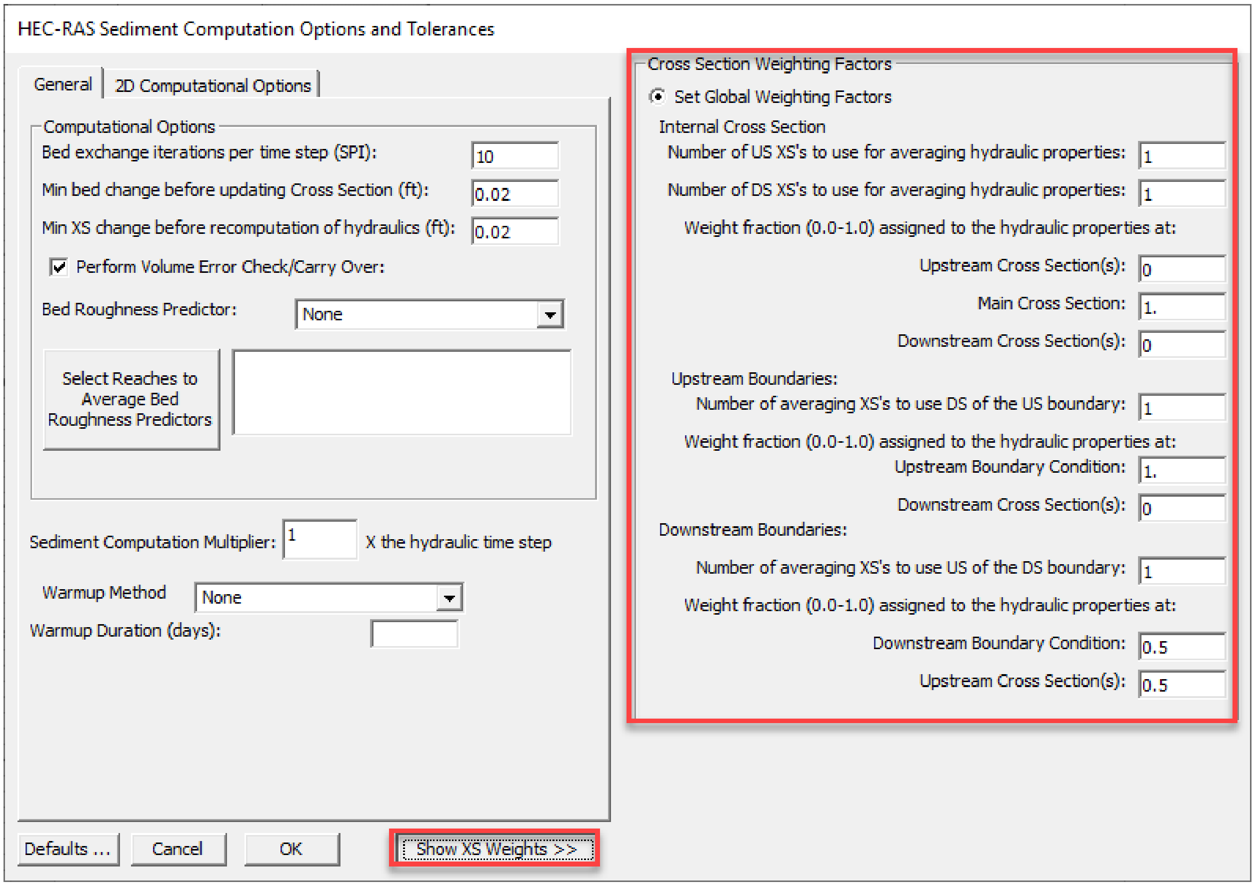
This method allows users to run sediment computations at some multiple of the hydraulic time step. For example, if the hydraulic model is stable at 6 seconds, and this multiplier is set to 10, HEC-RAS would compute sediment transport with a 1 minute computation increment.

Modelers can use this feature in conjunction with the Unsteady Hydraulics **Advanced Time Step Control** to optimize the stability-run time trade off.

Cross Section Weighting Factors (Default Recommended)

Cross sections are a bathymetric sample of the river form over a particular reach. Depending on their location, they can approximate the channel form and transport capacity well, or poorly. A 1D model assumes the cross section is representative of the control volume. Small divergences between the measured cross section and the reach-average behavior do not usually trouble hydraulic simulations (unless cross section selection is egregious, like missing a control point or non-orthogonal placement). But small hydrodynamic differences between cross sections can causes local deposition and erosion in an equilibrium sediment transport model.

Transport capacity fluctuates from cross section to cross section due to random changes in transport capacity. Sediment scoured from one cross section is often deposited in the next cross section. This numerical artifact often generates oscillations, alternating erosion-deposition patterns, particularly early in a simulation.



Bed exchange iterations per time step (SPI): 10

Min bed change before updating Cross Section (ft): 0.02

Min XS change before recomputation of hydraulics (ft): 0.02

☑ Perform Volume Error Check/Carry Over:

Bed Roughness Predictor: None

Sediment Computation Multiplier: 1 X the hydraulic time step

Warmup Method: None

Warmup Duration (days):

● Set Global Weighting Factors

Internal Cross Section

Number of US XS's to use for averaging hydraulic properties: 1

Number of DS XS's to use for averaging hydraulic properties: 1

Weight fraction (0.0-1.0) assigned to the hydraulic properties at:

Upstream Cross Section(s): 0

Main Cross Section: 1.

Downstream Cross Section(s): 0

Upstream Boundaries:

Number of averaging XS's to use DS of the US boundary: 1

Weight fraction (0.0-1.0) assigned to the hydraulic properties at:

Upstream Boundary Condition: 1.

Downstream Cross Section(s): 0

Downstream Boundaries:

Number of averaging XS's to use US of the DS boundary: 1

Weight fraction (0.0-1.0) assigned to the hydraulic properties at:

Downstream Boundary Condition: 0.5

Upstream Cross Section(s): 0.5

Figure 1-106. Cross Section Weights Editor (Press the Show XS Weights>> to show this).

HEC 6 introduced cross section weighting factors to smooth out these effects. Cross section weighting factors average the hydrodynamic parameters of several cross sections to compute transport capacity. Earlier versions of HEC-RAS adopted this feature as well as the 0.25-0.5-0.25 weighting default. This default gave half the weight to the computational cross section, and quarter weight to the upstream and downstream cross sections. The upstream and downstream weights could also be spread over multiple cross sections.

However, these weighting factors can also cause model instabilities (see Modeling Note). The defaults for this method changed in version 5.0, and more recent versions de-emphasized this feature even more, by requiring users to press a button to view this feature.

HEC-RAS retains hydraulic weighting for backward compatibility and user flexibility, but it is not recommended for most models, particularly simplified cross sections (e.g. trapezoid or rectangular channels). Current versions of HEC-RAS include “Warm Up” and hotstart options to deal with early simulation cross section adjustments.

Modeling note – Saw Tooth Instability and Weighting Factors: A “Saw Tooth” instability often indicates errors propagated by cross section weighting factors. Weighting factors are particularly problematic with rectangular, trapezoidal, or other simple cross sections. Try setting weighting factors to 0-1-0, which will only use hydrodynamics from the current cross section for sediment capacity calculation.

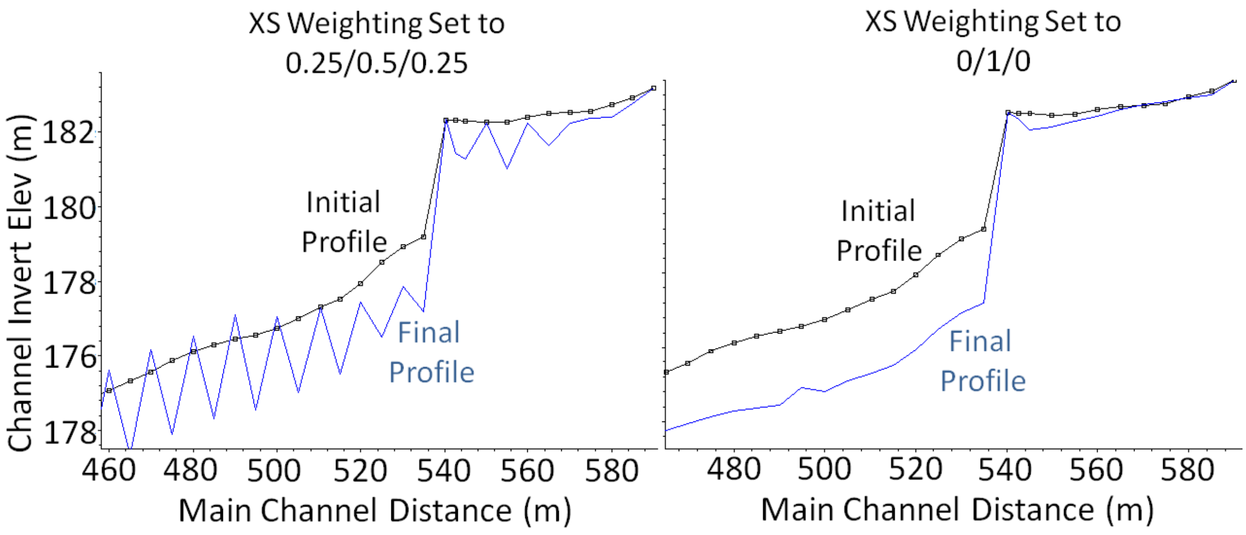


Figure 1-107: "Saw tooth" instability from averaging hydraulic properties over a discontinuity (left) compared to the stable solution that does not average hydraulic properties, only using the hydraulic properties of the cross section associated with the sediment control volume (right).

2D Computational Options

See the HEC-RAS 2D sediment manual for discussion of these options.

Dredging

Dredging removes sediment from the river beds mechanically. These processes can introduce system feedback (e.g. inducing deposition) and often must be modeled explicitly, because transport and continuity equations cannot account for anthropogenic processes. Therefore, HEC-RAS includes dredging capabilities, with multiple methods to incorporate dredging into sediment simulations. Go to **Options** menu of the **Sediment Analysis Editor** to find the **Dredging Events Editor** (Figure17-26)**.** HEC-RAS 5.0 includes several new dredging features.

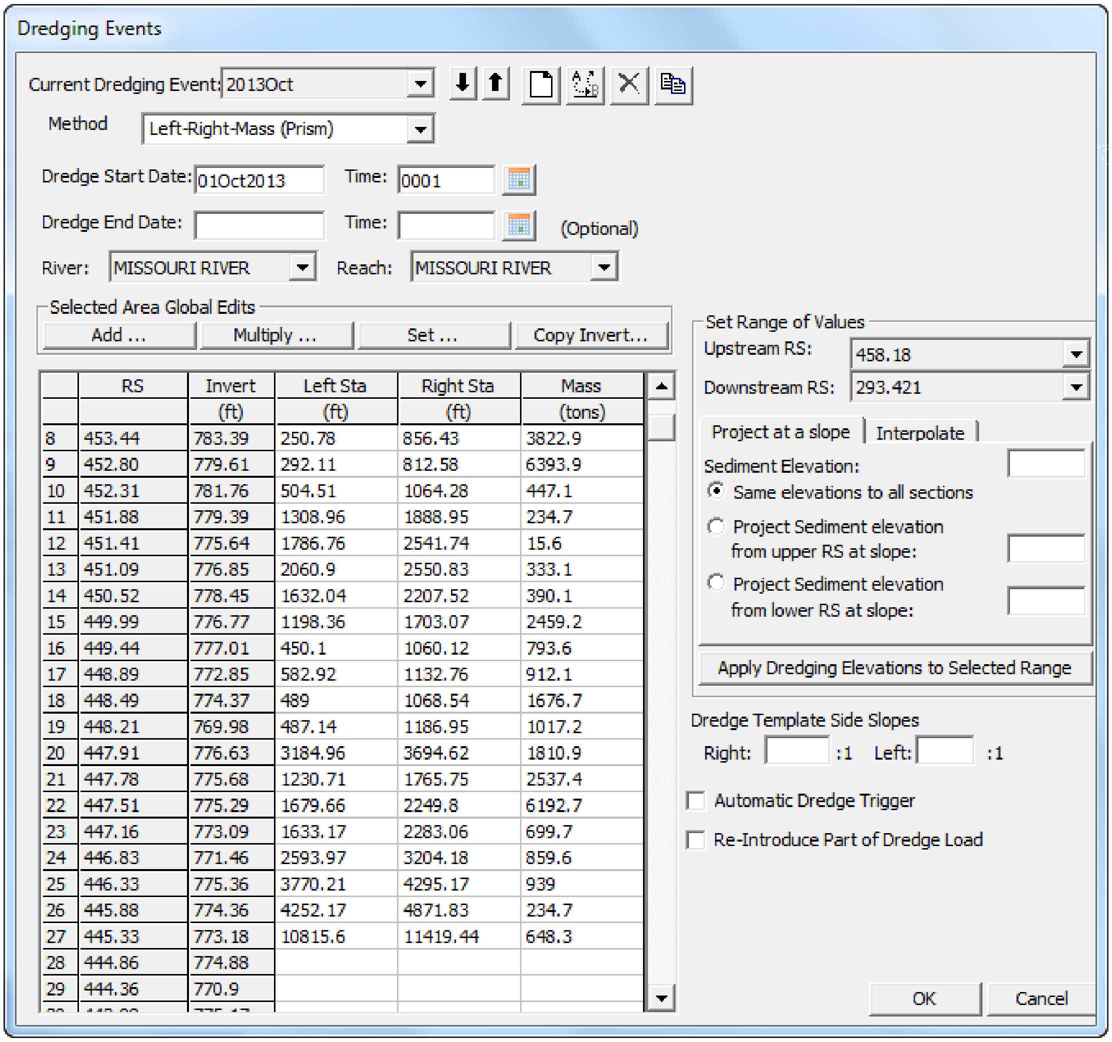
Create a **Dredging Event** by pressing the **New Dredging Event** button 🗋. A dredging event removes sediment from a cross section or cross sections at the **Dredging Start Time** or between the **Dredging Start Time** and **Dredging End Time**. Simulate complex dredging configurations or recurring dredging schedules over an extended simulation by defining multiple **Dredging Events.**

Select a **Method** for each **Dredging Event**. There are seven dredging methods, including two basic types: Elevation (the first three) and Mass (the last four).

Elevation Methods:

The elevation methods are generally for navigational dredging, where dredges remove sediment from the bed to a new bed elevation specified *a priori*. (See the Dredging Model in the Sample Data Sets). These methods superimpose a rectangular template on the cross section and remove all the material within.

Three ***Elevation Methods***, which define the **Elevation and Lateral Extent** of dredging. The ***Elevation Methods*** remove whatever sediment found in a spatial template. The **Dredging Editor** also includes four Mass Methods, methods that remove a prescribed mass from the cross section. The different methods take different approaches to translate the mass removal into cross section change.



Dredging Events

Current Dredging Event: 2013Oct

Method: Left-Right-Mass (Prism)

Dredge Start Date: 01Oct2013 Time: 0001

Dredge End Date: Time: (Optional)

River: MISSOURI RIVER Reach: MISSOURI RIVER

	RS	Invert (ft)	Left Sta (ft)	Right Sta (ft)	Mass (tons)
8	453.44	783.39	250.78	856.43	3822.9
9	452.80	779.61	292.11	812.58	6393.9
10	452.31	781.76	504.51	1064.28	447.1
11	451.88	779.39	1308.96	1888.95	234.7
12	451.41	775.64	1786.76	2541.74	15.6
13	451.09	776.85	2060.9	2550.83	333.1
14	450.52	778.45	1632.04	2207.52	390.1
15	449.99	776.77	1198.36	1703.07	2459.2
16	449.44	777.01	450.1	1060.12	793.6
17	448.89	772.85	582.92	1132.76	912.1
18	448.49	774.37	489	1068.54	1676.7
19	448.21	769.98	487.14	1186.95	1017.2
20	447.91	776.63	3184.96	3694.62	1810.9
21	447.78	775.68	1230.71	1765.75	2537.4
22	447.51	775.29	1679.66	2249.8	6192.7
23	447.16	773.09	1633.17	2283.06	699.7
24	446.83	771.46	2593.97	3204.18	859.6
25	446.33	775.36	3770.21	4295.17	939
26	445.88	774.36	4252.17	4871.83	234.7
27	445.33	773.18	10815.6	11419.44	648.3
28	444.86	774.88			
29	444.36	770.9			

Set Range of Values

Upstream RS: 458.18

Downstream RS: 293.421

Sediment Elevation:

● Same elevations to all sections

○ Project Sediment elevation from upper RS at slope:

○ Project Sediment elevation from lower RS at slope:

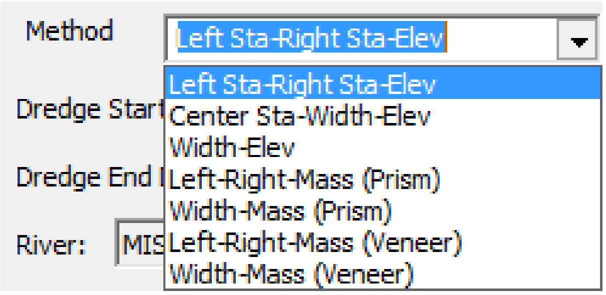
Dredge Template Side Slopes

Right: :1 Left: :1

☐ Automatic Dredge Trigger

☐ Re-Introduce Part of Dredge Load

Figure 17-26. Dredging events editor.



Method: Left Sta-Right Sta-Elev

Figure 1-108: Dredging Methods.

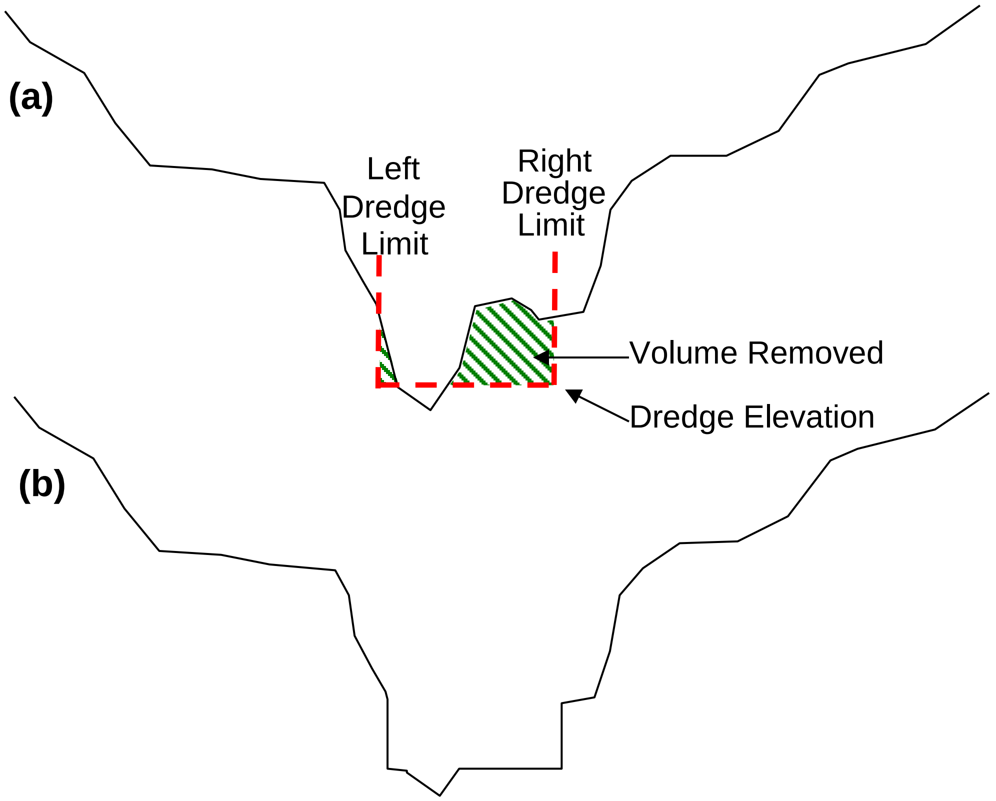


Figure 1-109: The top image (a) illustrates a schematic of a dredging template and an example cross section. All of the material inside the volume is removed at the dredge event time. The resulting cross section is depicted in (b) the bottom image.

The three elevation methods all remove sediment to the specified elevation but offer options for defining the horizontal dredging extents.

Left Sta–Right Sta–Elev: Input three parameters for each dredged cross section, including the left and right stations that bound the dredge template and the bottom elevation.

Center Station–Width–Elev: Sometimes dredging schedules are not defined in absolute cross section stations but width around a center station. In this method, define the center station of the dredge prism and the width.

Width–Elev: Computing the precise right and left dredge extent stations or the centerline can be time consuming and iterative in complex models with many alternatives. The Width-Elev method can expedite preliminary alternative analysis, requiring only the width and elevation of the dredge prism. HEC-RAS will then center it between the bank stations.

Mass Methods:

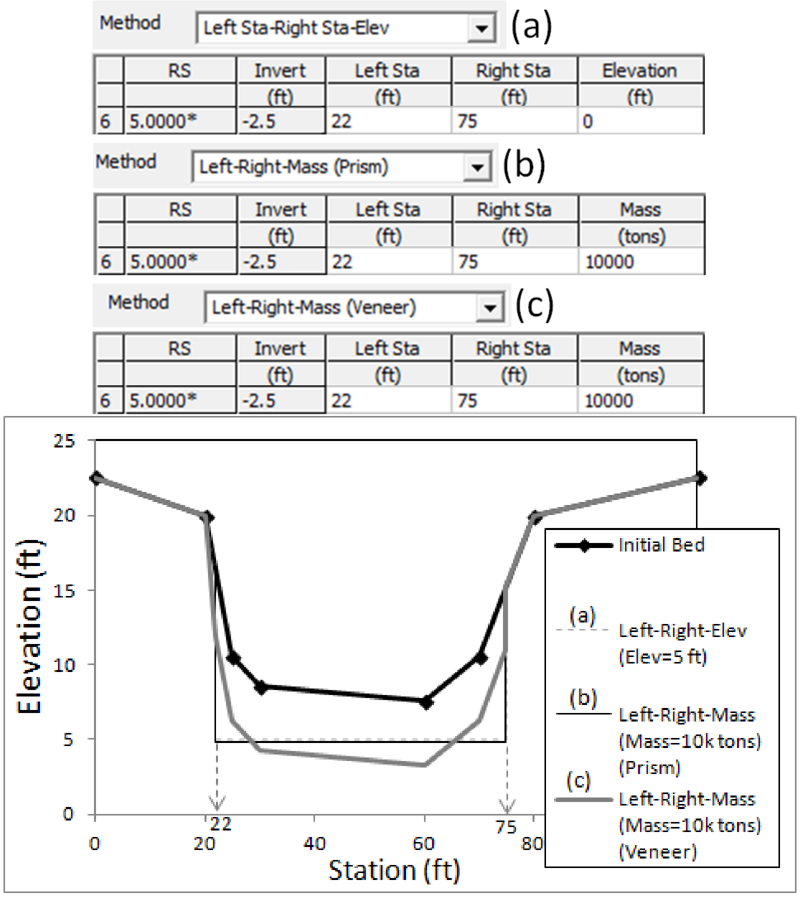
Sometimes dredge mass is known and the geometry of the dredge cut is not known. This is often the case for in-channel aggregate mining where historical records and permits specify mass. The mass methods remove user specified sediment mass from the cross section. The four mass options offer flexibility to translate mass removal into cross section change.

Left–Right–Mass (Prism): This feature is analogous to the **Left Sta–Right Sta–Elev** method. Input the left and right stations that bound the dredge template in precisely the same way. However, instead of specifying an elevation, specify the mass removed from that cross section, and given the dredging extents, HEC-RAS will calculate elevation, removing material from a rectangular dredging template (Prism) that removes the specified mass.

Width-Mass (Prism): This feature is analogous to the **Width–Elev** feature. It centers the rectangular dredge cut between the channel banks, computing the bottom elevation that removes the mass from the specified width.

Left–Right–Mass (Veneer): This method is similar to **Left–Right–Mass (Prism)**, except that dredged mass is no longer removed as a prism, but by the rules of the veneer method HEC-RAS uses to deposit and erode cross sections by other processes. HEC-RAS drops cross section nodes uniformly between the dredged limits (**Right** and **Left**) until cross section change reflects the dredged mass.

Width-Mass (Veneer): This method is identical to **Left–Right–Mass (Veneer)**, except that instead of dropping bank stations uniformly between user specified left and right dredge limits, nodes are dropped if they fall within the specified with between the movable bed limits.



Method: Left Sta-Right Sta-Elev (a)

	RS	Invert (ft)	Left Sta (ft)	Right Sta (ft)	Elevation (ft)
6	5.0000*	-2.5	22	75	0

Method: Left-Right-Mass (Prism) (b)

	RS	Invert (ft)	Left Sta (ft)	Right Sta (ft)	Mass (tons)
6	5.0000*	-2.5	22	75	10000

Method: Left-Right-Mass (Veneer) (c)

	RS	Invert (ft)	Left Sta (ft)	Right Sta (ft)	Mass (tons)
6	5.0000*	-2.5	22	75	10000

Figure 1-110: Input data (top) and HEC-RAS dredge geometry (bottom) for comparable a) the Left-Right-Elevation, b) Left-Right-Mass (Prism), and c) Left-Right Mass (Veneer) parameters.

Dredge End Date

Previous versions of HEC-RAS followed HEC 6, removing dredged mass instantaneously, in the time step closest to the **Dredge Event Start Date/Time**. Users could specify staged dredging with multiple dredging events, but this was tedious and still discontinuous. Instantaneous dredging is still the default method. All of the dredge methods only require one date. However, HEC-RAS 5.0 includes the option to distribute dredging over a time window, but pairing a **Dredge Start Date** with a **Dredge End Date**. This distributes the prescribed dredging over a time window.

The Dredge End Date was added to use with the four *Mass* dredge methods. Dividing a specified dredged mass over several time steps, removing proportional mass from each one is straight forward. Dredging end dates are a little more complicated in association with the E*levation* methods, because it has to update the scour rate to account for cross section aggradation or degredation over the dredge window, to arrive at the specified elevation at the end of the dredge window.

Set Range of Values

Dredging elevations are often constant over reaches or zones, making them easy to specify. However, HEC-RAS includes tools to project non-uniform dredge elevations at a slope upstream or downstream. The Set Values tools were adopted from the Channel Modification editor (link) to project dredge cut elevations.

Re-Introduce part of Dredged Load

Most dredge methods do not remove 100% of sediment but re-entrain sediment that was not actively transporting in the navigation channel. Users can model the fate and transport of these materials with the Reintroduction Dredge feature.

Click on the **Re-Introduce Part of Dredge Load** feature in the **Dredging Editor** (Figure 1-52), which will reveal the features in Figure 1-111.

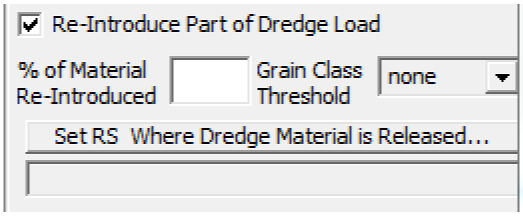


Figure 1-111: Re-Introduce Part of Dredge Load, options.

% or Material to Re-Introduce:

HEC-RAS will monitor dredged mass and will re-introduce this, user specified percentage, back into the model as Mass In (mass flowing into the control volume, as if it were coming in from a lateral boundary or upstream cross section). It will re-introduce mass proportional to the gradation of the mass removed (usually the gradation of the active layer).

Grain Class Threshold:

Of course, not all grain classes are likely to be lost during the dredge process. Fines are far more likely to re-entrain and transport downstream while gravel losses are usually too small to care about and immediately re-deposit. The **Grain Class Threshold** is a filter. Only grain classes finer than this threshed is re-entrained.

Set RS Where Dredge Material is Released:

Dredged materials are not always re-entrained where they are extracted. Push the **Set RS** button to inject dredge losses somewhere else in the model. All the dredged sediment can be transferred to another cross section if dredged materials are piped or barged downstream (e.g. % Re-Introduced = 100) using this feature.

Dredge Output

HEC-RAS tracks the dredged mass as an output variable and can be reported in mass or volume. The Dredged Mass is reported as a cumulative variable, which reports the total mass or volume removed from the cross section since the beginning of the simulation. Users can visualize this as a time series at a specific cross section, along the reach at a particular time, or the impact on cross section shape.

The mass dredged in a given time step, or the cumulative mass dredged in the model can be displayed in profile (Figure 1-112) and time series.

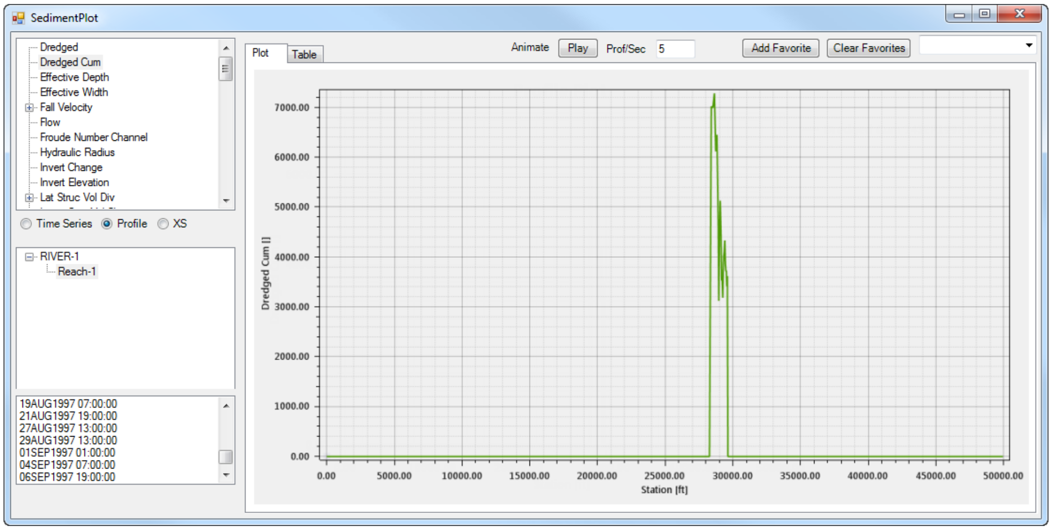


Figure 1-112: Cumulative Dredged Mass (Dredge Cum) profile output.

Sediment Transport Energy Slope

Most sediment transport equations are highly sensitive to the energy slope used. By default HEC-RAS computes this slope locally at the cross section by back calculating the friction slope from Manning's equation (**Local Energy Slope**), which in US Customary units, is:

$$S_f = \left(\frac{Flow}{Conveyance}\right)^2 = \left(\frac{Flow}{\frac{1.486 \cdot A \cdot R^{\frac{2}{3}}}{n}}\right)^2 .$$

However, at times, HEC 6 used the actual slope of the Energy Grade Line (**Average Energy Slope**) in the sediment transport equations, by computing the gradient between the upstream and downstream EGLs, so that:

$$S_f = \frac{EGL_{US\,XS} - EGL_{DS\,XS}}{DS\ Dist_{US\,XS} + DS\ Dist_{XS}}$$

Where:

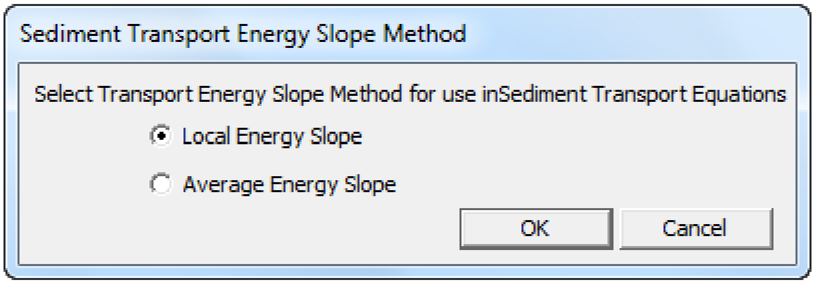
$EGL_{US\ XS}$ is the Energy Grade Line at the XS upstream of the computational node,

$EGL_{DS\ XS}$ is the Energy Grade Line at the XS downstream of the computational node,

$DS\ Dist_{US\ XS}$ is the downstream channel distance associated with the cross section upstream of the computational node (distance between the upstream cross section and the computational cross section) and

$DS\ Dist_{XS}$ is the downstream channel distance associated with the computational node (distance between the computational cross section and the next cross section downstream).

Users can choose between these energy slope approaches under **Options→Sediment Transport Energy Slope** on the **Sediment Analysis Editor** but will be rarely used (Figure 17-28). The **Local Energy Slope** is the conveyance calculation (and is default) and the **Average Energy Slope** is the slope computed from the EGLs of the bounding cross sections. These slopes can vary enough to affect sediment result substantially.


Sediment Transport Energy Slope Method

Select Transport Energy Slope Method for use inSediment Transport Equations

● Local Energy Slope

○ Average Energy Slope

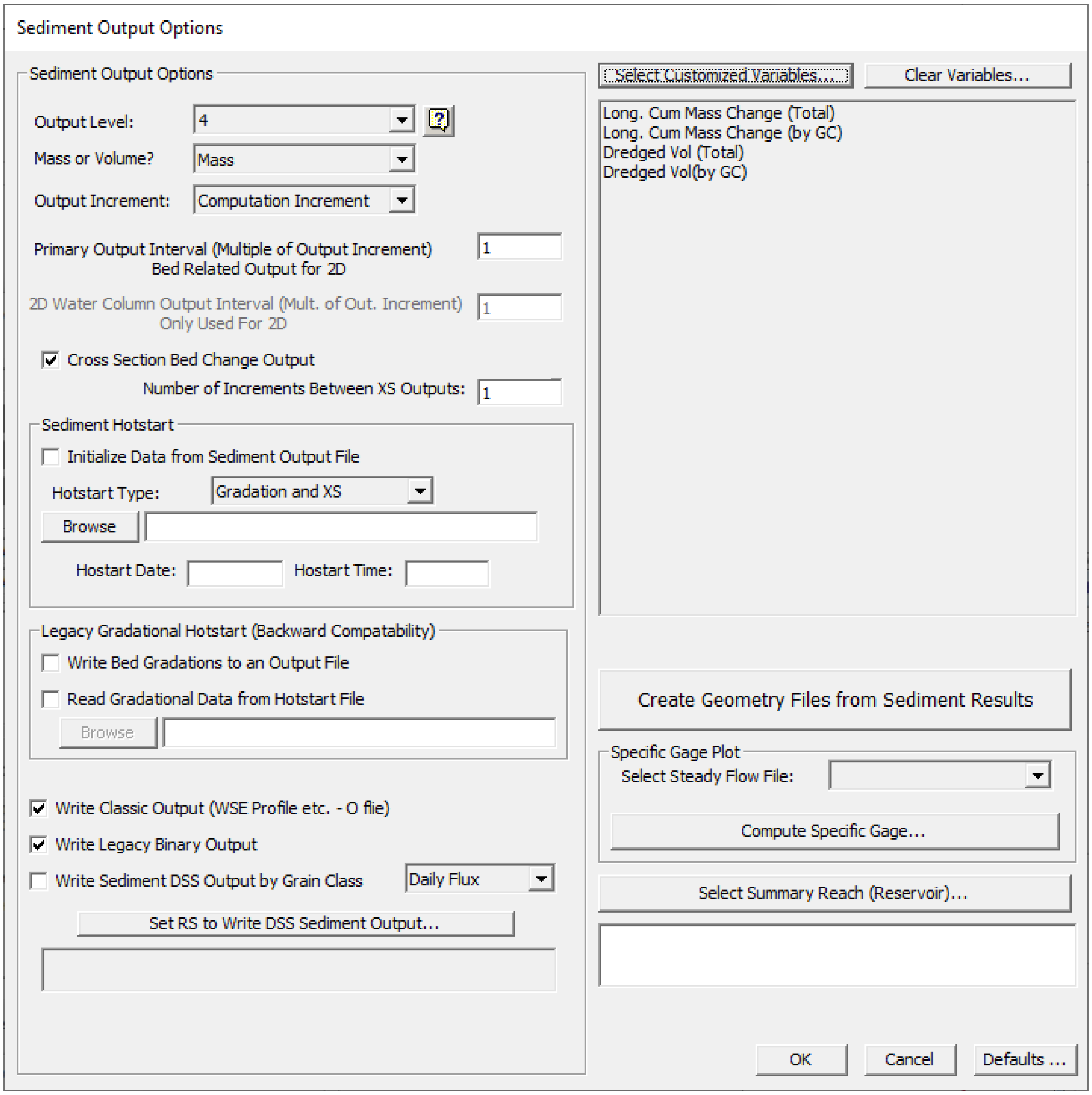
Figure 1-113: Sediment transport energy slope editor.

Sediment Output Options and Tolerances

Output Level

The sediment model in HEC-RAS can generate over a hundred result variables. Many of those variables also have sub-results as they are sub-divided by grain class or reported in either mass and volume. Output files can get very large, and the variable list can be unwieldy, when the calibration phase of a model study often evaluates the same three-to-five plots each run.

Therefore, HEC-RAS includes several tools to control the number of variables reported. The user can control the number of output variables, as well as the frequency at which HEC-RAS will generate them in the **Sediment Output Options**. The Output Level controls the variables output. Select and **Output Level** from one (four variables) to six (all variables) at the top of the **Sediment Output Options** window (Figure 1-114). The default output level is 4, which reports 14 variables at each time step. It is often advantageous to increase the level to six, to see all variables. However, sediment output files can get very large, because they output most variables by grain class, increasing file size by about an order of magnitude. Multi-Gigabyte sediment output files are common, but more output does not increase run time appreciably. Select the output level that optimizes the tradeoff between file size management and information required. The variables associated with each level are included in the following section, including and detailed description of many of the variables.



Sediment Output Options

Sediment Output Options

Output Level: 4

Mass or Volume? Mass

Output Increment: Computation Increment

Primary Output Interval (Multiple of Output Increment) Bed Related Output for 2D: 1

2D Water Column Output Interval (Mult. of Out. Increment) Only Used For 2D: 1

☑ Cross Section Bed Change Output

Number of Increments Between XS Outputs: 1

Sediment Hotstart

☐ Initialize Data from Sediment Output File

Hotstart Type: Gradation and XS

Hostart Date:

Hostart Time:

Legacy Gradational Hotstart (Backward Compatability)

☐ Write Bed Gradations to an Output File

☐ Read Gradational Data from Hotstart File

☑ Write Classic Output (WSE Profile etc. - O flie)

☑ Write Legacy Binary Output

☐ Write Sediment DSS Output by Grain Class: Daily Flux

Long. Cum Mass Change (Total)
Long. Cum Mass Change (by GC)
Dredged Vol (Total)
Dredged Vol(by GC)

Specific Gage Plot

Select Steady Flow File:

Figure 1-114. Sediment output options editor.

Modeling Note – Be Careful with Instantaneous Results: Any variable that does not have a Cum label is instantaneous. This is unproblematic for instantaneous variables like shear stress or concentration. However, if users do not choose to output every computation increment, mass flux and change variables will not balance and may miss peaks.

Table 1-4. Variables associated with each level of output.

Level 1

Level	Variables
Level 1	Invert Elevation (ft) (m) – The elevation of the channel invert of each cross section – the lowest elevation between the channel banks. Invert Change (ft) (m) – The total change in the invert (the lowest elevation station-elevation point between the bank stations) since the beginning of the simulation. Water Surface (ft) (m) – The water surface elevation at that at the cross section during the time step. Mass (or Volume) Bed Change Cum*: All (tons or ft^3) (tonnes or m^3) – Cumulative mass or volume added (+) or removed (-) from the control volume since the beginning of the simulation. Only Total in Level 1. For Grain Class specific results, increase to level 4. Long. Cum Mass (or Volume) Change (tons or ft^3) (tonnes or m^3)– The cumulative mass or volume change (see above) since the beginning of the simulation, summed from the upstream cross section in that reach. (e.g. the sum of the mass change for all of the cross sections between the selected XS and the upstream reach limit). The total value at the downstream XS of the reach is equal to the total mass change of the entire reach. This is a powerful model evaluation tool metric modelers become familiar with it. Only Total in Level 1. For Grain Class specific results, increase to level 4.

*Cum = Cumulative – results are summed since the beginning of the run

The Mass or Volume parameters track sediment mass movement through each control volume. Users can view discrete mass variables for each specified computation increment, as snapshots in time, or as cumulative masses, accumulated over time (CUM). All mass variables can also be viewed as volumes.

Modeling Note – Incremental Results Only Reflect Computation Increment: Incremental mass or volume results, that is output at intervals coarser than the computation increment (by default results are reported every 10 computation increments) can cause confusion. Because these mass results only reflect the single computation increment output, they will not sum to the cumulative result.

Level 2

Level 2	All Variables from Level 1. Level 2 includes additional hydraulic parameters used in the sediment model (which may be different than the HEC-RAS hydraulic output). Flow (cfs) (m^3/s) – The flow at the cross section at the time step. Velocity (ft/s) (m/s) – Average *channel*** velocity – the flow between the channel banks divided by the area of eht channel. Shear Stress (lb/ft^2) (Pa or N/m^2)– Channel average shear stress. The is the computational shear stress from the sediment computations: $$\tau = \gamma_w \cdot EfD \cdot S_f$$ Where, γ_w is the unit weight of water *EfD* is the Effective Depth *in the channel* (between the channel banks see level 3 for the EfD equation) and S_f is the friction slope (which can be local or averaged from the bounding cross sections – see Section on Sediment Energy Slope).†

** Because the sediment model uses channel hydraulics in the transport equations, the hydraulic output usually reflect channel hydraulics (i.e. only the hydraulics between the channel banks, excluding overbank flows). The channel shear and velocity are usually substantially higher than the cross section averages

†The computed sediment shear stress can differ from the shear stress displayed in the general, HEC-RAS hydraulic output. The HEC-RAS hydraulics do not compute shear stress, so the shear stress visualizations outside the sediment editors are computed on the fly from other hydraulic parameters. The hydraulic shear visualization is computed from:

$$\tau = \gamma_w \cdot R \cdot S_f = \gamma_w \cdot \frac{Area}{Pw} \cdot \left(\frac{Flow}{K}\right)$$

Where Pw is the wetted perimeter and K is conveyance. Note, the hydraulic display also computes the channel, overbanks, and full cross section, while the computational sediment shear is for the channel only.

Level 3

Level 3	Level 3 includes gradation data, some additional hydraulic parameters, and a sediment flux term. d_{50} Cover/Subsurface/ Inactive Layers (mm) – the median grain size of the specified mixing layer at that cross section. (Note: Layer names can change base on the mixing method – see Table 1-5) Note: All particle sizes are always in mm in input and output even if the model is in US customary units. d_{10} Cover/Subsurface/ Inactive Layers (mm) d_{90} Cover/Subsurface/ Inactive Layers (mm) Effective Depth (ft) – A weighted average depth that often reflects the total cross section shape and change more than the invert change. This is also used in the shear stress equation. $\text{Effective Depth} = \frac{\sum_{i=1}^{n} D_i \cdot A_i \cdot D_i^{2/3}}{\sum_{i=1}^{n} A_i \cdot D_i^{2/3}}$ Where D_i is the average water depth in each cross section element (the trapezoid subsection "i" associated with each station elevation point), A_i is the area of that element, and n is the number of subsections. Effective Width (f–) - Effective width is the comparable channel width that preserves cross section area given the Effective Depth - (Units: ft or m) $\text{Effective Width} = \frac{\sum_{i=1}^{n} A_i \cdot D_i^{2/3}}{\sum_{i=1}^{n} A_i \cdot D_i^{2/3}}$ Manning's n Channel (s/ft$^{1/3}$ or s/m$^{1/3}$) - This is the Manning's n value in the channel (between the channel banks). If the channel has laterally varied n values, it is the composite channel n. It can be dynamic in time if the water surface weights the composite n-values differently, if there is a flow, or seasonal n value dependency, or if a dynamic, sediment bed roughness predictor is selected. Unlike the Chezy equation the manning coefficient is *not* dimensionless. Froude Number Channel - The Froude number in the channel (between the channel banks). HEC-RAS computes the Froude Number as: $FR = \sqrt{\frac{{Q_{ch}}^2 \cdot W_{ch}}{g \cdot A_{ch}^3}}$ Where: Q_{ch} is the flow in the channel, $W_{ch}$is the top width of the channel, g is the acceleration of gravity and A_{ch} is the area of the channel, where the channel is the portion of the cross section between the channel banks.

	Mass (Vol) In Cum (tons or ft^3) (tonnes or m^3) – The total sediment flux into the control volume since the beginning of the simulation (Cum is "cumulative" in time. Mass In Cum at the upstream cross section should reflect the model boundary and the runtime sediment budget report. Only Total in Level 3. For Grain Class specific results, increase to level 4. Mass (Vol) Dredge Cum (tons or ft^3) (tonnes or m^3) – The total mass or volume dredged from that cross section since the beginning of the simulation. Note: This variable will only populate if the model has a dredging event. This output has also changed from version 5, which only reported instantaneous results.

Table 1-5: Bed Layer Mass/Volume and Gradation Index Variables by bed mixing algorithm.

Thomas (Ex5) and Copeland (Ex 7)	**Active Layer**
Cover (Mass/Vol) (GC)	Active (Mass/Vol) (GC)
Subsurface (Mass/Vol) (GC)	Inactive (Mass/Vol) (GC)
Inactive (Mass/Vol) (GC)	
Cover Thickness	Active Thickness
Subsurface Thickness	Inactive Thickness
Inactive Thickness	
d_{10},d_{16}, d_{50}, d_{84}, d_{90} Cover	d_{10},d_{16}, d_{50}, d_{84}, d_{90} Active
d_{10},d_{16}, d_{50}, d_{84}, d_{90} Subsurface	d_{10},d_{16}, d_{50}, d_{84}, d_{90} Inactive
d_{10},d_{16}, d_{50}, d_{84}, d_{90} Inactive	

Level 4

Level 4 (Mass or Vol by Grain Class)	Includes variables from levels 1-3. This is the default level, so it includes the most commonly used variables. Starting in level 4, the Mass and Volume results include total and each active grain class.+ This includes new Mass and Volume variables in this level as well as mass and volume variables (e.g. Mass Bed Change, Vol in CUM) inherited from previous levels. Sediment Concentration (mg/L) – HEC-RAS reports concentration of the flux out of the control volume. Therefore, Concentration is: $C \frac{{Mass\ Out}/{Time\ Step\ (days)}}{Flow}$ Slope (no units, ft/ft or m/m) – This is the Energy Slope used in the shear stress equation, which is either computed locally at the cross section $(Q/Conveyance)^{0.5}$ or the slope between the EGLs at the bounding cross sections. See the section on Sediment Transport Energy Slope. Lateral Load Mass (Volume) In (tons or ft^3) (tonnes or m^3) – This variable records the sediment entering the model through lateral boundary conditions at each cross section and time step. It is only the lateral loads for the computation increment, not a cumulative value. Total and by grain class. Lateral Structure Mass (or Vol) Div (ton or ft^3) (tonnes or m^3) – This tracks the sediment that is removed from each control volume (or added) by sediment associated with flow over a lateral structure. Total and by grain class. Mean Eff Channel Invert (ft) (–) - This is a measure of representative bed change. The Effective Channel Invert is the maximum *channel* elevation (the elevation associated with the higher channel bank station) minus the Effective Depth (see description in level 3). Mean Eff Channel Invert Change (ft) – This is the net change in the Mean Effective Invert since the beginning of the simulation. It is similar to the Invert Change variable, reporting bed elevation change (an intuitive measure of morphologic change) but is a more robust reflection of total cross section change than Invert Change, which can generate idiosyncratic results depending on how one node responds to the simulation. Invert Elevation Max (ft) (m)$^{\diamond}$ – The maximum channel invert (lowest elevation point between the channel banks) since the beginning of the simulation. The final profile indicates the maximum deposition at each cross section during the simulation. Invert Elevation Min (ft) (m)$^{\diamond}$ – The minimum channel invert (lowest elevation point between the channel banks) since the beginning of the simulation. The final profile indicates the maximum erosion at each cross section during the simulation.

	Mass (or Volume) Bed Change Cum: Max (tons or ft^3) – The maximum (positive) deposition in mass or volume since the beginning of the simulation. This result is monotonic. It only increases with time. Mass (or Volume) Bed Change Cum: Min (tons or ft^3) - The maximum negative mass or volume change since the beginning of the simulation. This result is monotonic. It only decreases (larger negative value) with time. Toffaleti Sub Zone Capacities: Toff Zone Capacity U (tons/day) (tonnes/day) – The fraction of the Toffaleti transport capacity computed in the "Upper Zone" – the top 60% (above t½1/2.5 Depth from the bottom) of the water column. Only written if the Toffaleti function is selected. Modelers sometimes compare the upper three zones of Toffaleti Capacity to suspended load measurements (which exclude bed load). Toff Zone Capacity M – The fraction of the Toffaleti transport capacity computed in the "Middle Zone" – approximately 31% of the water column in the zone between t½1/2.5 Depth and 1/11.24 Depth (from the bottom of the channel). Only written if the Toffaleti function is selected. Toff Zone Capacity L – The Toffaleti transport capacity computed in the "Lower Zone" – approximately the bottom 8-9% of the water column, excluding the bed zone. Only written if the Toffaleti function is selected. Toff Zone Capacity B – The "Bed Zone" portion of the Toffaleti transport capacity. This is the MPM capacity if the Toffaleti-MPM function is selected.

+To manage file size and simplify visualization, HEC-RAS only includes grain classes that exist in the model. So a model that only uses grain classes 6-9 will only include four grain-class specific results. However HEC-RAS also outputs intermediate grain classes that do not exist in the model. So if a model only includes two grain glasses, 6 and 9, it will output four grain classes, because it will also output zero mass/volume for grain classes 7 and 8.

Level 5

Level 5	Level 5 is intended to be a "mixing" level, which includes the more detailed results to help understand/troubleshoot the bed mixing algorithms. It also includes all of the terms required to balance the sediment budget for each control volume (or sub-reach). Level 5 also includes some preliminary (station movement and total mass) of BSTEM results (including all of the grain-class specific results) if the model includes any BSTEM cross sections. For BSTEM variable descriptions see the Output section of the BSTEM manual and Table 4-1. Includes all the variables from Levels 1-4 Mass Bed Change▲: (tons or ft^3) (tonnes or m^3) – The sediment eroded or deposited from the control volume in that computational increment (the Cumulative version of this variable is included in Level 1. Total and by grain class. Mass Out▲: (tons or ft^3) (tonnes or m^3) – Sediment flux leaving the control volume in that computation increment. The cumulative version of this result is included in Level 3. Total and by grain class. Mass In▲ and Mass In Cum: (tons or ft^3) (tonnes or m^3) – Sediment flux into the control volume, in the specific time series and for all time since the beginning of the simulation respectively. Total and by grain class. The mass balance for each control volume (for the simple Continuity approach) should be : $Mass\ Bed\ Change = Mass\ In - Mass\ Out$ Mass (Vol) Capacity and Mass (Vol) Capacity Cum (tons/day or ft^3/day) (tonnes/day or m^3/day) – this is the sum of the transport capacity computed for each grain class. This is before limiters like fall velocity or armoring are applied, so, usually: $Mass\ Bed\ Change \neq Mass\ In - Mass\ Capacity$ However, it provides a sense of how transport varies with the hydrodynamics and bed evolution. The Cumulative version of this parameter sums the total capacity for all time steps since the beginning of the simulation. Level 5 only includes the totals. HEC-RAS reports these by grain class in level 6. Temperature (°F) (°C) – Water temperature. Current versions of the model only allow one temperature per time step, so this can vary in time but not space. Thickness Cover (Active)• (ft) (m) – The vertical thickness of surficial layer of the bed mixing (sorting and armoring) algorithm. This is the Active Layer or the Cover Layer (in the Thomas or Copeland mixing methods). Thickness Subsurface (ft) (m) – The vertical thickness of an intermediate layer between the cover and inactive layer in the Thomas and Copeland mixing algorithms. The Active Layer method does not have a comparable layer.

	Thickens Inactive (ft) (m) – The vertical thickness of the deepest layer of the bed mixing (sorting and armoring) algorithm. All three methods use the same terminology for this. Mass Cover (Active) (Volume): (tons or ft^3) (tonnes or m^3) – The sediment mass or volume (total and by grain class) in the surface mixing layer (Active or Cover Layer) of the control volume. The other layers are included in Level 6. Fall Velocity – (ft/s) (m/s) Reports the fall velocity computed for each grain class. Also reports a "total" fall velocity which is a weighted average: $$Fall\,Velocity_{Total} = \sum_{i=1}^{n} Fall\,Velocity_i \cdot fraction_i$$ Where i is each grain class, and n is the number of grain classes in the model. This weighted fall velocity is just a summary heuristic, however. It has no physical analogue and is not used anywhere in the computations. The individual fall velocities can be useful, and vary with temperature. Because HEC-RAS currently only allows one temperature per time step, these values will be constant in space in only vary in time.

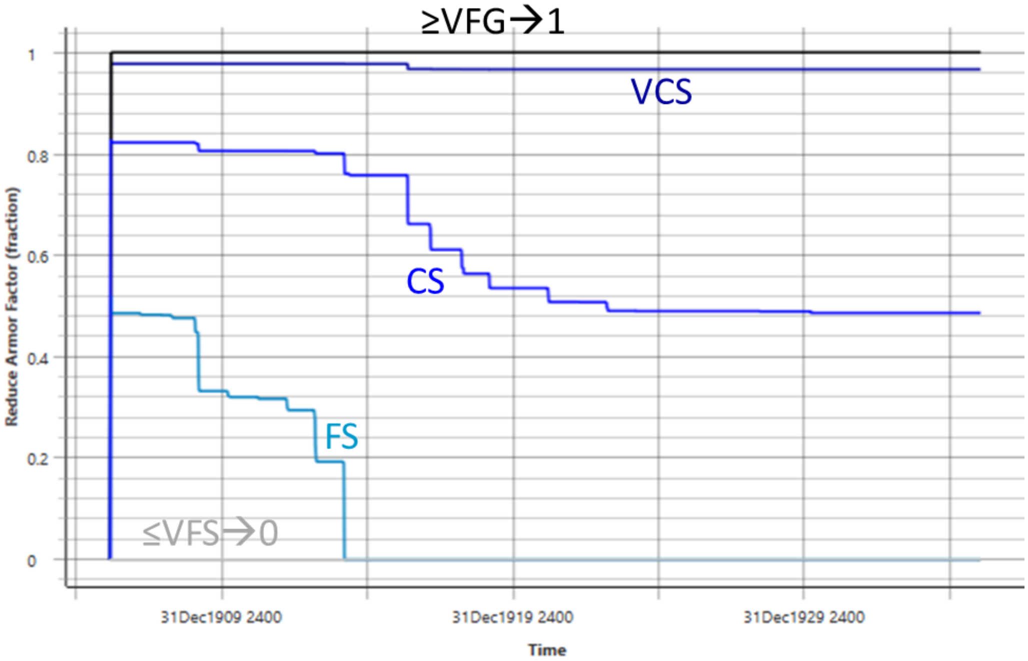
▲Be careful comparing the computational increment mass and volume results. They only report the result for the reported computation increment. If the Output Increment is set to more than 1 (default is 10) this result will skip the flux or bed change between the reported computational increment and the sum of the time series will not add up to the total flux or bed change.

•The names of these layers can change depending on the bed mixing algorithm. See Table 1-5 for descriptions of the output layer names associated with each mixing algorithm.

Level 6

Level 6	Level 6 includes some more detailed results and a wider suite of BSTEM results (including all of the grain-class specific results) if the model includes any BSTEM cross sections. For BSTEM variable descriptions see the Output section of the BSTEM manual and Table 4-1. Includes all variables from Levels 1-5. Mass (or Volume) Capacity (for every grain class) (tons/day or ft^3/day) – This is the transport capacity computed by the transport function for each grain class (which is the transport HEC-RAS actually uses in its grain-class independent rout Long. Cum Mass (or Volume) Movable Limits (tons or ft^3) - This is the same as the Longitudinal Cumulative Mass or Volume change in Level 1, except it excludes any bed change outside the movable bed limits. The Longitudinal Cumulative Mass (Volume) change sums the mass or volume change from the beginning of the simulation and from upstream-to-downstream, so that the downstream cross section at the last time step of the Longitudinal Cumulative Mass Curve (LCMC) is a summary of the total aggradation or degredation in that reach for the simulation. Comparing the full LCMC (or LCVC) to this one, that only reports the result in the movable bed limits, is a helpful way to differentiate between overbank and channel processes (e.g. determine what percentage of deposition is floodplain deposition or identify overbank deposition offsetting channel erosion). (Total and by grain class) Mass Subsurface (Volume): (tons or ft^3) (tonnes or m^3) – The sediment mass or volume (total and by grain class) in an intermediate mixing layer between the cover (which is in Level 5) and inactive layers in the Thomas and Copeland mixing methods. The Active Layer method does not have this layer. Mass Inactive (Volume): (tons or ft^3) (tonnes or m^3) – The sediment mass or volume (total and by grain class) in the deepest mixing layer of the control volume. The deepest mixing layer has the same name for all mixing algorithms. Hydraulic Radius – The area of the channel (the part of the cross section between the movable bed limits) divided by the wetted perimeter of the channel. Movable Elv L and Movable Elv R: (ft) (m) – These are the elevations of the movable bed limits. Tracking the MBL movement relative to the channel can be useful, but these are mainly used to track toe migration in BSTEM models. Movable Sta L and Movable Sta R: (ft) (m) – These are the stations (lateral stations of the station-elevation points) of the movable bed limits. These will remain constant unless the cross section has BSTEM parameters. Only the BSTEM algorithms move cross section station-elevation points laterally. Reduce Armor Factor (decimal between 0 and 1) – The Armor Reduction Factor determines how effective the cover layer is in the Thomas and Copeland

mixing algorithms. It is the "Armoring Ratio" in Figure 2-17 and Figure 2-20. HEC-RAS multiplies the capacity deficit of each grain class by this ratio (computed from the "equivalent particle diameters" of coarser particles in the cover layer). An armor ratio of 1 is no armoring, 0 is complete armoring (for that grain class) and anything in between is partial armoring. For example, in the figure below, all the grain gravel and cobble grain classes remain unarmored throughout the simulation (RAF=1). Very Fine Sand and finer grain classes are all completely armored after the first time step (RAF=1). Three sand size classes gradually armor over time, with fine sand fully armoring (goes to zero) during the simulation and Coarse Sand eventually reducing erosion by ~50% because of armoring effects (RAF=0.5).



Shear Velocity (ft/s) (m/s) – Shear velocity (u_*) is an expression of the shear stress with velocity units:

$$u_* = \sqrt{\frac{\tau}{\rho}}$$

where τ is the bed shear stress and ρ is the density of the fluid.

The shear velocity is a popular way to express shear and shows up in many of the equations and algorithms included in HEC-RAS because the ratio of fall velocity to shear velocity becomes a dimensionless parameters that has a range of meaningful transport applications.

d_{16} Cover/Subsurface/ Inactive Layers (mm) – The 16th percentile particles size of the specified mixing layer. Some practitioners prefer the d_{16} to d_{10} because it is two standard deviations below the mean.

d_{84} Cover/Subsurface/ Inactive Layers (mm) The 84th percentile particles size of the specified mixing layer. Some practitioners prefer the d_{84} to d_{90} because it is two standard deviations above the mean.

Only Customized

In general, if users **Select Customized Output** variables, HEC-RAS will add the selected variables to the results associated with the selected **Output Level**. However, this option turns off all automatic results, reporting only the results the user individually selects.

Output in Mass or Volume?

Converting between mass and volume in HEC-RAS is a relatively simple matter of multiplying or dividing by the unit weight of the material, though the multiplier is different for clay, silt, and cohesionless grain classes. Some users prefer to view the magnitude of erosion, deposition, transport or other variables either in mass or volume units. Volume is the default reporting unit but it can be switched to mass using this option. In recent versions, users can get both by selecting whichever choice is not selected in this drop-down in the **Customized Variables** tool.

Modeling Note - Calibrating to Volume: Repeated cross sections are the most common and – often - the most reliable calibration data. Repeated cross sections can be converted to volume change by multiplying the area change by the control volume reach length, or can be summed from upstream to downstream to compare Longitudinal Cumulative Volume Change Curves (See later) HEC-RAS produces. Therefore, while mass change can be more intuitive, volume change is often easier to compare to common calibration data.

Modeling Note – What if I want Mass AND Volume?: The default sediment results will only report the mass/volume results (e.g. Mass/Volume Bed Change) in the form selected in this option. However, users can add the other one with the Customized Output option. So if you select Volume but also want Mass bed change, simply select it and HEC-RAS will write both.

Set Output Increment

Controlling the Quasi-Unsteady Sediment Output Increment

Outputting data periodically can also reduce file size, without eliminating output variables. Control output frequency with the **Number of Increments Between Outputs** parameter (Figure 1-114). First select the basic output 'unit' with the **Output Increment**, then specify the number of increments between outputs:

Output Increment:

HEC-RAS has four options increments to choose from. Two increments are the two time steps used in the quasi-unsteady flow editor (the **Flow Duration** and **Computational Increment**) and the other two are regular time increments (**Hours** and **Days**). The **Computation Increment** defined in the **Quasi-Unsteady Flow Editor** (Figure 1-3) is the default output increment. This option also generates output at the end of each flow duration, whether it is a multiple of the **Computation Increment** or not. Users can also request output every **Flow Duration** or some multiple of them.

Both the **Computation Increment** and the **Flow Duration Output Increment** can distort animated profile results in time (if they are not constant). Larger or rapidly changing flows are often modeled with smaller Computation Increment, which will generate more output profiles during these morphologically active times. Temporal distortion can be valuable or problematic when visualizing results. Consider pros and cons.

The other two options, hours and days, set the output increment to a constant absolute time. This avoids the temporal distortion in the time series plots and animations but can result in skipping over interesting changes and overemphasize boring, low change, periods.

After selecting the **Output Increment**, define the number of **Output Increments** between results using the **Number of Increments Between Profile/Time Series Outputs**. HEC-RAS will write output for every selected variable at this multiple of the base increment. For example, in Figure 1-114 (the default values) HEC-RAS writes results every ten computation increments.

Modeling Note – Discrete Output for the Increment NOT the Elapsed Time: HEC-RAS reports incremental output like Mass Out, Mass In, or Mass Bed Change (the mass entering, leaving, and depositing/eroding in the control volume in a time step) for the last computational increment. Therefore, if the output increment is longer than the computational increment, HEC-RAS will not sum data between the output increment. Instead a series of 'snapshots' in time are reported. The cumulative variables are usually more helpful for tracking mass through a simulation. To compute increments, select the cumulative outputs and subtract or output every computational increment.

Modeling Note - Setting Output Increment in Unsteady Sediment Transport: The legacy ("Old") sediment output does not work well with unsteady sediment transport. View unsteady sediment output with the new HDF5 viewer (**View→Sediment Output**) and control the output increment with the **Mapping Output Interval**. Sometimes HEC-RAS will provide unsteady sediment results with the legacy viewer if the output increment is set to 1.

Set Cross Section Bed Change Output

HEC-RAS can plot and animate cross section changes computed as part of a sediment run. Cross section data is usually much more memory intensive since the vertical position of each node on each cross section is stored. Therefore, cross section output is turned off by default and must be selected by checking the **Cross Section Bed Change Output** check box. When users select cross section output the multiple that controls cross section output is multiples of the profile output. For example, in Figure 1-114 output is generated every 10th profile output or every 100th computation increment. To set the cross section output to write for every profile set the **Number of Profiles Outputs Between XS Outputs** to 1.

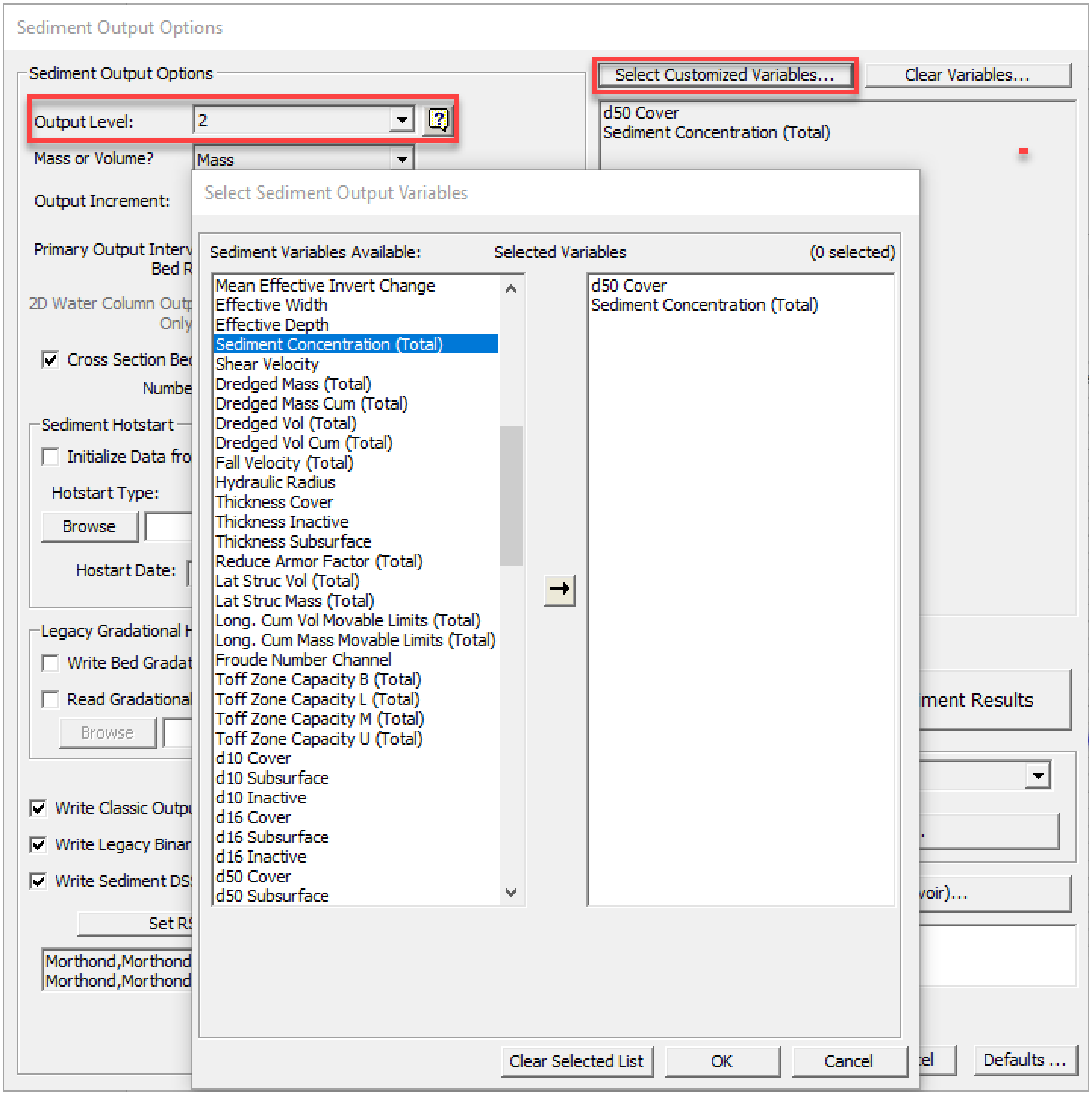
As a default HEC-RAS reports variables after every tenth computational increment and at the end of each flow duration. Choosing a less frequent output interval yields a minor improvement in run times.

Modeling Note – Large Output Files**:** Choosing a high Output Level (e.g. 6) and a low time increment between outputs (e.g. 1) can produce extremely large sediment output files. The classical viewers have a 2GB limit. If output files grow larger than that limit, they will not open, and large files under that limit can be very sluggish. The new HDF5 sediment output viewer can open much larger files, working well with multi-GB files. However, small time steps and large variable requests can produce very large (e.g. a 20 year unsteady sediment model run at a 5 min time step can produce a 30GB output file) which can impact performance.

Select Customized Output

HEC-RAS sediment simulations generate a lot of data. The **Output Level** forces users to chose between minimizing the results, or getting a lot of data they did not want to get the results they do want. The current version of HEC-RAS has added **Customized Output** to address that issue.

The Customized Output will add the user selected variables to the results from the Output Level, so users can choose a very basic output level (e.g. 2 or 3), and just add the results they are interested in. Or they can choose **Only Customized** under the output level and HEC-RAS will only write the user selected variables. To customize the output level, press the **Select Customized Variables** button. Select Customized Variables…



Sediment Output Options

Output Level: 2

Mass or Volume? Mass

☑ Cross Section Bed

☐ Initialize Data fro

☐ Write Bed Gradat

☐ Read Gradational

☑ Write Classic Outpu

☑ Write Legacy Binar

☑ Write Sediment DS

Morthond,Morthond
Morthond,Morthond

d50 Cover
Sediment Concentration (Total)

Select Sediment Output Variables

Sediment Variables Available:

Mean Effective Invert Change
Effective Width
Effective Depth
Sediment Concentration (Total)
Shear Velocity
Dredged Mass (Total)
Dredged Mass Cum (Total)
Dredged Vol (Total)
Dredged Vol Cum (Total)
Fall Velocity (Total)
Hydraulic Radius
Thickness Cover
Thickness Inactive
Thickness Subsurface
Reduce Armor Factor (Total)
Lat Struc Vol (Total)
Lat Struc Mass (Total)
Long. Cum Vol Movable Limits (Total)
Long. Cum Mass Movable Limits (Total)
Froude Number Channel
Toff Zone Capacity B (Total)
Toff Zone Capacity L (Total)
Toff Zone Capacity M (Total)
Toff Zone Capacity U (Total)
d10 Cover
d10 Subsurface
d10 Inactive
d16 Cover
d16 Subsurface
d16 Inactive
d50 Cover
d50 Subsurface

Selected Variables (0 selected)

d50 Cover
Sediment Concentration (Total)

Figure 1-115: Select customized output results.

HEC-RAS adds these variables to the result file and they show up as options in the sediment result plotter (Figure 1-116).

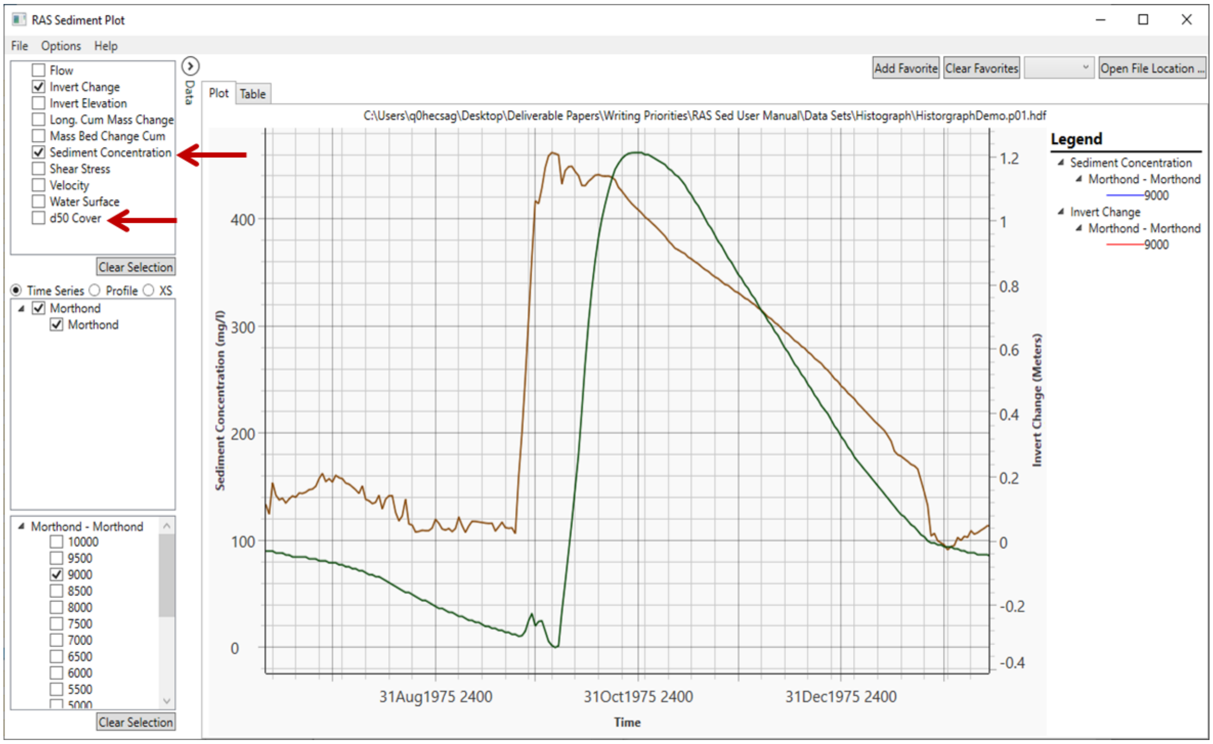
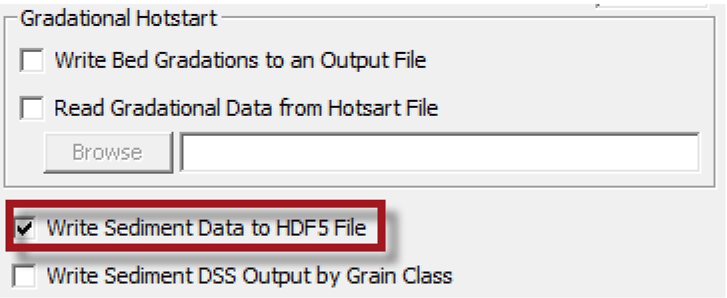


Figure 1-116: Result includes the standard Level 2 results and the two selected in the previous figure.

To delete customized variables, double click on them in the list and to delete all of them press the **Clear Variable** button.

HDF5 output

Recent versions of HEC-RAS write results to HDF5, a binary data standard that users can access with free, public domain, viewers, and which is much easier to use and faster to access than the customized binary output used for previous sediment output. HDF5 files can be large, so HEC-RAS provides the option to write them or not. But they should be written for most sediment modeling applications. If they get too large, change the output increment. The current release version of HEC-RAS writes HDF5 files by default. The **Sediment Output** viewer access these data and will not work unless this feature is selected. If you open an HEC-RAS sediment model develop in a previous version and the Sediment Output does not work, you may need to turn this feature on to write the HDF5 output.


Gradational Hotstart

☐ Write Bed Gradations to an Output File

☐ Read Gradational Data from Hotsart File

☑ Write Sediment Data to HDF5 File

☐ Write Sediment DSS Output by Grain Class

Figure 1-117: Select the HDF5 sediment output required for the new sediment output viewer.

Modeling Note – Data Mining the HDF5 file: One of the advantages of moving to HDF5 output is that user can access the data directly with free, open source, editors (like HDFView) or can write code against these files to generate customized plots and isolate interesting results. See more about accessing these data externally in the section

HEC-RAS generates two HDF5 files, storing the geometry data in one named (plan name).gxx.hdf and the results in a file named (plan name).pxx.hdf (where xx is the geometry or plan number). Sediment results are written to the *.pxx.hdf file in the Results→Sediment→Output Blocks→Base Output→Sediment Time Series folder (Figure 1-118). HEC-RAS writes time series for each cross section (or profiles for each time step) to the **Cross Sections** folder (Figure 1-119) and updated cross sections for each requested time step to **Cross section SE**. Metadata, the profile names (time) and the cross section id's (space) that correspond to the rows and columns are stored in the **Time** entry under the **Sediment Time Series** (Figure 1-118) and the **River Reach Station** entry under **Cross Section SE** respectively. Cross section data are stored in **Cross Section SE** at each output cross section with two entries, a "value" entry with all the station-elevation for all cross sections at that time step stored sequentially and an "info" entry which stores the metadata to parse this string, reporting the first and last point in each cross section, named in the **River Reach Station** entry.

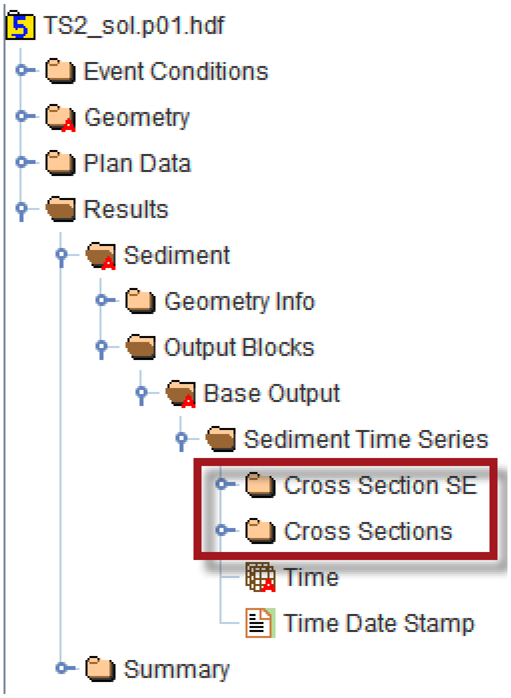
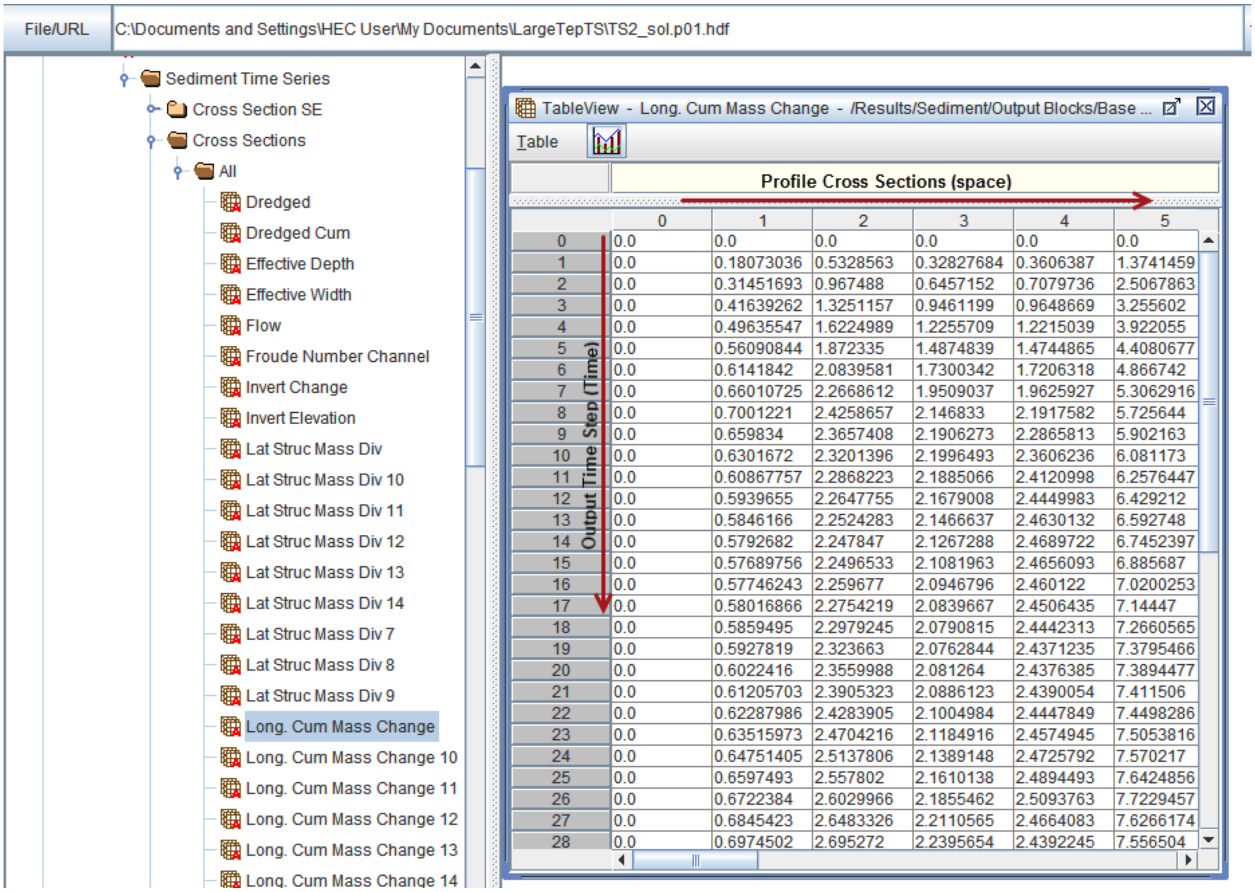
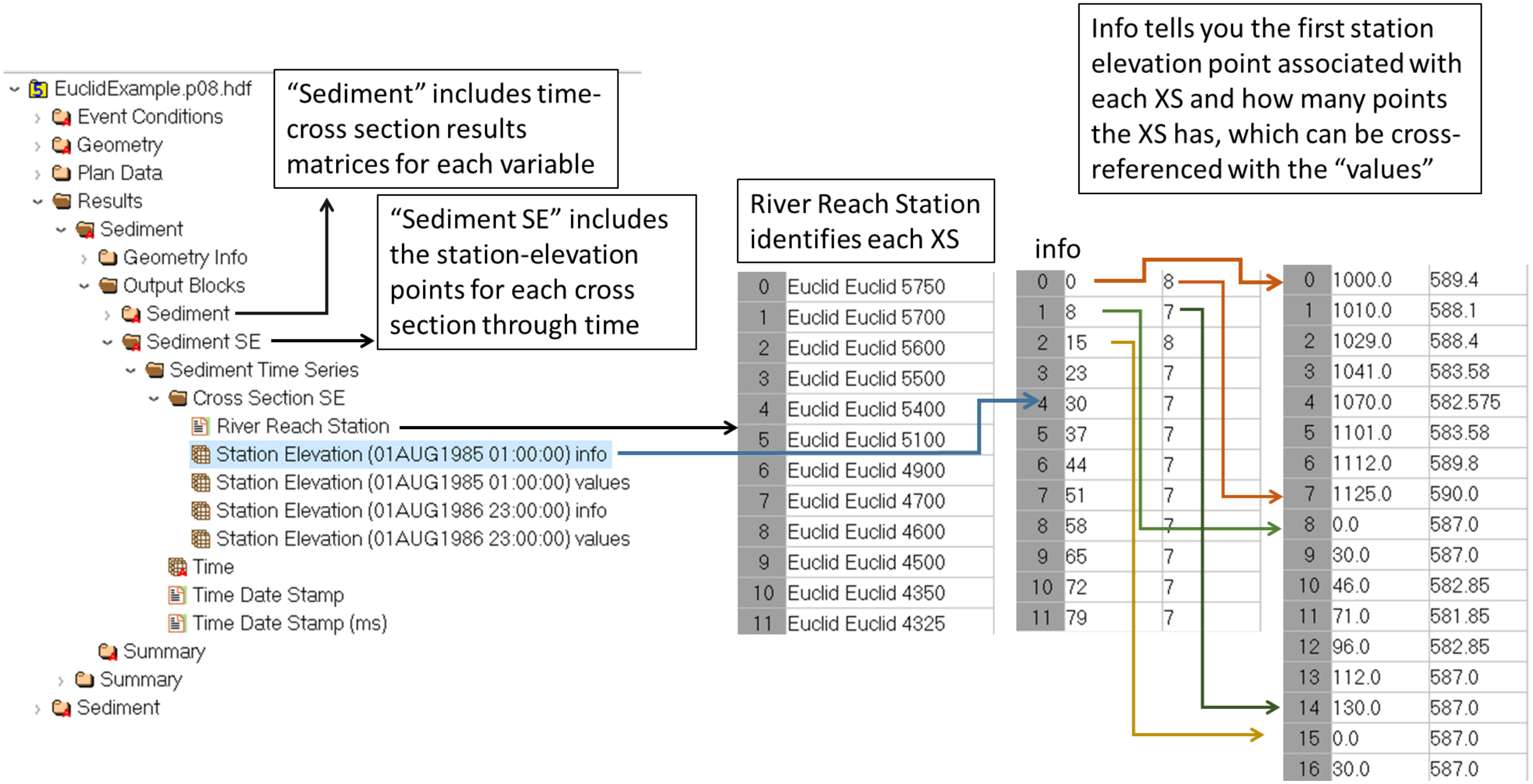


*Figure 1-118: Sediment output in the *.pxx.hdf file.*



	0	1	2	3	4	5
0	0.0	0.0	0.0	0.0	0.0	0.0
1	0.0	0.18073036	0.5328563	0.32827684	0.3606387	1.3741459
2	0.0	0.31451693	0.967488	0.6457152	0.7079736	2.5067863
3	0.0	0.41639262	1.3251157	0.9461199	0.9648669	3.255602
4	0.0	0.49635547	1.6224989	1.2255709	1.2215039	3.922055
5	0.0	0.56090844	1.872335	1.4874839	1.4744865	4.4080677
6	0.0	0.6141842	2.0839581	1.7300342	1.7206318	4.866742
7	0.0	0.66010725	2.2668612	1.9509037	1.9625927	5.3062916
8	0.0	0.7001221	2.4258657	2.146833	2.1917582	5.725644
9	0.0	0.659834	2.3657408	2.1906273	2.2865813	5.902163
10	0.0	0.6301672	2.3201396	2.1996493	2.3606236	6.081173
11	0.0	0.60867757	2.2868223	2.1885066	2.4120998	6.2576447
12	0.0	0.5939655	2.2647755	2.1679008	2.4449983	6.429212
13	0.0	0.5846166	2.2524283	2.1466637	2.4630132	6.592748
14	0.0	0.5792682	2.247847	2.1267288	2.4689722	6.7452397
15	0.0	0.57689756	2.2496533	2.1081963	2.4656093	6.885687
16	0.0	0.57746243	2.259677	2.0946796	2.460122	7.0200253
17	0.0	0.58016866	2.2754219	2.0839667	2.4506435	7.14447
18	0.0	0.5859495	2.2979245	2.0790815	2.4442313	7.2660565
19	0.0	0.5927819	2.323663	2.0762844	2.4371235	7.3795466
20	0.0	0.6022416	2.3559988	2.081264	2.4376385	7.3894477
21	0.0	0.61205703	2.3905323	2.0886123	2.4390054	7.411506
22	0.0	0.62287986	2.4283905	2.1004984	2.4447849	7.4498286
23	0.0	0.63515973	2.4704216	2.1184916	2.4574945	7.5053816
24	0.0	0.64751405	2.5137806	2.1389148	2.4725792	7.570217
25	0.0	0.6597493	2.557802	2.1610138	2.4894493	7.6424856
26	0.0	0.6722384	2.6029966	2.1855462	2.5093763	7.7229457
27	0.0	0.6845423	2.6483326	2.2110565	2.4664083	7.6266174
28	0.0	0.6974502	2.695272	2.2395654	2.4392245	7.556504

Figure 1-119: Time series (vertical) and profile (horizontal) data for each output variable recorded in the Hdf5 file.



- EuclidExample.p08.hdf
  - Event Conditions
  - Geometry
  - Plan Data
  - Results
    - Sediment
      - Geometry Info
      - Output Blocks
        - Sediment
        - Sediment SE
          - Sediment Time Series
            - Cross Section SE
              - River Reach Station
              - Station Elevation (01AUG1985 01:00:00) info
              - Station Elevation (01AUG1985 01:00:00) values
              - Station Elevation (01AUG1986 23:00:00) info
              - Station Elevation (01AUG1986 23:00:00) values
            - Time
            - Time Date Stamp
            - Time Date Stamp (ms)
      - Summary
    - Summary
  - Sediment

"Sediment" includes time-cross section results matrices for each variable

"Sediment SE" includes the station-elevation points for each cross section through time

River Reach Station identifies each XS

Info tells you the first station elevation point associated with each XS and how many points the XS has, which can be cross-referenced with the "values"

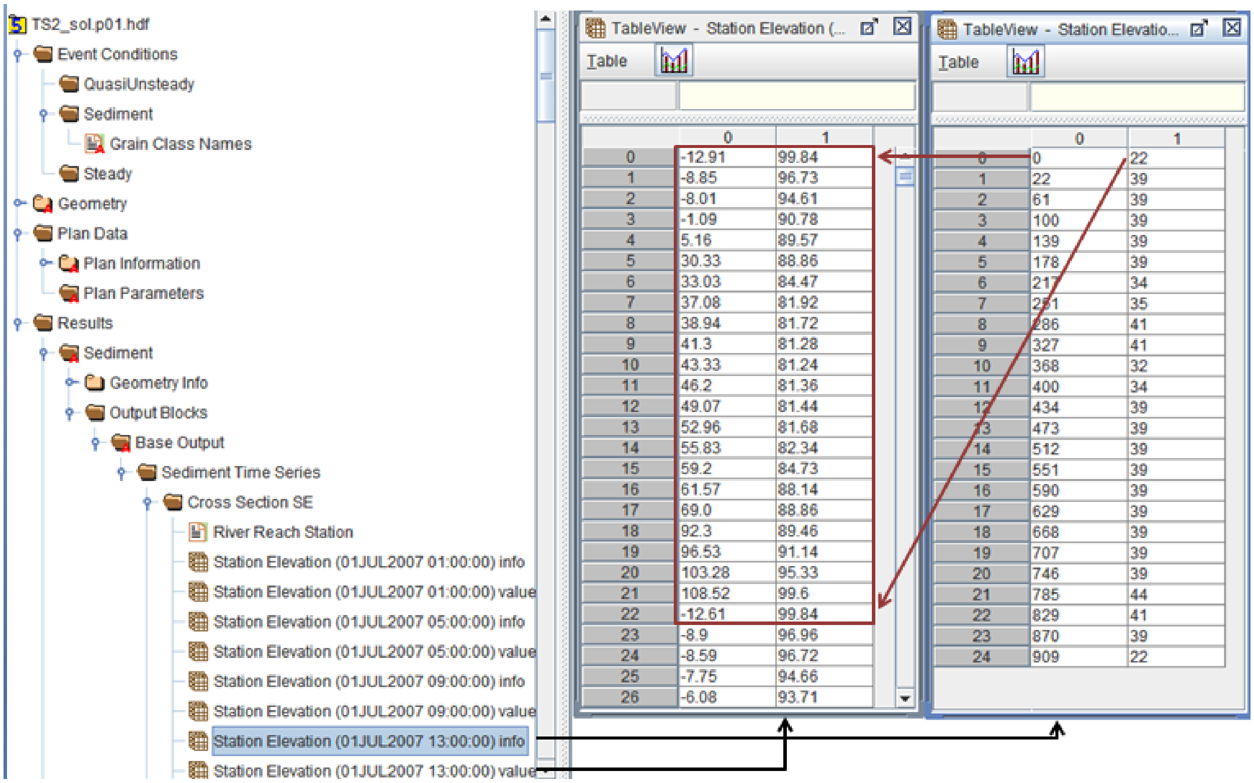
0	Euclid Euclid 5750
1	Euclid Euclid 5700
2	Euclid Euclid 5600
3	Euclid Euclid 5500
4	Euclid Euclid 5400
5	Euclid Euclid 5100
6	Euclid Euclid 4900
7	Euclid Euclid 4700
8	Euclid Euclid 4600
9	Euclid Euclid 4500
10	Euclid Euclid 4350
11	Euclid Euclid 4325

info

0	0	8
1	8	7
2	15	8
3	23	7
4	30	7
5	37	7
6	44	7
7	51	7
8	58	7
9	65	7
10	72	7
11	79	7

0	1000.0	589.4
1	1010.0	588.1
2	1029.0	588.4
3	1041.0	583.58
4	1070.0	582.575
5	1101.0	583.58
6	1112.0	589.8
7	1125.0	590.0
8	0.0	587.0
9	30.0	587.0
10	46.0	582.85
11	71.0	581.85
12	96.0	582.85
13	112.0	587.0
14	130.0	587.0
15	0.0	587.0
16	30.0	587.0

Figure 1-120: HEF5 Station-Elevation (SE) output. HEC-RAS writes the station-elevation data for each time step (See Time Date Stamp) for all cross sections in two continuous columns (the "value" record). The "info" record coordinates with the "River Reach Station" record to identify where each cross section begins and ends.



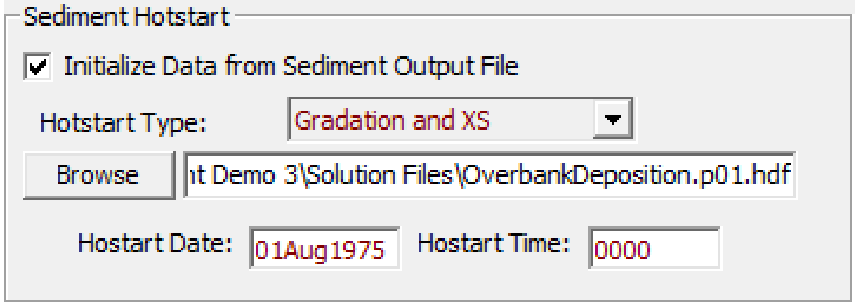
	0	1
0	-12.91	99.84
1	-8.85	96.73
2	-8.01	94.61
3	-1.09	90.78
4	5.16	89.57
5	30.33	88.86
6	33.03	84.47
7	37.08	81.92
8	38.94	81.72
9	41.3	81.28
10	43.33	81.24
11	46.2	81.36
12	49.07	81.44
13	52.96	81.68
14	55.83	82.34
15	59.2	84.73
16	61.57	88.14
17	69.0	88.86
18	92.3	89.46
19	96.53	91.14
20	103.28	95.33
21	108.52	99.6
22	-12.61	99.84
23	-8.9	96.96
24	-8.59	96.72
25	-7.75	94.66
26	-6.08	93.71

	0	1
0	0	22
1	22	39
2	61	39
3	100	39
4	139	39
5	178	39
6	217	34
7	251	35
8	286	41
9	327	41
10	368	32
11	400	34
12	434	39
13	473	39
14	512	39
15	551	39
16	590	39
17	629	39
18	668	39
19	707	39
20	746	39
21	785	44
22	829	41
23	870	39
24	909	22

Figure 1-121:Another example of HDF5 cross section output. All model cross sections are reported as a single set of station elevation points in the "values" item and the beginning and end of each cross section are defined in the "info" item. In this example, the first cross section (defined in the River Reach Station item) includes rows 0 to 22.

Sediment Hotstart From Output File (Versions 6.0+)

The new (HEC-RAS 6.0 and later) Sediment Hostart feature will initialize the model with the cross sections and bed gradations from any output time period in a sediment transport output file.



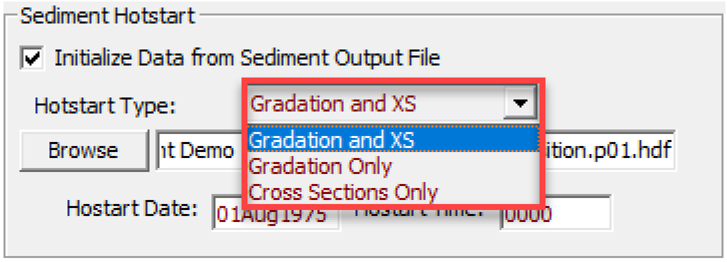
☑ Initialize Data from Sediment Output File

Hotstart Type: Gradation and XS

ıt Demo 3\Solution Files\OverbankDeposition.p01.hdf

Hostart Date: 01Aug1975 Hostart Time: 0000

Modeling Note/Warning: All hotstart features require that the model used to develop the hotstart file has the same cross sections and other nodes (bridges, inline/lateral structures, etc…) as the simulation file uses. HEC-RAS has some logic to try to reconcile hotstart files with extra or missing cross sections (relative to the starting geometry). But users should just be careful that the geometry used to generate the hotstart file has the same cross sections (and other features) as the geometry file in the plan that uses it.



☑ Initialize Data from Sediment Output File

Hotstart Type: Gradation and XS

ıt Demo … ition.p01.hdf

Hostart Date: 01Aug1975

0000

Figure 1-122: Select which data HEC-RAS should import from the result file.

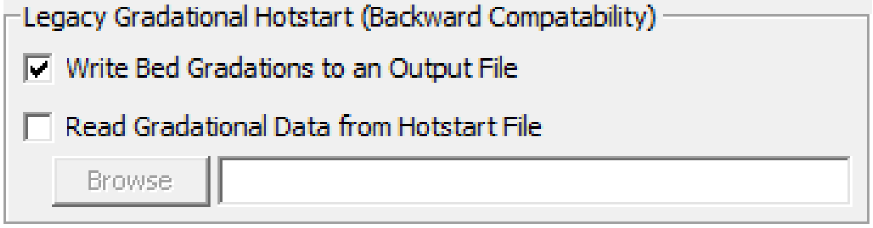
Gradation Hotstart (5.x Legacy Version)

Note: This feature is superseded by the Sediment Hotstart from and Output File. It has been retained for backward compatibility, but new models should use the new feature, which is much more powerful, flexible, and intuitive.

Sediment bed gradations are often vertically discontinuous (e.g. a thin, coarse armor layer often covers finer, well graded/poorly sorted sub surface material). HEC-RAS accounts for cover layers computationally with the bed sorting and armoring algorithm, but it can be useful to start simulations with different gradations in the cover/active layer and the subsurface/inactive layer.

Users can manually define and select separate cover layers using the **Options→Mixing Options** menu or users can import layer-specific bed gradations from a previous HEC-RAS sediment run with the **Gradation Hotstart tool** (Figure 1-114).

The **Gradation Hotstart** has two steps. First, an HEC-RAS sediment model must write out sediment gradation data. Select the **Write Bed Gradations to an Output File** check box under **Gradational Hotstart (**Figure 1-123**)**.

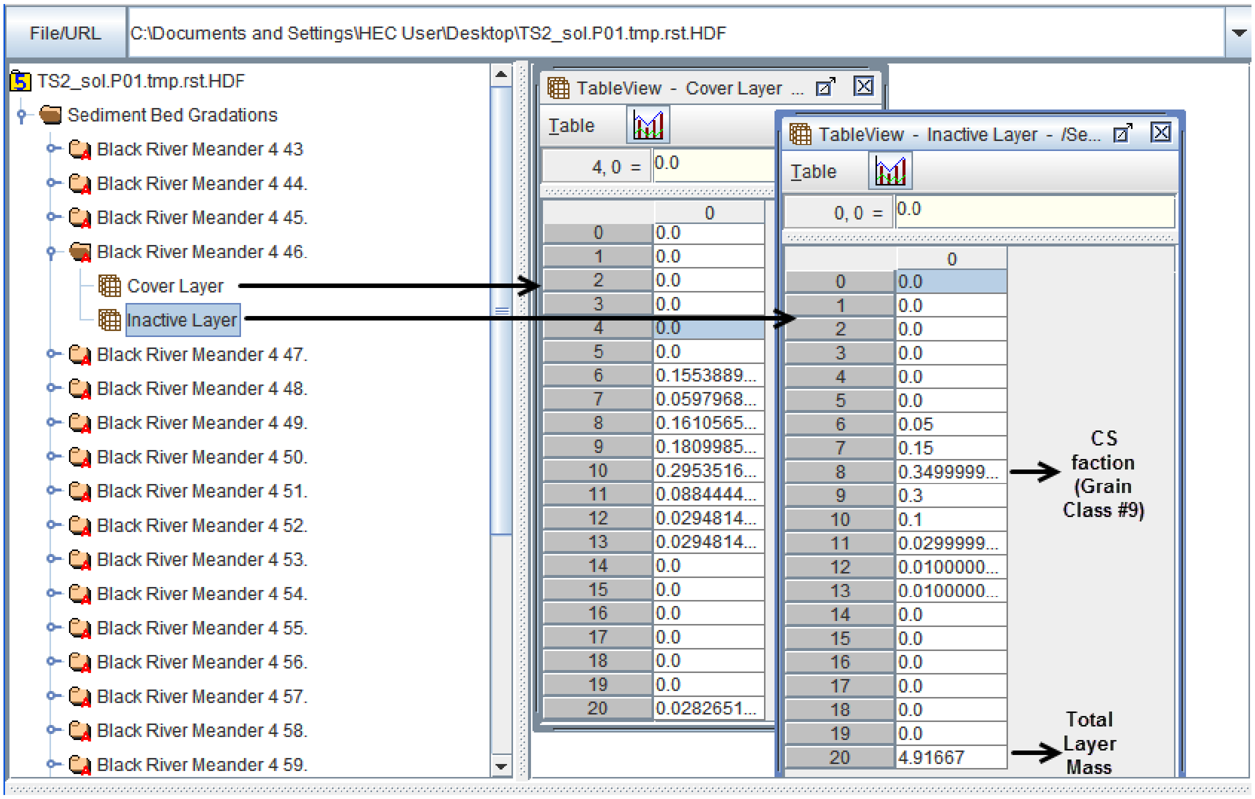


☑ Write Bed Gradations to an Output File

☐ Read Gradational Data from Hotstart File

Figure 1-123: Check the "Write hotstart" box to write gradations to the gradational hotstart file.

This will write an HDF5 file (*.tmp.rst.HDF extension) with the bed gradation for each mixing layer of each cross section (Figure 1-124). HEC-RAS writes the faction associated with each grain class in rows 0-19 and the total layer mass in row 20, and will read these in automatically as initial conditions if prompted.



File/URL C:\Documents and Settings\HEC User\Desktop\TS2_sol.P01.tmp.rst.HDF

TableView - Cover Layer

4, 0 = 0.0

	0
0	0.0
1	0.0
2	0.0
3	0.0
4	0.0
5	0.0
6	0.1553889...
7	0.0597968...
8	0.1610565...
9	0.1809985...
10	0.2953516...
11	0.0884444...
12	0.0294814...
13	0.0294814...
14	0.0
15	0.0
16	0.0
17	0.0
18	0.0
19	0.0
20	0.0282651...

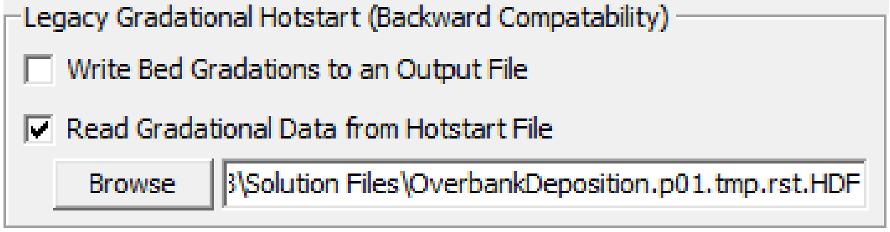
TableView - Inactive Layer - /Se...

0, 0 = 0.0

	0
0	0.0
1	0.0
2	0.0
3	0.0
4	0.0
5	0.0
6	0.05
7	0.15
8	0.3499999...
9	0.3
10	0.1
11	0.0299999...
12	0.0100000...
13	0.0100000...
14	0.0
15	0.0
16	0.0
17	0.0
18	0.0
19	0.0
20	4.91667

Figure 1-124: HDF5 hotstart file. Each cross section has mass data by grain class for the cover layer and the sub-surface layer.

To use a **Gradational Hotstart** file as initial bed gradations, check the **Read Gradational Data from Hotstart File** check box in **Gradational Hostart** box, then **Browse** to the HDF5 hotstart file (Figure 1-125).



Legacy Gradational Hotstart (Backward Compatability)

☐ Write Bed Gradations to an Output File

☑ Read Gradational Data from Hotstart File

Browse 3\Solution Files\OverbankDeposition.p01.tmp.rst.HDF

Figure 1-125: Selecting a hotstart gradation file as starting cross section gradations.

HEC-RAS always requires user specified gradations in the sediment editor, but HEC-RAS will use hotstart gradations instead of gradations specified in the sediment editor when users select the hotstart feature. However if the geometry includes cross sections that do not exist in the hotstart file, the program will default to the gradations specified in the sediment editor.

Modeling Note – Gradation Warm Up Simulation: The feature can be used to perform a 'warm up' run to develop starting bed gradations for the actual simulation. TD13 (HEC, 1992) and Thomas and Chang (2008) recommend running a 'robustness test' to evaluate the numerical stability of 1D sediment models. Robustness runs involve running a constant representative flow (often the 'channel forming discharge') through model until the solution converges on a final stable geometry. By requesting a gradational hotstart file a robustness test and selecting them as the Hostart gradations of the actual simulation, the robustness test can double as a 'bed gradation warm up' and will reduce the numerical fluctuations early in the simulation as the mixing algorithms converge on stable gradations.

Write Classic Output (WSE Profile etc. – O file)

Recent versions of the sediment model write results to HDF5 and read those results with the sediment plotter. Sediment output files can get very large, and the HEC-RAS sediment transport model writes two additional files that can get very large (and affect run time) that may not be useful to users. HEC-RAS provides switches to turn these output files off.

The O file is the standard steady flow output file. Both the quasi-unsteady and unsteady sediment models write hydraulic results to the O file so users can view the standard hydraulic output with the standard hydraulic results tools (e.g. the profile plot, the cross section plot, the generalized output plot, the results tables).

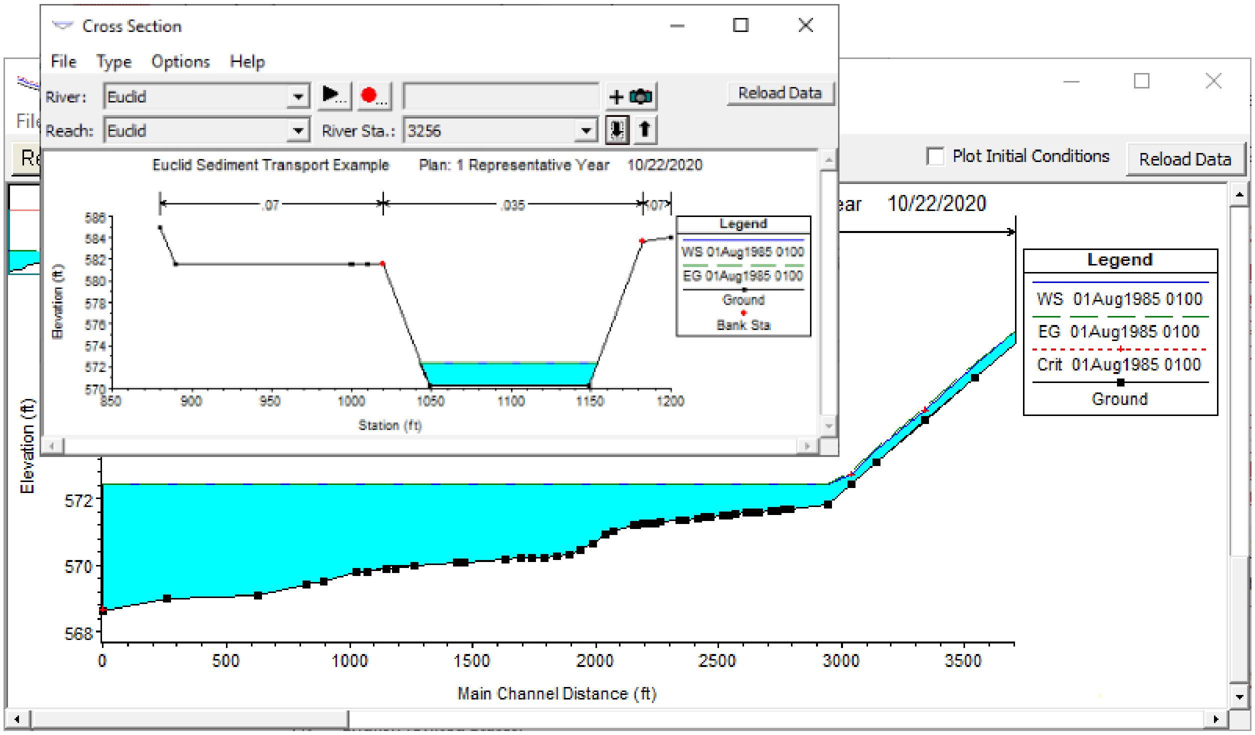


*Figure 1-126: Examples of the standard hydraulic results that read from the .O file (e.g. EuclidExample.O08). These plots will not work if the O file grows larger than **2GB** it will not plot but users can still get sediment and hydraulic data from the Sediment Plotter. This feature can turn the .O file writes off if these files are too large.*

The 1D sediment model in HEC-RAS is a decadal scale model and is usually most effective when applied to multi-decadal calibrations and projections. So hydraulic output files can get large. If the O. file grows **larger than 2GB**, it will not plot and it has trouble writing to disk over 4GB. The sediment HDF5 file does not have these limitations (which is part of the reason HEC-RAS migrated to this file format). Therefore, HEC-RAS can plot the sediment results (and hydraulic output associated with the sediment results) if the fie gets large.

Modelers can use the Output Increment to request less output. But this feature also allows users to turn the steady flow output off, saving disk space and run time, and get all of their results from the sediment plotter.

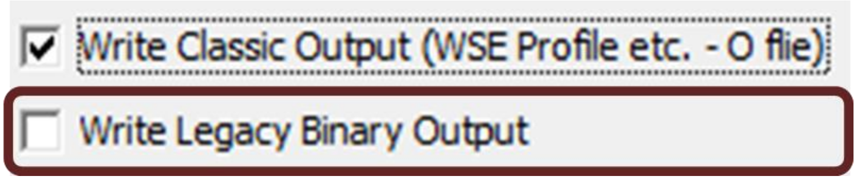
☑ Write Classic Output (WSE Profile etc. - O flie)

☐ Write Legacy Binary Output

Figure 1-127: This option turns off the standard hydraulic output during a sediment simulation. Models that deselect this option will only write results to the sediment plotter.

Write Legacy Binary Output

The sediment plotter in HEC-RAS 6.0 and later reads the HDF results which can read large files (though very large files will degrade performance – so output increment management can still be helpful). But these recent versions of HEC-RAS still include legacy sediment results viewers for users who have built a work-flow comfort level with them.



☑ Write Classic Output (WSE Profile etc. - O flie)

☐ Write Legacy Binary Output

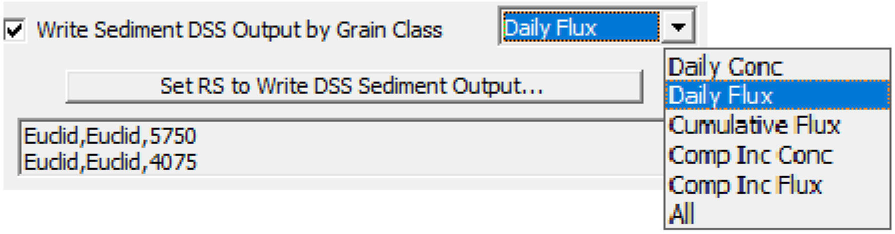
Figure 1-128: This feature turns the binary file off (or on) that HEC-RAS only used for the legacy sediment result viewers (which have been superseded by the new sediment plotter).

One of these legacy viewers read a binary output file which can get large, and like the O file (see previous section) will not plot if it grows larger than 2GB. There is no reason to write this file if you are not using the original sediment result viewers. (Then new sediment plotter has all of the functionality of the previous viewers and many new features, so HEC recommends transitioning to this tool.) Unless you are using these legacy viewers, this file is only taking up disk space and run time. This interface option allows users to choose whether to write it.

New projects, created in version 6.0 or later do not write these files by default. So users have to check this box to use the legacy sediment output. But models created in earlier versions will write these files by default. By deselecting this feature, HEC-RAS will stop writing these files that are generally unnecessary.

DSS Output

Quasi-unsteady sediment analysis does not generate DSS data by default. Users can request limited DSS time series at any cross section(s). HEC-RAS will write out a DSS file named (project name).PXX.sed.dss (where XX is the plan number). This feature only works for quasi-unsteady analyses.



☑ Write Sediment DSS Output by Grain Class

Daily Flux

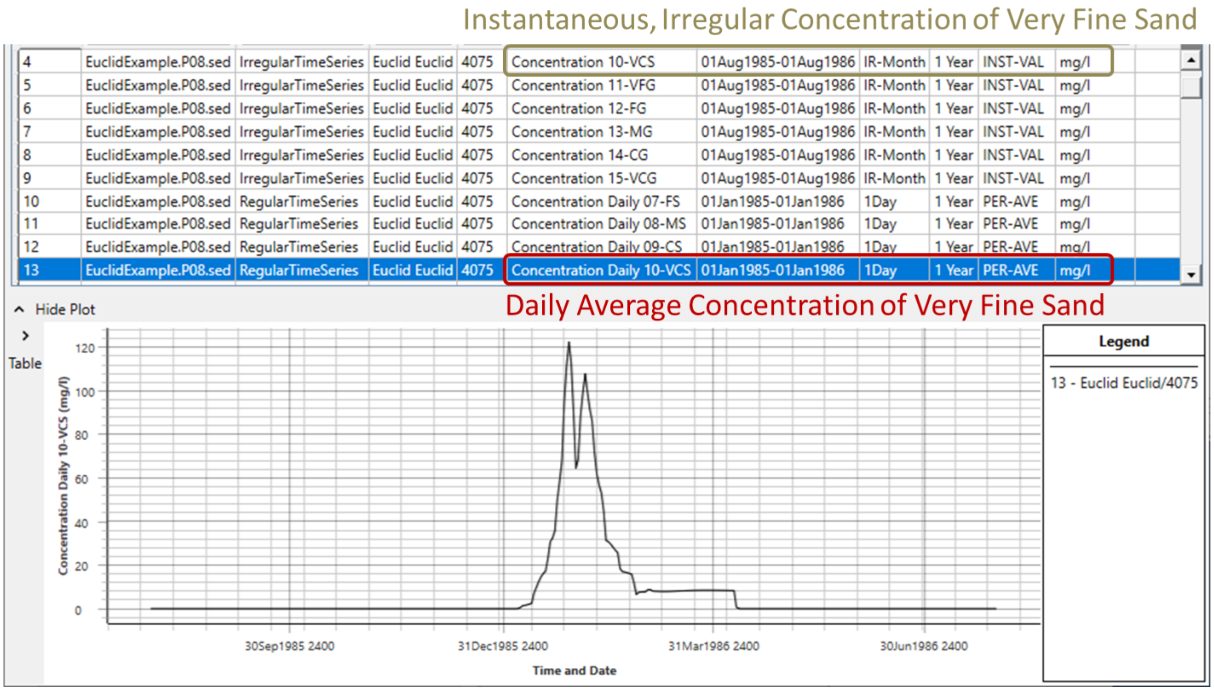
Euclid,Euclid,5750
Euclid,Euclid,4075

Figure 1-129: Selecting a Daily Flux DSS sediment output at two cross sections.

Users can choose one or more cross sections to write DSS output. To add additional cross sections press the **Set RS to Write DSS Sediment Output…** button. To delete or clear a node from the DSS list <u>double click on list</u>. Double clicking removes nodes.

Users can also select five different DSS results (or all five)[1]. Different result options generate different DSS formats, and some of them trigger HEC-RAS to write multiple Results. All DSS results are written by grain size.

HEC-RAS can write Concentration as an instantaneous value at for each computational increment (INST-VAL, IR-Month) or average the Concentration over each day, which it writes as a regular daily time series (PER-AVE, 1Day). The mass flux leaving the cross-section control volume has three options instantaneous flux for each Computational Increment (INST-VAL, IR-Month), daily period cumulative data (PER-AVE, 1Day) that accumulates mass over time, and an instantaneous cumulative mass flux (INST-VAL, IR-Month).

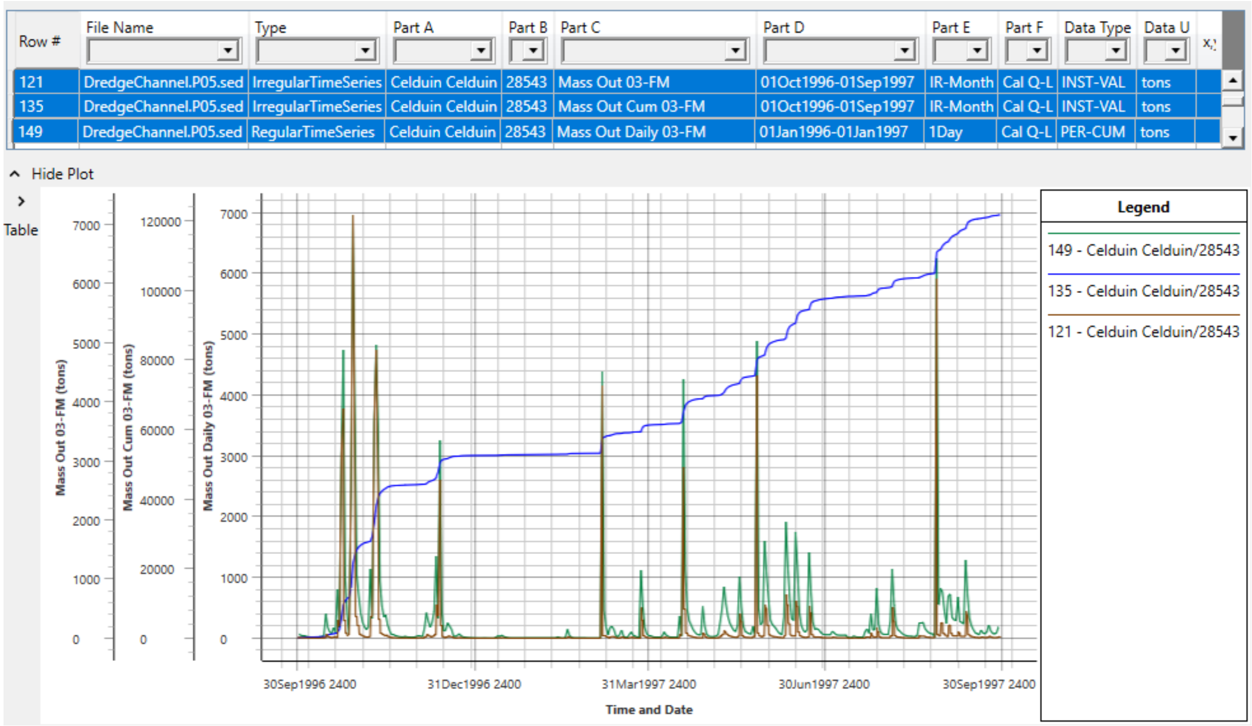


4	EuclidExample.P08.sed	IrregularTimeSeries	Euclid Euclid	4075	Concentration 10-VCS	01Aug1985-01Aug1986	IR-Month	1 Year	INST-VAL	mg/l
5	EuclidExample.P08.sed	IrregularTimeSeries	Euclid Euclid	4075	Concentration 11-VFG	01Aug1985-01Aug1986	IR-Month	1 Year	INST-VAL	mg/l
6	EuclidExample.P08.sed	IrregularTimeSeries	Euclid Euclid	4075	Concentration 12-FG	01Aug1985-01Aug1986	IR-Month	1 Year	INST-VAL	mg/l
7	EuclidExample.P08.sed	IrregularTimeSeries	Euclid Euclid	4075	Concentration 13-MG	01Aug1985-01Aug1986	IR-Month	1 Year	INST-VAL	mg/l
8	EuclidExample.P08.sed	IrregularTimeSeries	Euclid Euclid	4075	Concentration 14-CG	01Aug1985-01Aug1986	IR-Month	1 Year	INST-VAL	mg/l
9	EuclidExample.P08.sed	IrregularTimeSeries	Euclid Euclid	4075	Concentration 15-VCG	01Aug1985-01Aug1986	IR-Month	1 Year	INST-VAL	mg/l
10	EuclidExample.P08.sed	RegularTimeSeries	Euclid Euclid	4075	Concentration Daily 07-FS	01Jan1985-01Jan1986	1Day	1 Year	PER-AVE	mg/l
11	EuclidExample.P08.sed	RegularTimeSeries	Euclid Euclid	4075	Concentration Daily 08-MS	01Jan1985-01Jan1986	1Day	1 Year	PER-AVE	mg/l
12	EuclidExample.P08.sed	RegularTimeSeries	Euclid Euclid	4075	Concentration Daily 09-CS	01Jan1985-01Jan1986	1Day	1 Year	PER-AVE	mg/l
13	EuclidExample.P08.sed	RegularTimeSeries	Euclid Euclid	4075	Concentration Daily 10-VCS	01Jan1985-01Jan1986	1Day	1 Year	PER-AVE	mg/l

Figure 1-130: DSS results with the two types of Concentration time series.

---

[1] These DSS output options were expanded in version 6.0. Earlier versions had much more limited DSS output.



Row #	File Name	Type	Part A	Part B	Part C	Part D	Part E	Part F	Data Type	Data U
121	DredgeChannel.P05.sed	IrregularTimeSeries	Celduin Celduin	28543	Mass Out 03-FM	01Oct1996-01Sep1997	IR-Month	Cal Q-L	INST-VAL	tons
135	DredgeChannel.P05.sed	IrregularTimeSeries	Celduin Celduin	28543	Mass Out Cum 03-FM	01Oct1996-01Sep1997	IR-Month	Cal Q-L	INST-VAL	tons
149	DredgeChannel.P05.sed	RegularTimeSeries	Celduin Celduin	28543	Mass Out Daily 03-FM	01Jan1996-01Jan1997	1Day	Cal Q-L	PER-CUM	tons

Figure 1-131: Three types of Mass Out (flux leaving the control volume) results available in the DSS output.

The time series written to DSS are equivalent to the MASS Out Cum variable in HEC-RAS, computing the cumulative total sediment mass leaving the control volume over time by grain class. Cumulative mass time series are stored by grain class (part C indicates that they are sediment data, the grain class number and the grain class name) and stored as irregular monthly (IR-Month) data.

Create Geometry Files from Sediment Results

It is very common for users to convert the results from a sediment simulation into a new HEC-RAS geometry file. The most common motivation for this is re-evaluating risk assessment (e.g. run HEC-FDA, the 1% flood or a 2% riparian flow) for future conditions, after a period of record sediment simulation. However, this feature can also useful for "robustness" tests or model warm-up.

To create a geometry file from the updated cross sections from a sediment transport simulation press the **Create Geometry Files from Sediment Results** button on the **Sediment Output Options** menu.

A dialogue will appear (Figure 1-132) with all the result profiles from the sediment simulation. Select one or more of these to convert the cross-section station-elevation points from that (those) time(s) in the simulation into geometry files. For example, to create a geometry file from the final simulation result, scroll to the bottom profile and select it.

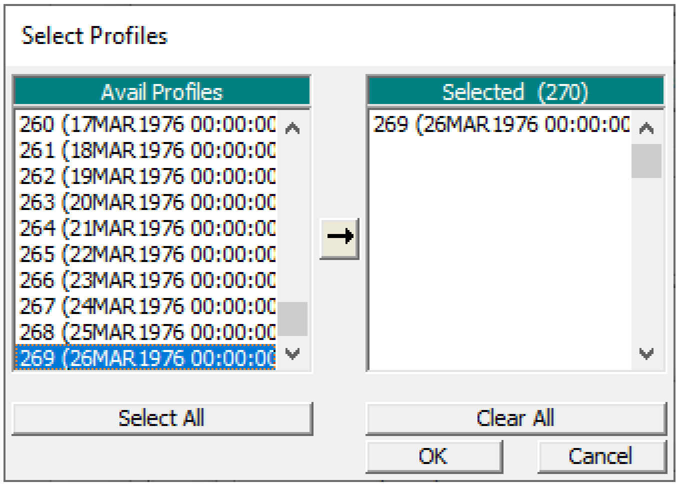
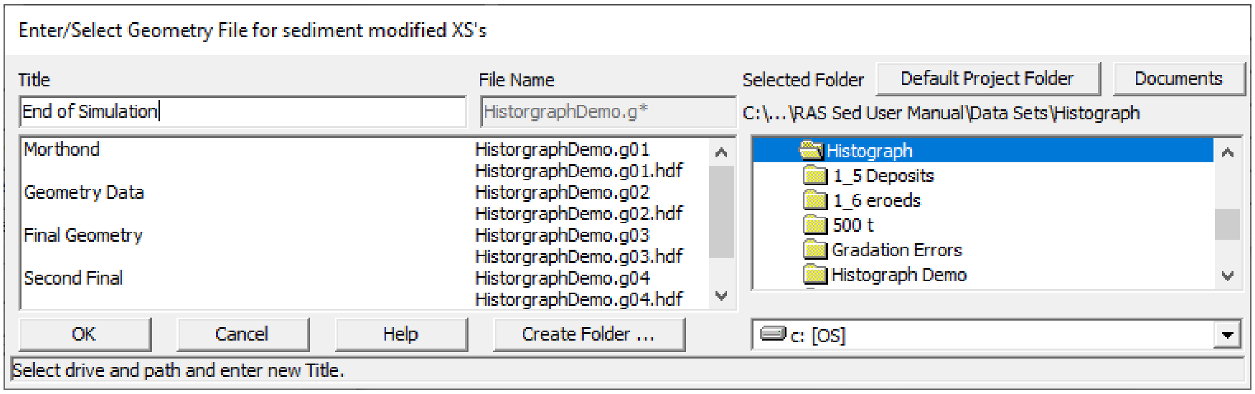


Figure 1-132: Select one or more profiles to create geometry files.

A naming dialogue will appear for each of the profiles selected. Name the geometry file(s)



Title: End of Simulation

File Name: HistorgraphDemo.g*

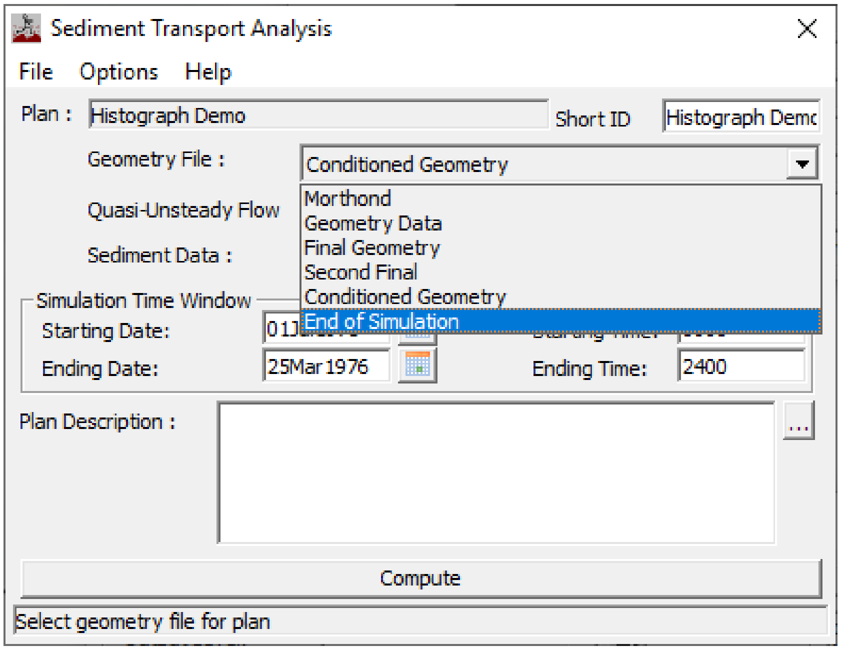
Selected Folder: C:\...\RAS Sed User Manual\Data Sets\Histograph

Select drive and path and enter new Title.

Figure 1-133: Give each new geometry file a unique name. They will be added to the HEC-RAS project.

The new geometry file will inherit all of the parameters, variables, settings and features of the geometry file used for the sediment simulation (e.g. n-values, ineffective flow areas, structures, etc…) and will only update the station-elevation points (and, in cases where BSTEM is not used, only the elevations of those points).

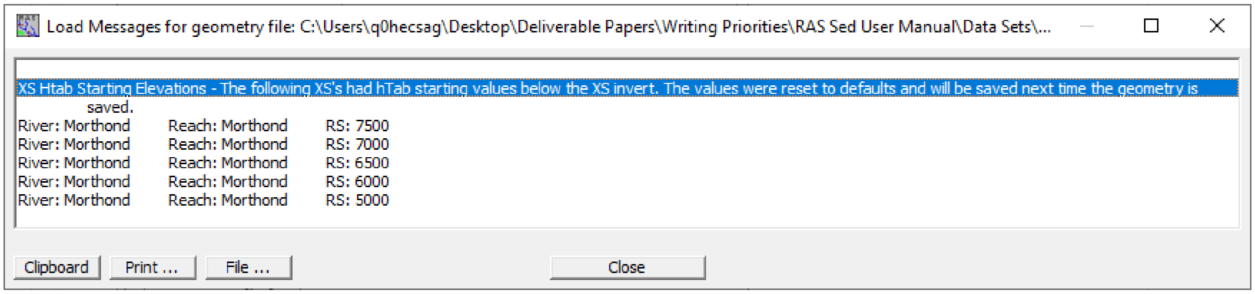
HEC-RAS will add the new geometry file to the project, and it becomes available for new steady, unsteady or sediment simulations.



Plan : Histograph Demo
Short ID Histograph Demc
Geometry File : Conditioned Geometry
Morthond
Geometry Data
Final Geometry
Second Final
Conditioned Geometry
End of Simulation
Quasi-Unsteady Flow
Sediment Data :
Simulation Time Window
Starting Date: 01J
Ending Date: 25Mar1976
Ending Time: 2400
Plan Description :
Select geometry file for plan

Figure 1-134: HEC-RAS adds the new geometry file to the project and it becomes available for future simulations.

Modeling Note – XS Htab Starting Elevation Error: When using a geometry file created from a sediment simulation in a new hydraulic or sediment simulation, the new simulation will often throw an Htab error (Figure 1-135). The HTab (Hydraulic Table) editor sets the increments for the pre-processed hydraulic computations and is supposed to start at or near the thalweg. The new geometry file inherits these from the geometry file used during the sediment simulation, but the thalwegs of many of the cross sections have probably changed.

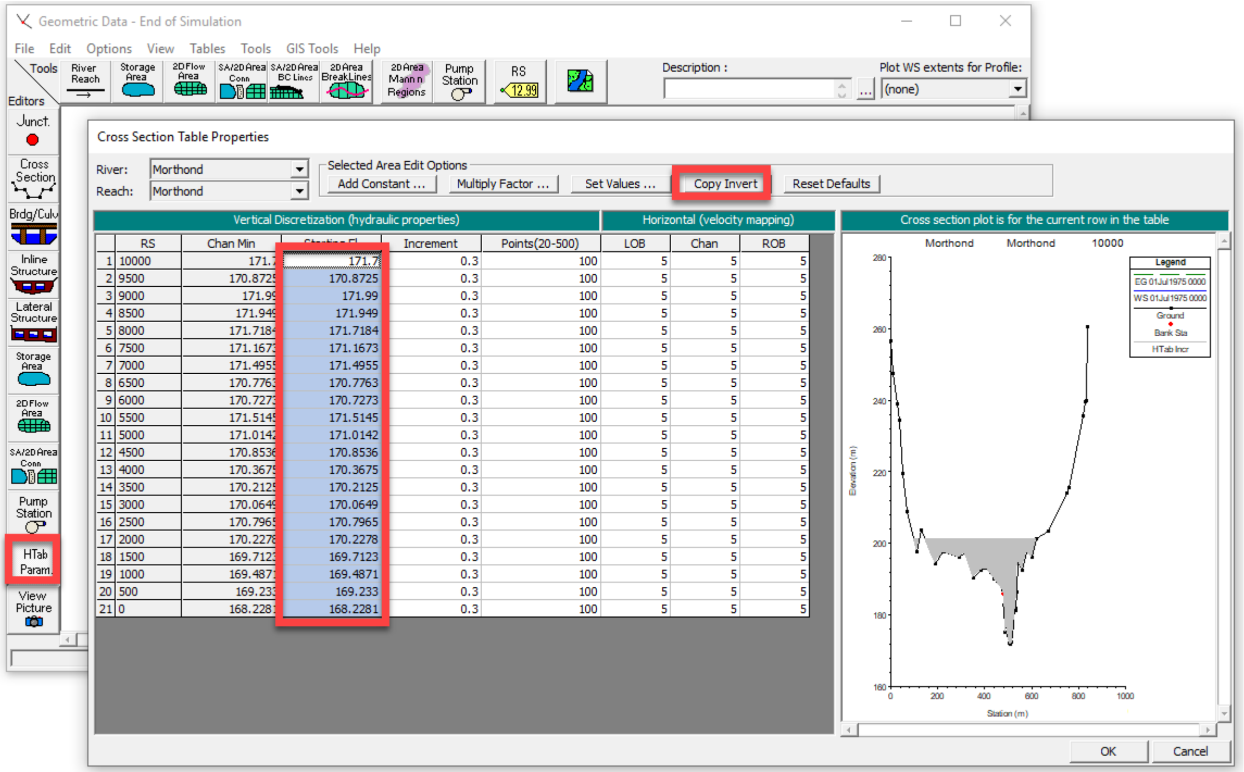


Load Messages for geometry file: C:\Users\q0hecsag\Desktop\Deliverable Papers\Writing Priorities\RAS Sed User Manual\Data Sets\...

```
XS Htab Starting Elevations - The following XS's had hTab starting values below the XS invert. The values were reset to defaults and will be saved next time the geometry is
        saved.
River: Morthond      Reach: Morthond      RS: 7500
River: Morthond      Reach: Morthond      RS: 7000
River: Morthond      Reach: Morthond      RS: 6500
River: Morthond      Reach: Morthond      RS: 6000
River: Morthond      Reach: Morthond      RS: 5000
```

Figure 1-135: Common HTab error encountered when using a geometry file created from a sediment transport simulation result.

This issue has a simple fix. Open the geometry file and press the HTab button on the left, vertical, button bar (you may need to expand the geometry editor vertically to see it). This will open the **Cross Section Table** Properties editor (Figure 1-136). Select the header of the **Starting El** column to select all of the initial elevations. Then press the **Copy Invert** button. This will reset the base elevation of all the HTab tables and will clear up the error message.



River: Morthond
Reach: Morthond

	Vertical Discretization (hydraulic properties)					Horizontal (velocity mapping)		
	RS	Chan Min	Starting El	Increment	Points(20-500)	LOB	Chan	ROB
1	10000	171.7	171.7	0.3	100	5	5	5
2	9500	170.8725	170.8725	0.3	100	5	5	5
3	9000	171.99	171.99	0.3	100	5	5	5
4	8500	171.949	171.949	0.3	100	5	5	5
5	8000	171.7184	171.7184	0.3	100	5	5	5
6	7500	171.1673	171.1673	0.3	100	5	5	5
7	7000	171.4955	171.4955	0.3	100	5	5	5
8	6500	170.7763	170.7763	0.3	100	5	5	5
9	6000	170.7273	170.7273	0.3	100	5	5	5
10	5500	171.5145	171.5145	0.3	100	5	5	5
11	5000	171.0142	171.0142	0.3	100	5	5	5
12	4500	170.8536	170.8536	0.3	100	5	5	5
13	4000	170.3675	170.3675	0.3	100	5	5	5
14	3500	170.2125	170.2125	0.3	100	5	5	5
15	3000	170.0649	170.0649	0.3	100	5	5	5
16	2500	170.7965	170.7965	0.3	100	5	5	5
17	2000	170.2278	170.2278	0.3	100	5	5	5
18	1500	169.7123	169.7123	0.3	100	5	5	5
19	1000	169.4871	169.4871	0.3	100	5	5	5
20	500	169.233	169.233	0.3	100	5	5	5
21	0	168.2281	168.2281	0.3	100	5	5	5

Figure 1-136: Workflow to fix the HTab starting elevation error.

Specific Gage Post-Processor

Note: The Specific Gage Tool was redesigned in version HEC-RAS 6.0 and will be different than previous versions. Previous versions ran this process as part of a sediment simulation. The new version is a post-processor that creates new geometry files from the HDF5 output files.

A specific gage analyses can be a useful way to measure and calibrate long term aggradation and degradation in settings with abundant historical water surface elevation data but little bed elevation information. Specific gage analyses tracks the water surface elevations associated with defined flows, to evaluate historical aggradation or degradation without direct bed elevation evidence (Figure 1-137 and Figure 1-138).

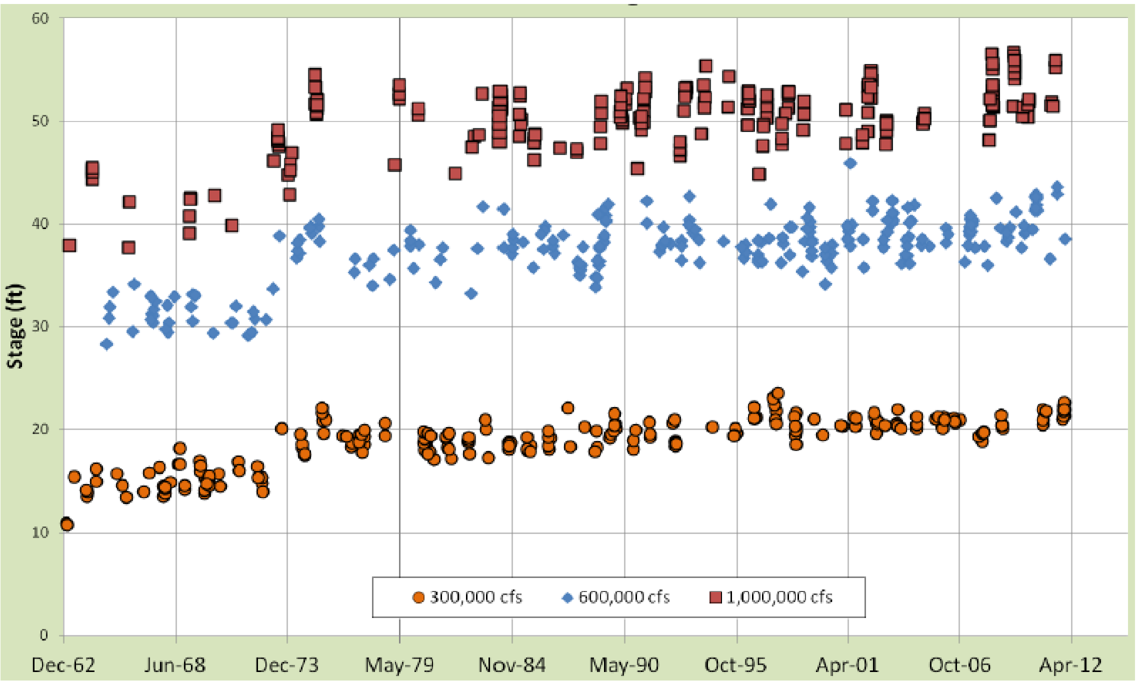


Figure 1-137: Example Specific Gage plot from Red River Landing Gage from 1943-2011 (Little and Biedanharn, 2014).

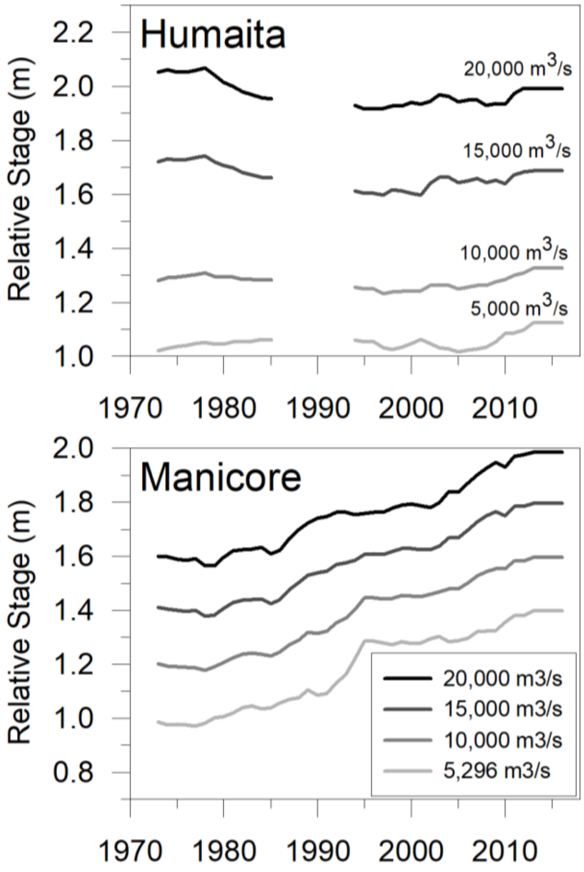
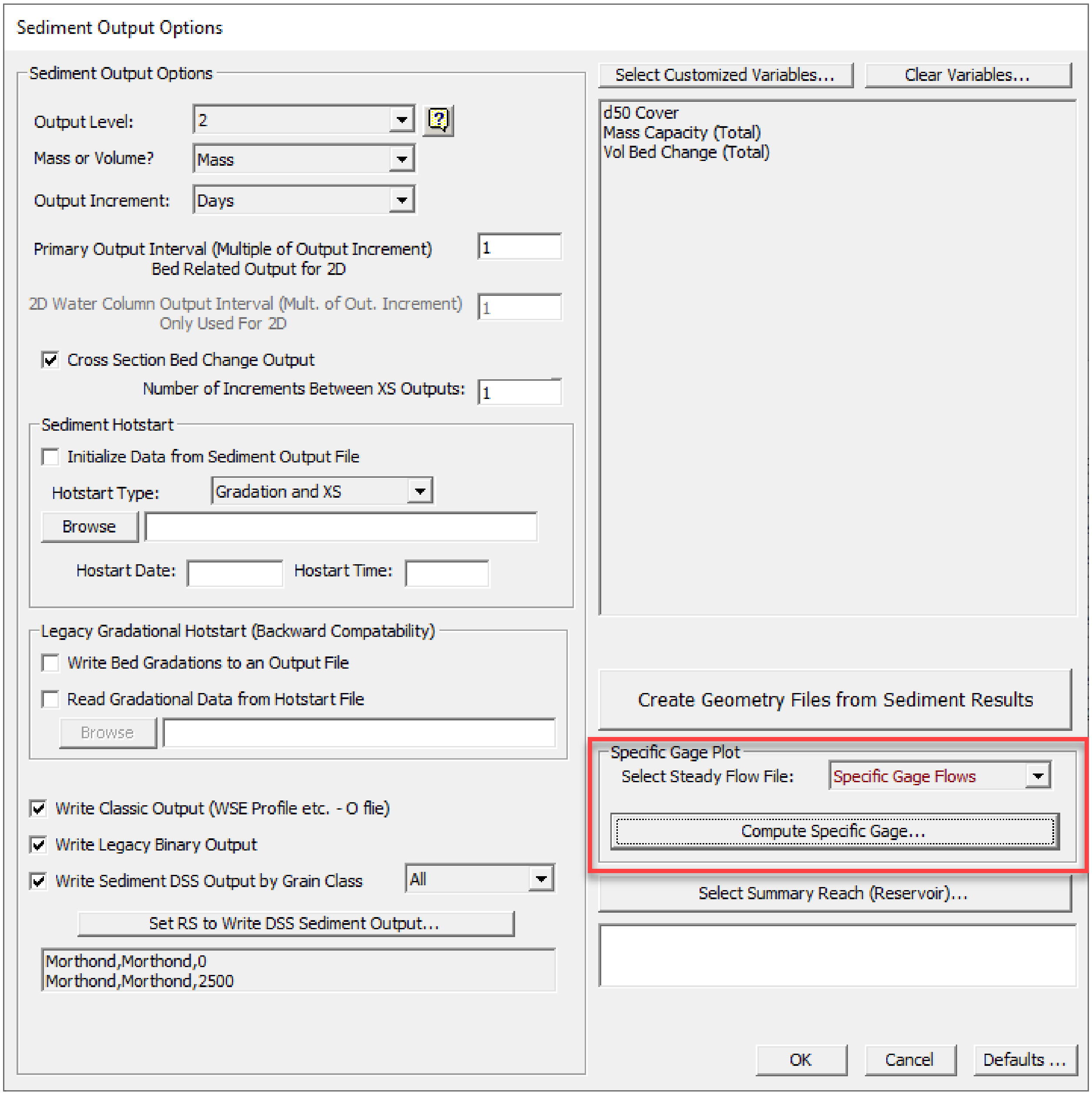


Figure 1-138: Specific gage plots for the upper Madeira River (from Gibson et al., 2019).

With the Specific Gage capability in HEC-RAS users can compare movable bed simulations to historic specific gage data. The current version of HEC-RAS includes a Specific Gage post-processor which converts mobile bed simulation results into geometry files and then runs repeated steady flow analyses to produce the data required to generate Specific Gage plots. To perform a Specific Gage Analysis elect **Options→Sediment Output Options and Tolerances** in the **Sediment Analysis Window** (Figure 1-139).



Sediment Output Options

Sediment Output Options

Output Level: 2

Mass or Volume? Mass

Output Increment: Days

Primary Output Interval (Multiple of Output Increment) Bed Related Output for 2D: 1

2D Water Column Output Interval (Mult. of Out. Increment) Only Used For 2D: 1

☑ Cross Section Bed Change Output

Number of Increments Between XS Outputs: 1

Sediment Hotstart

☐ Initialize Data from Sediment Output File

Hotstart Type: Gradation and XS

Hostart Date:

Hostart Time:

Legacy Gradational Hotstart (Backward Compatability)

☐ Write Bed Gradations to an Output File

☐ Read Gradational Data from Hotstart File

☑ Write Classic Output (WSE Profile etc. - O flie)

☑ Write Legacy Binary Output

☑ Write Sediment DSS Output by Grain Class: All

Morthond,Morthond,0
Morthond,Morthond,2500

d50 Cover
Mass Capacity (Total)
Vol Bed Change (Total)

Specific Gage Plot

Select Steady Flow File: Specific Gage Flows

Figure 1-139: Specific Gage Post Processor

The Specific Gage Post processor performs a steady flow analysis with consistent, pre-defined flows, and geometries mined from the HEC-RAS sediment output. At each date and time specified in the **Specific Gage Plot** editor HEC-RAS will:

- Create a new geometry file from the sediment output (updated cross sections) at the output time step closest to that specified in the Specific Gage Plot editor.

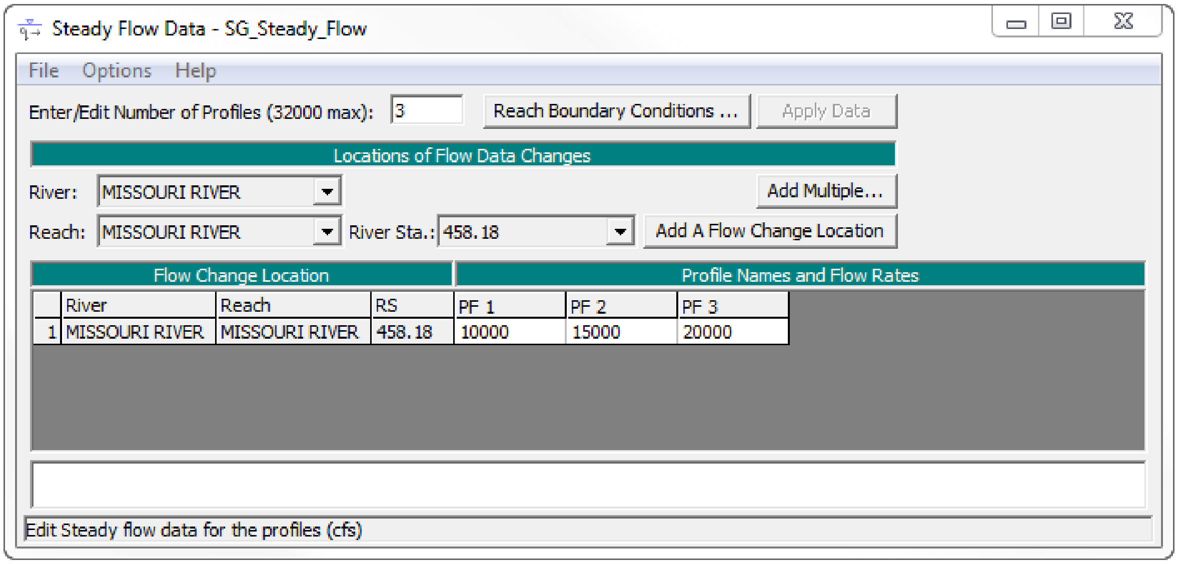
- Create a new Steady Flow plan for each selected date by pairing the new geometry with the Steady Flow file selected in the dropdown box.

- Copy the flow file and save the new geometry and plan files in a new project in a new sub-folder.

- Run each steady flow plan.

- Create a table with the water surface elevation at each cross section from each intermediate sediment output geometry for each flow specified in the steady flow editor.

The Specific Gage feature is a Steady Flow post-processor that inherits evolving cross-section data over time, from the sediment output files. It creates a series of dated, steady flow, plans and runs the steady flow engine to compute water surface elevation time series at each cross section. The Specific Gage feature requires a **Steady Flow** file. Therefore, create a **Steady Flow** file and run it with the initial sediment geometry to test it.



Enter/Edit Number of Profiles (32000 max): 3

River: MISSOURI RIVER

Reach: MISSOURI RIVER

River Sta.: 458.18

	Flow Change Location			Profile Names and Flow Rates		
	River	Reach	RS	PF 1	PF 2	PF 3
1	MISSOURI RIVER	MISSOURI RIVER	458.18	10000	15000	20000

Edit Steady flow data for the profiles (cfs)

Figure 1-140: Steady flow file built to support the specific gage analysis, selected in the drop down box in the previous figure. The Specific Gage Analysis will perform a steady flow analysis with each of these flows and geometries created from sediment output at each date specified in the previous figure.

The steady flow file should include the flows targeted for water surface elevation trend analysis and must be a complete steady flow file with all of the data required to perform a steady flow analysis with the geometry file used in the sediment transport analysis (e.g. downstream boundary conditions, reservoir elevations, gate settings, etc…).

After creating a steady flow file and testing it with a Steady Flow simulation, open the **Sediment Output Options and Tolerances** editor from the **Options** menu of the **Sediment Analysis** dialog (from the original Sediment Analysis project and plan). Select the steady flow file created for the Specific Gage analysis in drop down box as depicted in (Figure 1-141). Then press the **Compute Specific Gage** button (Figure 1-142).

HEC-RAS will prompt for an "Analysis Name." The analysis will generate several steady flow files and output, so it creates a sub folder in the project directory with this name.

Define the name of the analysis in this dialogue (Figure 1-142) and make sure the name is unique, and not the name of any existing folders.

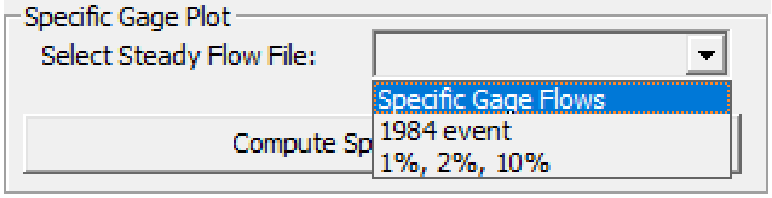
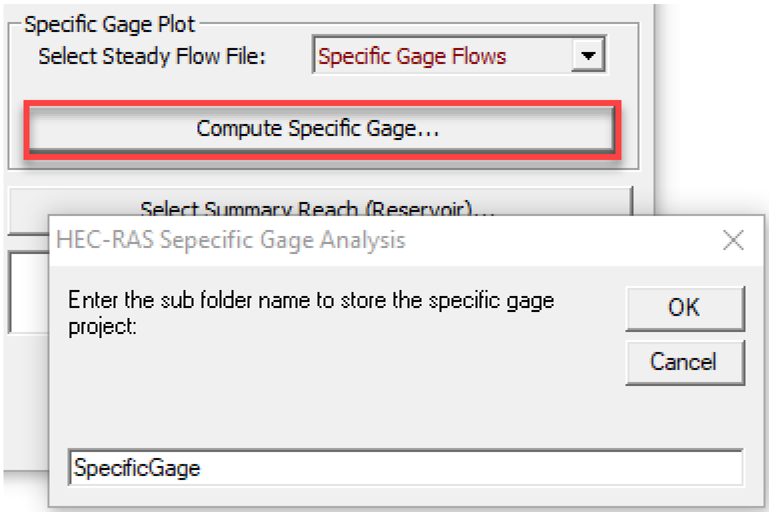


Figure 1-141: Specific Gage drop down box populates with all steady flow files (.fxx) in the project. Select the appropriate steady flow file to combine with the geometries built from the sediment output.*



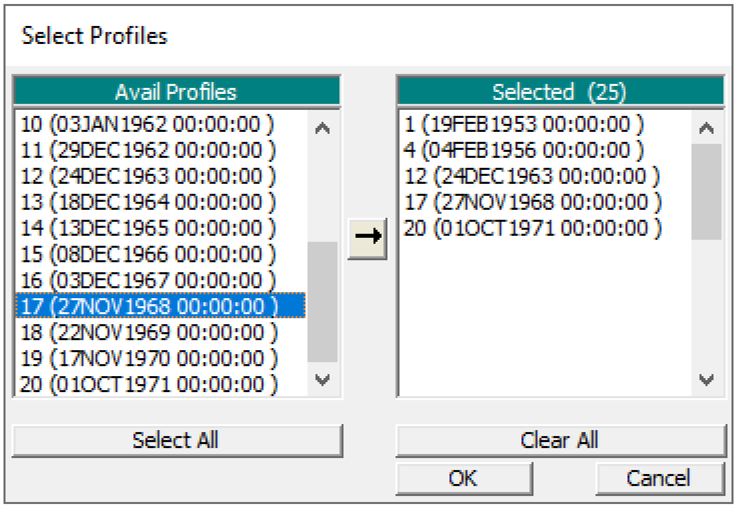
Select Steady Flow File: Specific Gage Flows

Enter the sub folder name to store the specific gage project:

SpecificGage

Figure 1-142: Name the Specific Gage Analysis (which will become the name of the Steady Flow sub-folder).

HEC-RAS will then launch a dialogue with all of the sediment output profiles, named by their simulation dates. Select (double click or press the → button) the times that the Specific Gage analysis should evaluate water surface elevations for the constant flows (Figure 1-143).



Avail Profiles

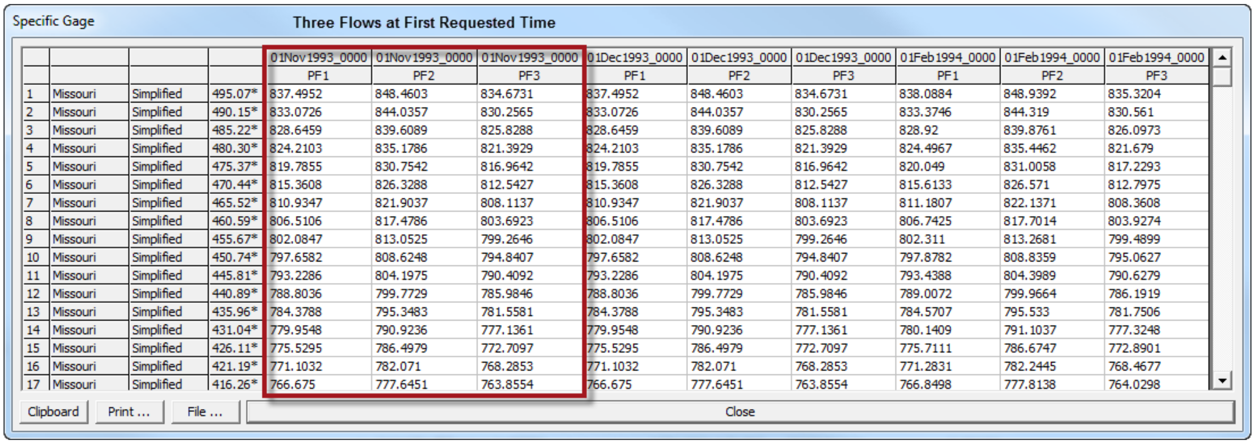
10 (03JAN1962 00:00:00)
11 (29DEC1962 00:00:00)
12 (24DEC1963 00:00:00)
13 (18DEC1964 00:00:00)
14 (13DEC1965 00:00:00)
15 (08DEC1966 00:00:00)
16 (03DEC1967 00:00:00)
17 (27NOV1968 00:00:00)
18 (22NOV1969 00:00:00)
19 (17NOV1970 00:00:00)
20 (01OCT1971 00:00:00)

Selected (25)

1 (19FEB1953 00:00:00)
4 (04FEB1956 00:00:00)
12 (24DEC1963 00:00:00)
17 (27NOV1968 00:00:00)
20 (01OCT1971 00:00:00)

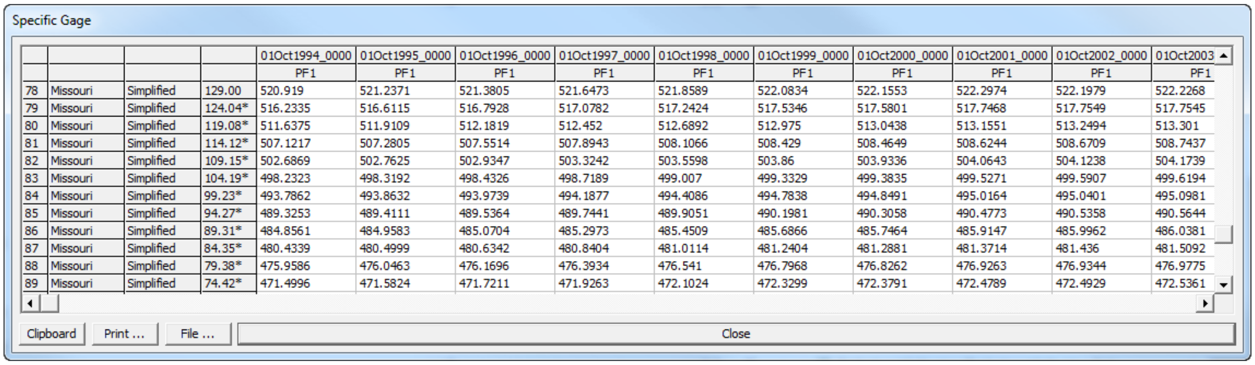
Figure 1-143: Select times to evaluate the Specific Gage elevations (select from the list of sediment simulation profiles).

Then press **OK** to launch the post processor. This will prompt the user for a file name, will generate a new project file in a sub folder (using the name provided), create a geometry file from the sediment output of the active plan at each specified date/time, pair each with the flow file by creating steady flow plans for each, run each steady flow plan. After the analysis the steady flow project, plans, and output exist in the sub folder and can be reviewed or analyzed independently. However, the Specific Gage feature also consolidates the water surface profiles for each flow in the steady flow file for each date in the Specific Gage editor in a table (Figure 1-144 and Figure 1-145) that can be easily translated into Specific Gage plots.



				01Nov1993_0000	01Nov1993_0000	01Nov1993_0000	01Dec1993_0000	01Dec1993_0000	01Dec1993_0000	01Feb1994_0000	01Feb1994_0000	01Feb1994_0000
				PF1	PF2	PF3	PF1	PF2	PF3	PF1	PF2	PF3
1	Missouri	Simplified	495.07*	837.4952	848.4603	834.6731	837.4952	848.4603	834.6731	838.0884	848.9392	835.3204
2	Missouri	Simplified	490.15*	833.0726	844.0357	830.2565	833.0726	844.0357	830.2565	833.3746	844.319	830.561
3	Missouri	Simplified	485.22*	828.6459	839.6089	825.8288	828.6459	839.6089	825.8288	828.92	839.8761	826.0973
4	Missouri	Simplified	480.30*	824.2103	835.1786	821.3929	824.2103	835.1786	821.3929	824.4967	835.4462	821.679
5	Missouri	Simplified	475.37*	819.7855	830.7542	816.9642	819.7855	830.7542	816.9642	820.049	831.0058	817.2293
6	Missouri	Simplified	470.44*	815.3608	826.3288	812.5427	815.3608	826.3288	812.5427	815.6133	826.571	812.7975
7	Missouri	Simplified	465.52*	810.9347	821.9037	808.1137	810.9347	821.9037	808.1137	811.1807	822.1371	808.3608
8	Missouri	Simplified	460.59*	806.5106	817.4786	803.6923	806.5106	817.4786	803.6923	806.7425	817.7014	803.9274
9	Missouri	Simplified	455.67*	802.0847	813.0525	799.2646	802.0847	813.0525	799.2646	802.311	813.2681	799.4899
10	Missouri	Simplified	450.74*	797.6582	808.6248	794.8407	797.6582	808.6248	794.8407	797.8782	808.8359	795.0627
11	Missouri	Simplified	445.81*	793.2286	804.1975	790.4092	793.2286	804.1975	790.4092	793.4388	804.3989	790.6279
12	Missouri	Simplified	440.89*	788.8036	799.7729	785.9846	788.8036	799.7729	785.9846	789.0072	799.9664	786.1919
13	Missouri	Simplified	435.96*	784.3788	795.3483	781.5581	784.3788	795.3483	781.5581	784.5707	795.533	781.7506
14	Missouri	Simplified	431.04*	779.9548	790.9236	777.1361	779.9548	790.9236	777.1361	780.1409	791.1037	777.3248
15	Missouri	Simplified	426.11*	775.5295	786.4979	772.7097	775.5295	786.4979	772.7097	775.7111	786.6747	772.8901
16	Missouri	Simplified	421.19*	771.1032	782.071	768.2853	771.1032	782.071	768.2853	771.2831	782.2445	768.4677
17	Missouri	Simplified	416.26*	766.675	777.6451	763.8554	766.675	777.6451	763.8554	766.8498	777.8138	764.0298

Figure 1-144: Specific Gage summary output including stages for three flows at three dates.



				01Oct1994_0000	01Oct1995_0000	01Oct1996_0000	01Oct1997_0000	01Oct1998_0000	01Oct1999_0000	01Oct2000_0000	01Oct2001_0000	01Oct2002_0000	01Oct2003
				PF1	PF1	PF1	PF1	PF1	PF1	PF1	PF1	PF1	PF1
78	Missouri	Simplified	129.00	520.919	521.2371	521.3805	521.6473	521.8589	522.0834	522.1553	522.2974	522.1979	522.2268
79	Missouri	Simplified	124.04*	516.2335	516.6115	516.7928	517.0782	517.2424	517.5346	517.5801	517.7468	517.7549	517.7545
80	Missouri	Simplified	119.08*	511.6375	511.9109	512.1819	512.452	512.6892	512.975	513.0438	513.1551	513.2494	513.301
81	Missouri	Simplified	114.12*	507.1217	507.2805	507.5514	507.8943	508.1066	508.429	508.4649	508.6244	508.6709	508.7437
82	Missouri	Simplified	109.15*	502.6869	502.7625	502.9347	503.3242	503.5598	503.86	503.9336	504.0643	504.1238	504.1739
83	Missouri	Simplified	104.19*	498.2323	498.3192	498.4326	498.7189	499.007	499.3329	499.3835	499.5271	499.5907	499.6194
84	Missouri	Simplified	99.23*	493.7862	493.8632	493.9739	494.1877	494.4086	494.7838	494.8491	495.0164	495.0401	495.0981
85	Missouri	Simplified	94.27*	489.3253	489.4111	489.5364	489.7441	489.9051	490.1981	490.3058	490.4773	490.5358	490.5644
86	Missouri	Simplified	89.31*	484.8561	484.9583	485.0704	485.2973	485.4509	485.6866	485.7464	485.9147	485.9962	486.0381
87	Missouri	Simplified	84.35*	480.4339	480.4999	480.6342	480.8404	481.0114	481.2404	481.2881	481.3714	481.436	481.5092
88	Missouri	Simplified	79.38*	475.9586	476.0463	476.1696	476.3934	476.541	476.7968	476.8262	476.9263	476.9344	476.9775
89	Missouri	Simplified	74.42*	471.4996	471.5824	471.7211	471.9263	472.1024	472.3299	472.3791	472.4789	472.4929	472.5361

Figure 1-145: Specific Gage summary output including stages for one flow at the beginning of each water year.

Modeling Note – Other Uses for the Specific Gage Feature: Since the Specific Gage analysis was added, users have leveraged it for several alternate analyses. Any analyses that requires steady flow analyses at intermittent times in a sediment transport analyses (e.g. loss of reservoir storage, flood mapping) can use the Specific Gage tool to generate a project with separate steady flow runs using geometries from intermediate times in a sediment transport model.

Modeling Note – I press OK and nothing happens: Make sure a sediment plan with simulation results is open and is the active plan.

Wish List: Alternate (easier) specific gage analysis tool: Another way to analyze specific gage results would involve plotting computed stages within user-specified flow ranges (potentially, with observed data) in the Sediment Plotter.

Viewing Results

The sediment output has evolved over the years, keeping up with new output formats and visualization technology in HEC-RAS. This has led to an idiosyncratic output legacy, where each of the last three major releases have featured a new sediment visualization tool.

HEC-RAS writes detailed sediment and hydraulic output during sediment simulation and can display these results in three sets of plots and tables in spatial, temporal, or cross section formats. For most purposes, the new Sediment Results Viewer will be superior to the legacy plotters.

Sediment Results Viewer

New Features in the New Sediment Results Viewer

The sediment results viewer (new in HEC-RAS version 6.0) combines the advantages of the previous viewers and includes several new features. This new viewer allows users to view results from multiple sediment plans at the same time and view simultaneous time series results on separate axes – if they plot meaningfully on different scales.

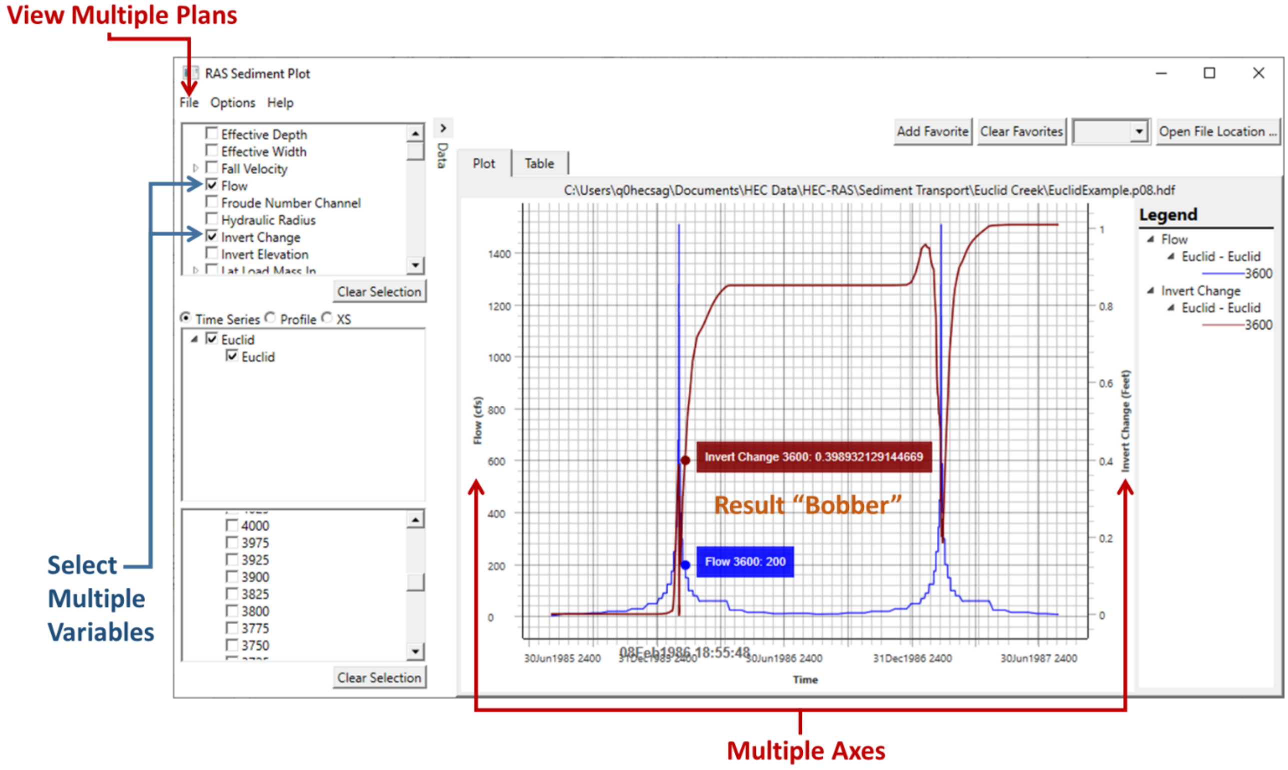
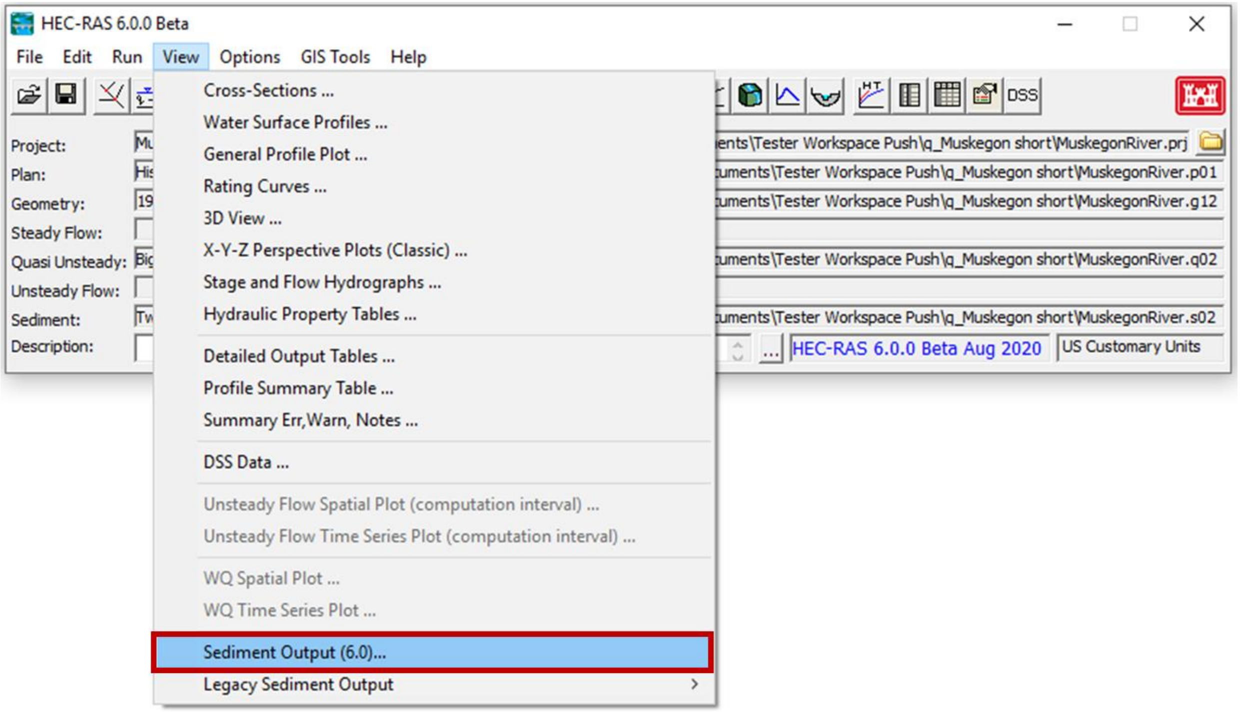


Figure 1-146: New features of the sediment plotter released with HEC-RAS 6.0

The new sediment results viewer has the same three modes that previous viewers had.

- Time Series
- Profile
- Cross section

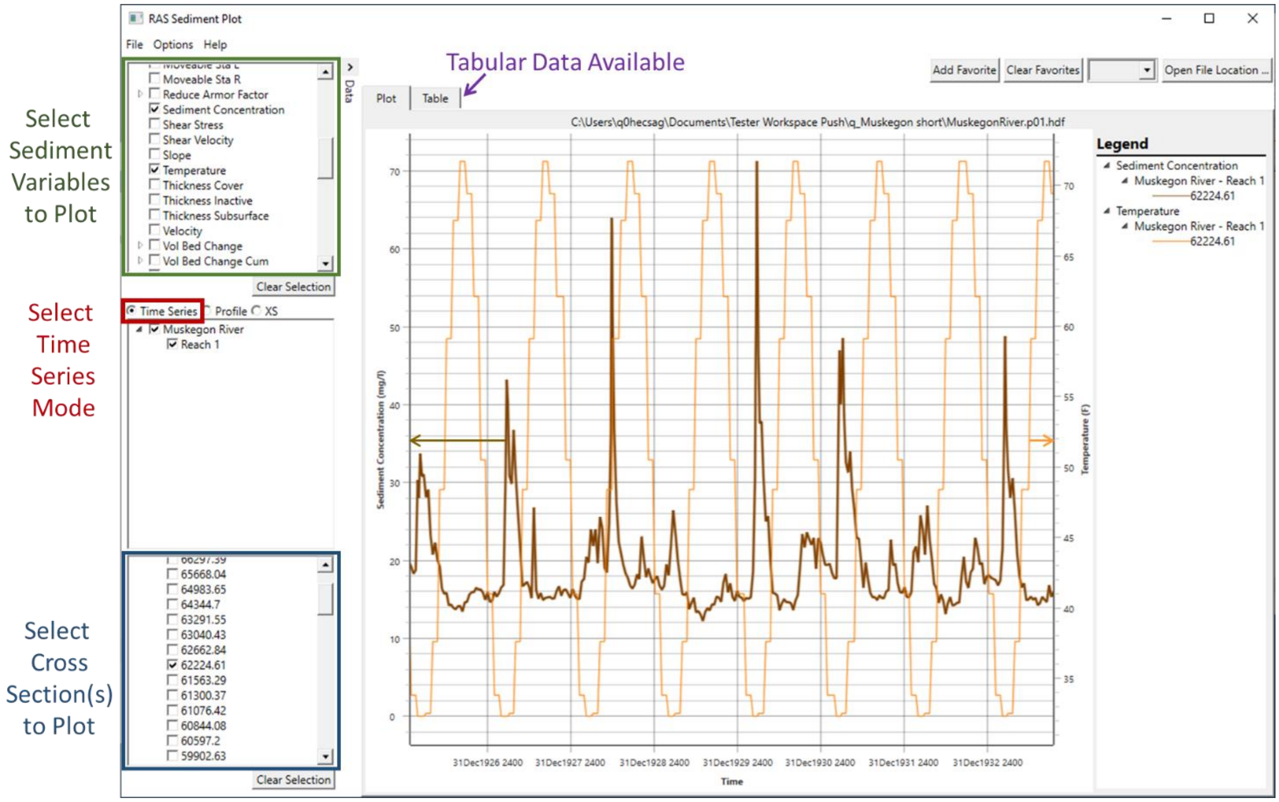
There is no button on the main HEC-RAS editor to view sediment results. To access Sediment Results Select **View→Sediment Output (6.0)...** from the main HEC-RAS menu (see figure below).

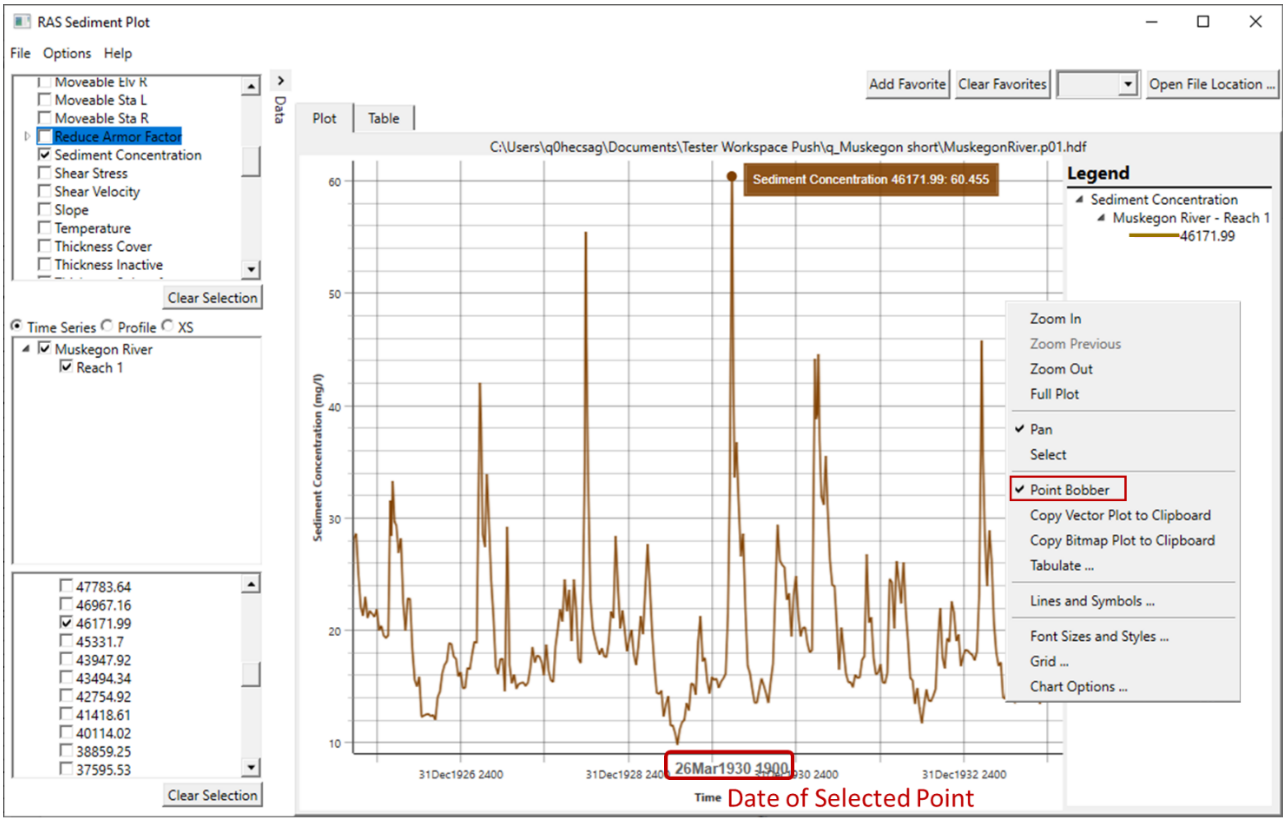


Time Series

Time series results can be extremely valuable to analyze after a sediment transport simulation. To view sediment time series select the **Time Series** mode on the left bar of the Sediment Results Viewer. Then select one or more variables to plot in the upper left box and one or more cross sections to view them in the lower left box. The first figure below plots regular month-averaged temperature the model used and several years of concentration results for a single cross section. These results plot on separate axes (concentration left, temperature right) because they report in different magnitudes. The color scheme and line weights were edited (right click on plot and select **Lines and Symbols** to edit lines or add points). To get tabular data click on the **Table** tab.

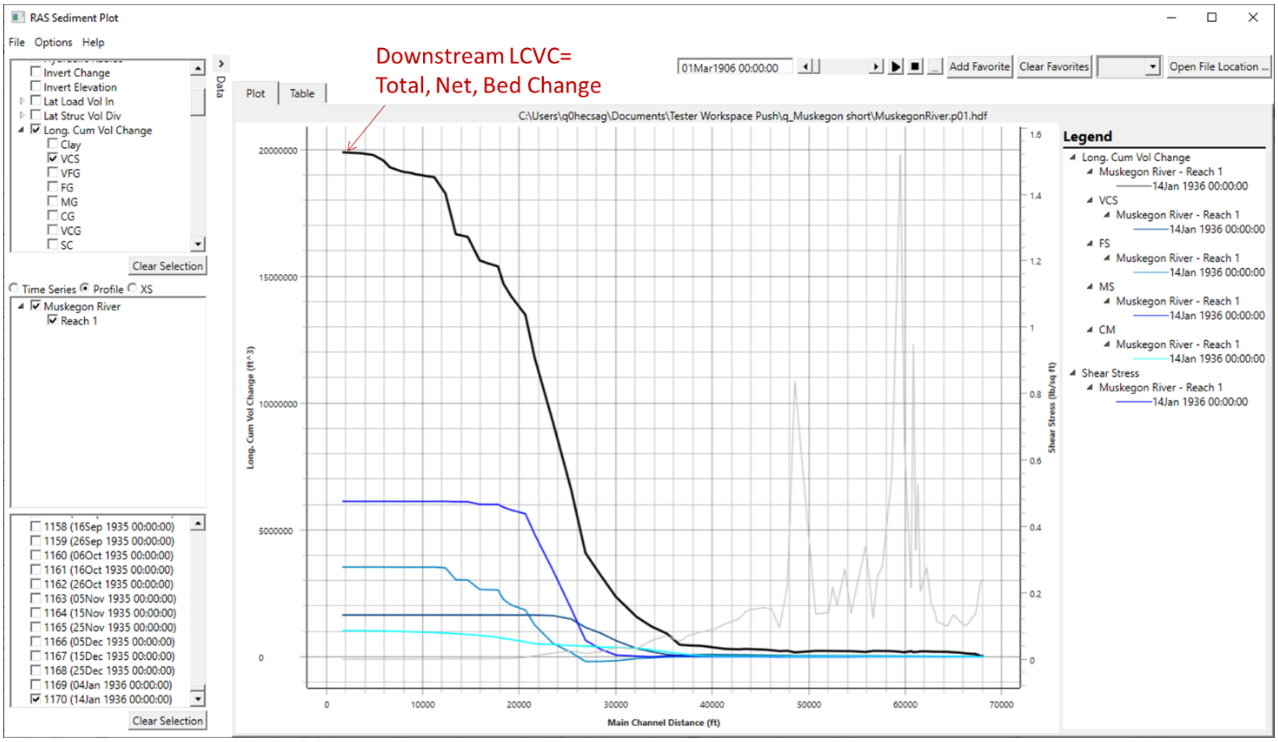
The second plot below demonstrates how to query the value and date of individual points from a time series plot. Right click on the plot and turn on the **Point Bobber**. Once the **Point Bobber** is on, you can hover over a location on the time series (like the peak concentration in the figure below) and the plotter will return the value and provide the date and time of the value along the time axis.


Select Sediment Variables to Plot
Select Time Series Mode
Select Cross Section(s) to Plot
Tabular Data Available
RAS Sediment Plot
File Options Help
Moveable Sta R
Reduce Armor Factor
Sediment Concentration
Shear Stress
Shear Velocity
Slope
Temperature
Thickness Cover
Thickness Inactive
Thickness Subsurface
Velocity
Vol Bed Change
Vol Bed Change Cum
Clear Selection
Time Series Profile XS
Muskegon River
Reach 1
65668.04
64983.65
64344.7
63291.55
63040.43
62662.84
62224.61
61563.29
61300.37
61076.42
60844.08
60597.2
59902.63
Clear Selection
Plot Table
Add Favorite Clear Favorites Open File Location ...
C:\Users\q0hecsag\Documents\Tester Workspace Push\q_Muskegon short\MuskegonRiver.p01.hdf
Legend
Sediment Concentration
Muskegon River - Reach 1
62224.61
Temperature
Muskegon River - Reach 1
62224.61
Sediment Concentration (mg/l)
Temperature (F)
Time
31Dec1926 2400
31Dec1927 2400
31Dec1928 2400
31Dec1929 2400
31Dec1930 2400
31Dec1931 2400
31Dec1932 2400

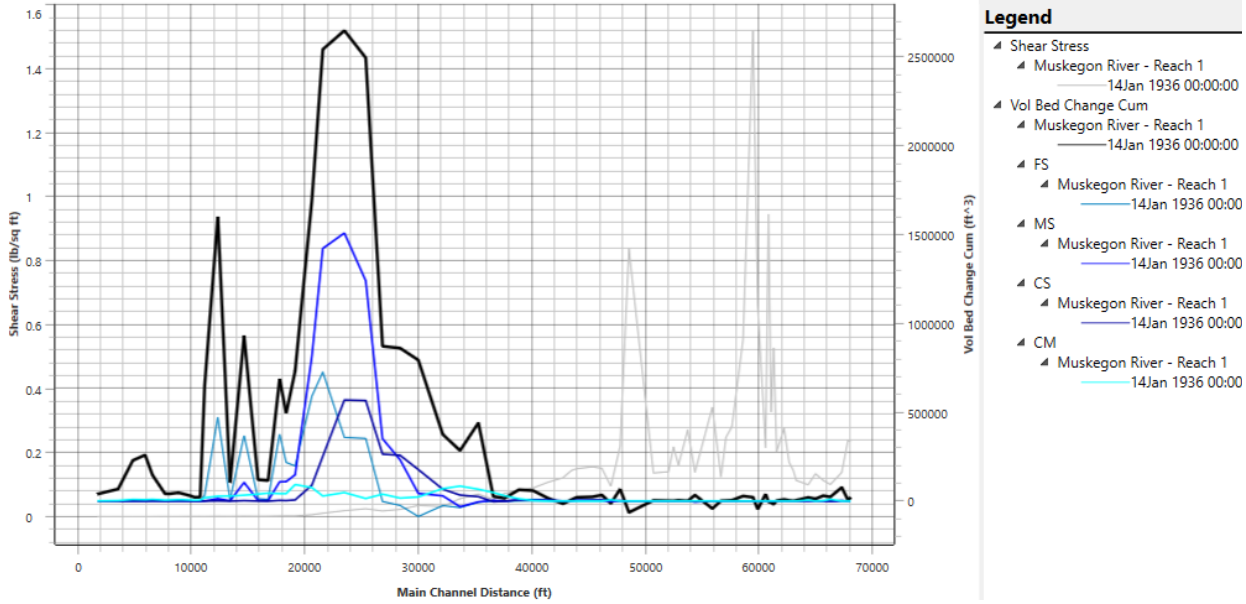

RAS Sediment Plot
File Options Help
Moveable Elv R
Moveable Sta L
Moveable Sta R
Reduce Armor Factor
Sediment Concentration
Shear Stress
Shear Velocity
Slope
Temperature
Thickness Cover
Thickness Inactive
Clear Selection
Time Series Profile XS
Muskegon River
Reach 1
47783.64
46967.16
46171.99
45331.7
43947.92
43494.34
42754.92
41418.61
40114.02
38859.25
37595.53
Clear Selection
Plot Table
Add Favorite Clear Favorites Open File Location ...
C:\Users\q0hecsag\Documents\Tester Workspace Push\q_Muskegon short\MuskegonRiver.p01.hdf
Sediment Concentration 46171.99: 60.455
Legend
Sediment Concentration
Muskegon River - Reach 1
46171.99
Zoom In
Zoom Previous
Zoom Out
Full Plot
Pan
Select
Point Bobber
Copy Vector Plot to Clipboard
Copy Bitmap Plot to Clipboard
Tabulate ...
Lines and Symbols ...
Font Sizes and Styles ...
Grid ...
Chart Options ...
Sediment Concentration (mg/l)
Time
31Dec1926 2400
31Dec1928 2400
26Mar1930 1900
31Dec1932 2400
Date of Selected Point

Profile

Profiles can be useful for several analyses, but they are used most often to evaluate bed change and bed gradation evolution. The figure below plots Longitudinal Cumulative Volume Change for a reservoir model (positive slope is deposition the downstream value is the total net bed change for the simulation) with several of the most important grain classes and shear stress (light grey). The results show the river deposits in the low shear backwater, and the grain classes deposit in different locations. The second plot shows the same results, but with the cumulative volume change (total for the simulation but not summed from upstream to downstream).



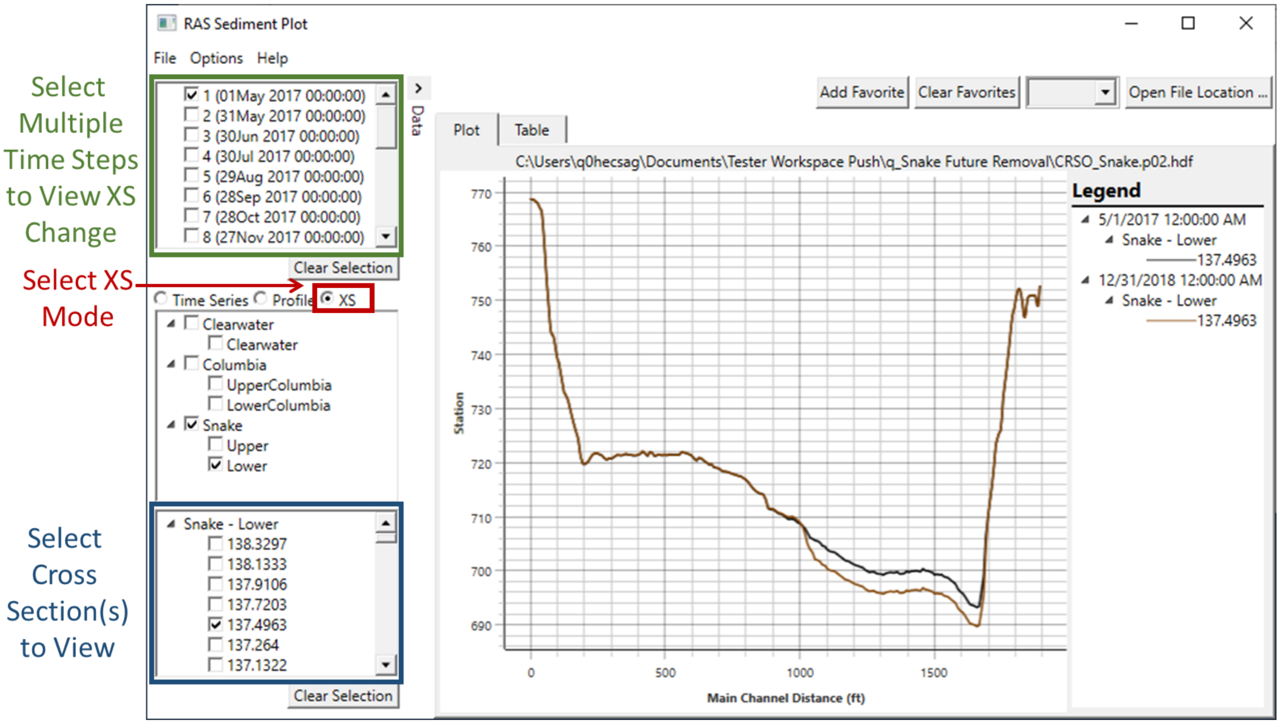
Downstream LCVC=
Total, Net, Bed Change



Modeling Note – Expect a Time Lag the First Time the Plotter Accesses Profile Data: The HEC-RAS data model makes retrieving time series data much faster than retrieving profile data. Therefore, profile data can lag more than time series data in the sediment viewer. This should only happen the first time you request a particular profile variable. HEC-RAS will generate a sub-folder with a transposed results file, that the plotter can access more efficiently if the modeler requests the profile data again.

Cross Sections

Cross section change is one of the central features of a mobile boundary sediment transport model. Reviewing cross section change is also one of the easiest way to identify numerical artifacts and unintended consequences of modeling choices, making models more realistic and robust. To view cross section change select XS button in the left pane of the Sediment Plotter. The upper pane will populate the time stamps that HEC-RAS generated cross section output and the lower left pane lists the cross sections available to view. Plot the cross sections at multiple time steps to help visualize cross section change. It is important to view at least the final cross section shapes to make sure that erosion and deposition were simulated in physically believable patterns.



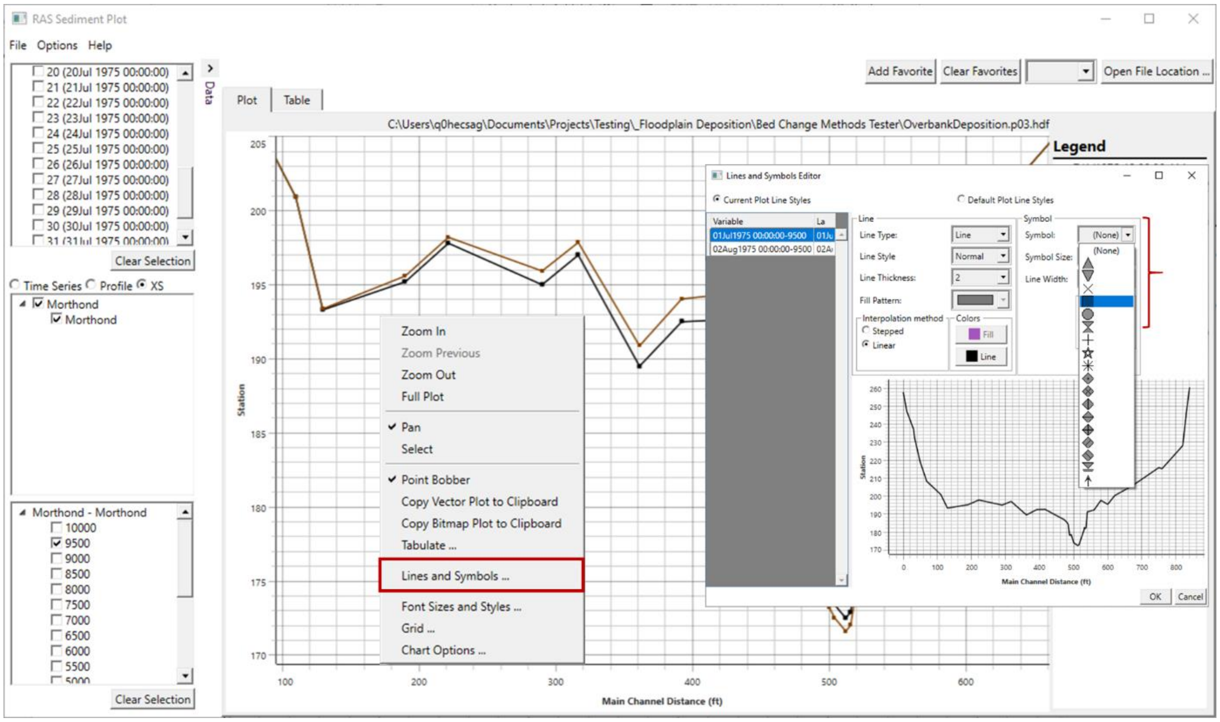
Select Multiple Time Steps to View XS Change

Select XS Mode

Select Cross Section(s) to View

C:\Users\q0hecsag\Documents\Tester Workspace Push\q_Snake Future Removal\CRSO_Snake.p02.hdf

Modeling Note – Station Elevation Points: The sediment results viewer only includes lines (no points) by default. Points take require more resources to render, slowing the plotter down substantially. But station-elevation points are often helpful when viewing cross section results. To turn points on, right click on the results, and select **Lines and Symbols** (see figure below).



Wish List – Plot Water Surface and Movable Bed Limits with Cross Section Results

Wish List – We would like to provide several additional sediment results

- Standard Rating Curves
- User Defined Result Rating Curves (variable 1 vs variable 2, variable 3)
- Sediment gradation curves (particle size vs % finer)
- Gradation over space and time (temporal or longitudinal area plot of grain class %)
- Heat map in time-cross section space (where result magnitude is represented by the color intensity in a time-space plot)
- Specific gage output (plot the water surface elevations associated with defined flow ranges over time)

Wish List – Integrate sediment results into standard HEC-RAS viewers (Rating Curve, generalized profile, hydrograph, etc…)

Modeling Note - Invert Change Limitation: This can return good results and is appropriate for scour chains but can also lead to data distortions and does not optimize the value of repeated cross sections or bathymetry data. Computing mass or volume change from repeated cross sections or bathymetry and comparing to **Mass/Vol Bed Change CUM or Longitudinal Mass/Vol Change** is better modeling practice. (Units: ft or m).

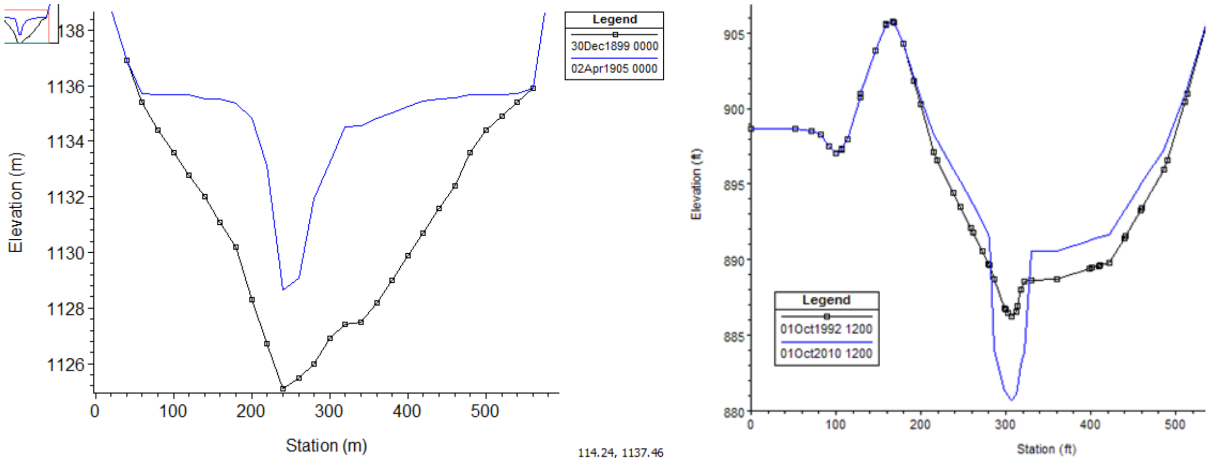


Figure 1-147: Common bed change results where invert change does not capture actual morphological change.

Output Variables

The description of the variables in each output level in the Output Level Section describes each output variable, categorized by available level. The Output Variables are listed here in alphabetical order with more description, example visualizations, and modeling notes.

Sediment Transport Output Variables

Variable Name	**Units**	**Description**
Active Thickness	ft/m	Thickness of the active layer at the start of each computational time step. Used in the simple active layer bed sorting and armoring routine.
Armor Reduction: All	(fraction)	Fraction that the total sediment transport capacity is reduce to, based on the concepts of a cover layer computation.
Armor Reduction: Class 1-20	(fraction)	Fraction for each individual grain size, that the transport capacity is reduce to, based on the concepts of a cover layer computation.
Ch Froude Num	-	Main channel Froude number at the end of the current computational time step.
Ch Invert El	ft/m	Minimum elevation of the main channel at each output time step.

Ch Manning n	s/ft$^{1/3/}$ s/m$^{1/3}$	Main channel manning's n value.
Cover Thickness	ft/m	Thickness of the cover layer at the end of each computational time step. Used in the Exner 5 bed sorting and armoring routine.
d_{16} Cover/Subsurface/Inactive (ft)		The 16th percentile particles size of the specified mixing layer. Some practitioners prefer the d_{16} to d_{10} because it is two standard deviations below the mean.
d_{84} Cover/Subsurface/Inactive Layers		The 84th percentile particles size of the specified mixing layer. Some practitioners prefer the d_{84} to d_{90} because it is two standard deviations above the mean.
d50 Active	mm	d50 of the active layer of the simple active layer bed sorting and armoring routine.
d50 Cover	mm	d50 of the cover layer at the end of the computational increment. Used in the Exner 5 bed sorting and armoring routine.
d50 Inactive	mm	d50 of the inactive layer at the end of each computational time step. Used in the Exner 5 and simple active layer bed sorting and armoring routine.
d50 Subsurface	mm	d50 of the surface layer material at the end of the computational time step. Used in the Exner 5 bed sorting and armoring routine.
d90 Active	mm	d90 of the active layer of the simple active layer bed sorting and armoring routine.
d90 Cover	mm	d90 of the cover layer at the end of the computational increment. Used in the Exner 5 bed sorting and armoring routine.
d90 Inactive	mm	d90 of the inactive layer at the end of each computational time step. Used in the Exner 5 and simple active layer bed sorting and armoring routine.
d90 Subsurface	mm	d90 of the surface layer material at the end of the computational time step. Used in the Exner 5 bed sorting and armoring routine.
Dredge Vol Cum	ft^3/m^3	Total volume of sediment removed from each cross section by the dredging routines.

Eff Depth	ft/m	Effective depth of the water in the mobile portion of the cross section, at the end of the computational time step.
Eff Width	ft/m	Effective width of the water in the mobile portion of the cross section, at the end of the computational time step.
EG Slope	ft/ft / m/m	Slope of the energy grade line at each output time step. This can be a point value at the cross section or an average value between cross sections.
Fall Velocity	ft/s / m/s	Reports the fall velocity computed for each grain class. Also reports a "total" fall velocity which is a weighted average
Flow	ft^3/s / m^3/s	Total flow at the cross section for each output time step.
Hydraulic Radius	--	The area of the channel (the part of the cross section between the movable bed limits) divided by the wetted perimeter of the channel.
Invert Change	ft/m	The total change in the invert (the lowest elevation station-elevation point between the bank stations) since the beginning of the simulation.
Invert Elevation	ft/m	The elevation of the channel invert of each cross section – the lowest elevation between the channel banks.
Invert Elevation Max	ft/m	The maximum channel invert (lowest elevation point between the channel banks) since the beginning of the simulation.
Invert Elevation Min	ft/m	The minimum channel invert (lowest elevation point between the channel banks) since the beginning of the simulation.
Lateral Load Mass Lateral Load Vol	tons/ tonnes ft^3/m^3	This variable records the sediment entering the model through lateral boundary conditions at each cross section and time step. It is only the lateral loads for the computation increment, not a cumulative value. Total and by grain class.
Lateral Structural Mass	tons/ tonnes	This tracks the sediment that is removed from each control
Lateral Structural Vol	ft^3/m^3	volume (or added) by sediment associated with flow over a lateral structure. Total and by grain class.
Long. Cum Mass change	tons/tonnes	Total change in bed mass (or Volume), cumulative in space and time. Spatial accumulation is from the current cross section to the upstream end of the river reach in which this cross section resides.

Long. Cum Mass Movable Limits (tons)	Sums the mass or volume change from the beginning of the simulation and from upstream-to-downstream, so that the downstream cross section at the last time step of the Longitudinal Cumulative Mass Curve (LCMC) is a summary of the total aggradation or degradation in that reach for the simulation. Comparing the full LCMC (or LCVC) to this one, that only reports the result in the movable bed limits, is a helpful way to differentiate between overbank and channel processes (e.g. determine what percentage of deposition is floodplain deposition or identify overbank deposition offsetting channel erosion). (Total and by grain class)
Mass Bed Change: All tons	Incremental total mass change in the bed for the current computational time step.
Mass Bed Change: Class 1–20 (tons)	Incremental mass change in the bed for the current time step,
Mass Bed Change Cum: All (tons)	Cumulative mass of the change in the bed elevation over time.
Mass Bed Change Cum: class 1-20 (tons)	Cumulative mass of the change in bed elevation over time, per grain size fraction (Bins 1 – 20). This only displays the size fraction bins that are being used.
Mass Bed Change Cum: Max (tons)	The maximum (positive) deposition in mass or volume since the beginning of the simulation. This result is monotonic. It only increases with time.
Mass Bed Change Cum: Min (tons)	The maximum negative mass or volume change since the beginning of the simulation. This result is monotonic. It only decreases (larger negative value) with time.
Mass Capacity: All tons/day	Transport capacity in total mass at the current computational time step.
Mass Capacity: Class 1-20 (tons/day)	Transport capacity in mass, by grain size fraction, at the current computational time step.
Mass Cover: All tons/tonnes	Total tons of material in the cover layer at the end of each computational time step. Used in the Exner 5 bed sorting and armoring routine.
Mass Cover: Class 1-20 (tons)	Tons of material in the cover later at the end of each computational time step, by individual grain size fraction. Used in the Exner 5 bed sorting and armoring routine.
Mass Dredge Cum tons/tonnes	The total mass or volume dredged from that cross section since the beginning of the simulation.

Mean Eff Ch Invert	ft/m	Average channel invert elevation computed by subtracting the effective depth of the main channel from the water surface elevation.
Mean Eff Ch Invert Change	ft/m	Change in the average channel invert elevation, which is computed by subtracting the effective depth of the main channel from the water surface elevation.
Mass Inactive: All	tons/tonnes	Total tons of material in the inactive layer at the end of each computational time increment.
Mass Inactive: Class 1-20 (tons)		Tons of material in the inactive layer at the end of each computational increment, by individual grain size fraction.
Mass In: All	tons/tonnes	Total sediment mass, for all grain size classes, coming into the sediment control volume, per individual computational time step.
Mass In: Class 1-20	tons/tonnes	Sediment mass entering the sediment control volume per grain size fraction, per computational time step by individual grain size fraction.
Mass In Cum: All	tons/tonnes	Cumulative total sediment mass entering the sediment control volume for a specific cross section, per individual computational time step.
Mass In Cum: Class 1-20 (tons)		Cumulative sediment mass entering the sediment control volume per grain size fraction, at a cross section, per computational time step.
Mass Out: All	tons/tonnes	Total sediment mass, for all grain size classes, going out of the sediment control volume, per individual computational time step.
Mass Out: Class 1-20	tons/tonnes	Sediment mass leaving the sediment control volume per grain size fraction, per computational time step.
Mass Out Cum: All	tons/tonnes	Cumulative total sediment mass leaving the sediment control volume for a specific cross section, per individual computational time step.
Mass Out Cum: Class 1-20		Cumulative sediment mass leaving the sediment control volume per grain size fraction, at a cross section, per computational time step.
Mass Subsurface: All	tons/tonnes	Total tons of material in the surface layer at the end of each computational time step.

Mass Subsurface: Class 1-20 (tons)		Tons of material in the surface layer at the end of each computational time step, by individual grain size fraction.
Mass (Vol) In Cum	tons/tonnes	The total sediment flux into the control volume since the beginning of the simulation
Movable Elv L and R	ft/m	These are the elevations of the movable bed limits. Tracking the MBL movement relative to the channel can be useful, but these are mainly used to track toe migration in BSTEM models.
Movable Sta L and R	ft/m	These are the stations (lateral stations of the station-elevation points) of the movable bed limits. These will remain constant unless the cross section has BSTEM parameters. Only the BSTEM algorithms move cross section station-elevation points laterally.
Reduce Armor Factor	--	The Armor Reduction Factor determines how effective the cover layer is in the Thomas and Copeland mixing algorithms. It is the “Armoring Ratio” in Figure 2-17 and Figure 2-20. HEC-RAS multiplies the capacity deficit of each grain class by this ratio (computed from the “equivalent particle diameters ” of coarser particles in the cover layer). An armor ratio of 1 is no armoring, 0 is complete armoring (for that grain class) and anything in between is partial armoring.
Sediment Discharge	tons/day	Total sediment discharge in tons/day going out of the sediment control volume for a specific cross section, per individual computational time step.
Sediment Concentration (mg/l)		Total sediment concentration in mg/liter going out of the sediment control volume at the end of the computational time step.
Shear Stress	lb/sq ft	Average shear stress of the movable portion of the bed at each time step.
Shear Velocity u*	ft/s	Shear velocity. Used in Shields diagram and several sediment transport potential equations.
Slope		This is the Energy Slope used in the shear stress equation, which is either computed locally at the cross section $(Q/Conveyance)^{0.5}$ or the slope between the EGLs at the bounding cross sections.
Subsurface Thickness	ft/m	Thickness of the surface layer at the end of each computational time step. Used in the Exner 5 and simple active layer bed sorting and armoring routine.

Temperature	^{o}F/^{o}C	Water temperature. Current versions of the model only allow one temperature per time step, so this can vary in time but not space.
Thickens Inactive	ft/m	The vertical thickness of the deepest layer of the bed mixing (sorting and armoring) algorithm. All three methods use the same terminology for this.
Thickness Cover	ft/m	The vertical thickness of surficial layer of the bed mixing (sorting and armoring) algorithm. This is the Active Layer or the Cover Layer (in the Thomas or Copeland mixing methods).
Thickness Subsurface	ft/m	The vertical thickness of an intermediate layer between the cover and inactive layer in the Thomas and Copeland mixing algorithms. The Active Layer method does not have a comparable layer.
Toff Zone Capacity B	tons/day tonnes/day	The “Bed Zone” portion of the Toffaleti transport capacity. This is the MPM capacity if the Toffaleti-MPM function is selected.
Toff Zone Capacity L	tons/day tonnes/day	The Toffaleti transport capacity computed in the “Lower Zone” – approximately the bottom 8-9% of the water column, excluding the bed zone. Only written if the Toffaleti function is selected.
Toff Zone Capacity M	tons/day tonnes/day	The fraction of the Toffaleti transport capacity computed in the “Middle Zone” – approximately 31% of the water column in the zone between t½1/2.5 Depth and 1/11.24 Depth (from the bottom of the channel). Only written if the Toffaleti function is selected.
Toff Zone Capacity U	tons/day tonnes/day	The fraction of the Toffaleti transport capacity computed in the “Upper Zone” – the top 60% (above t½1/2.5 Depth from the bottom) of the water column. Only written if the Toffaleti function is selected. Modelers sometimes compare the upper three zones of Toffaleti Capacity to suspended load measurements (which exclude bed load).
Velocity	ft/s	Average velocity of the movable portion of the bed at each time step.
Water Surface	ft/m	The water surface elevation at that at the cross section during the time step.

Visualizing HDF5 Results with R and Python

Reading HEC-RAS HDF5 Results with R

Multiple packages read HDF5 data into R. The sample code below uses the Bioconducter package, available at: www.bioconductor.org.

Reading Results Matrix

The easiest way to deal with HEC-RAS results in R involves reading a time-space result matrix directly into an R dataframe and then interacting with the dataframe. The simplest data call involves defining a path to the HDF output file and an HDF path to the result.

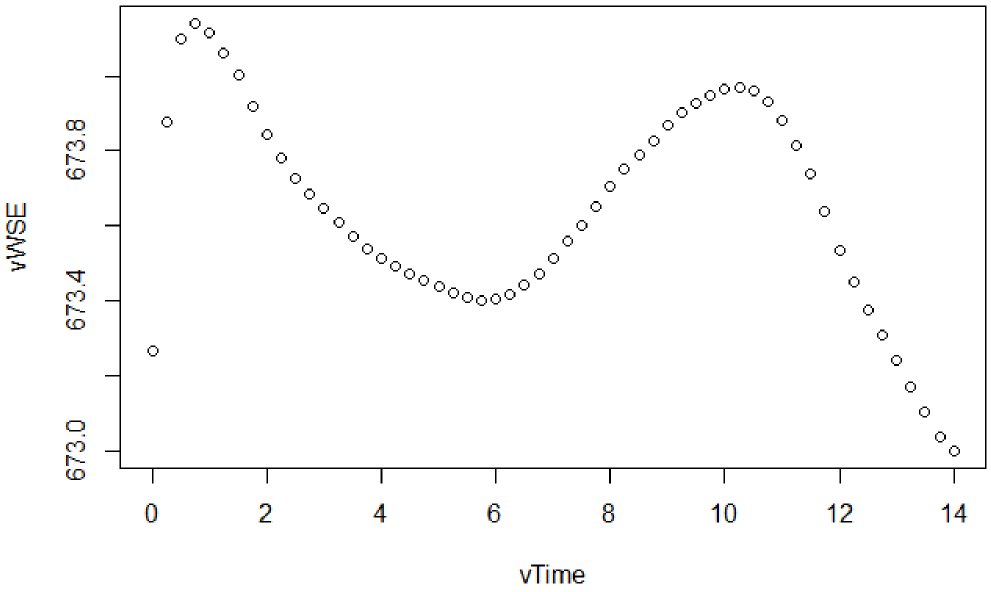
For example, the following arguments import all of the water surface elevations, for all cells into a dataframe:

```
FilePath<-"C:\\Users\\q0hecsag\\Documents\\Projects\\2D Sediment\\TestFile.p02.hdf"
```

```
dfWSE<-h5read(FilePath,"/Results/Unsteady/Output/Output Blocks/Base Output/Unsteady Time Series/2D Flow Areas/Chippewa/Water Surface")
```

To plot stage hydrograph at a specific cell (e.g. to compare with observed data):

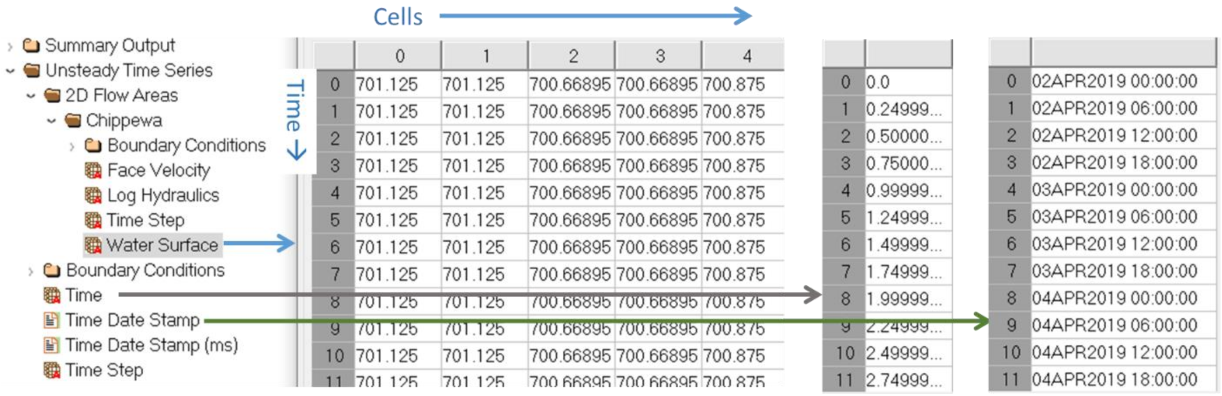
```
vTime<-h5read(DynamicPath,"/Results/Unsteady/Output/Output Blocks/Base Output/Unsteady Time Series/Time")

vWSE<-dfWSE[Cell,]

plot (vTime,vWSE)
```



(Note: vTime is just the relative time from the beginning of the simulation. The next section describes how to format HEC-RAS formatted date-time data)

Formatting HEC-RAS Date-Time Data in R

The HDF5 Data in HEC-RAS include two time results that match the rows of the result matrix.



	0	1	2	3	4
0	701.125	701.125	700.66895	700.66895	700.875
1	701.125	701.125	700.66895	700.66895	700.875
2	701.125	701.125	700.66895	700.66895	700.875
3	701.125	701.125	700.66895	700.66895	700.875
4	701.125	701.125	700.66895	700.66895	700.875
5	701.125	701.125	700.66895	700.66895	700.875
6	701.125	701.125	700.66895	700.66895	700.875
7	701.125	701.125	700.66895	700.66895	700.875
8	701.125	701.125	700.66895	700.66895	700.875
9	701.125	701.125	700.66895	700.66895	700.875
10	701.125	701.125	700.66895	700.66895	700.875
11	701.125	701.125	700.66895	700.66895	700.875

0	0.0
1	0.24999...
2	0.50000...
3	0.75000...
4	0.99999...
5	1.24999...
6	1.49999...
7	1.74999...
8	1.99999...
9	2.24999...
10	2.49999...
11	2.74999...

0	02APR2019 00:00:00
1	02APR2019 06:00:00
2	02APR2019 12:00:00
3	02APR2019 18:00:00
4	03APR2019 00:00:00
5	03APR2019 06:00:00
6	03APR2019 12:00:00
7	03APR2019 18:00:00
8	04APR2019 00:00:00
9	04APR2019 06:00:00
10	04APR2019 12:00:00
11	04APR2019 18:00:00

Time is the relative, elapsed, time since the beginning of the simulation. This is a simple approach. R can interpret **Time** as a numerical vector and can plot any column (Cell or XS) of any of the results against it without further formatting.

However, plotting against absolute time is often better, particularly when comparing to observed data with their own time reference. R will import the **Time Date Stamp** as a *string* vector. You must define the date format to convert this to a date.

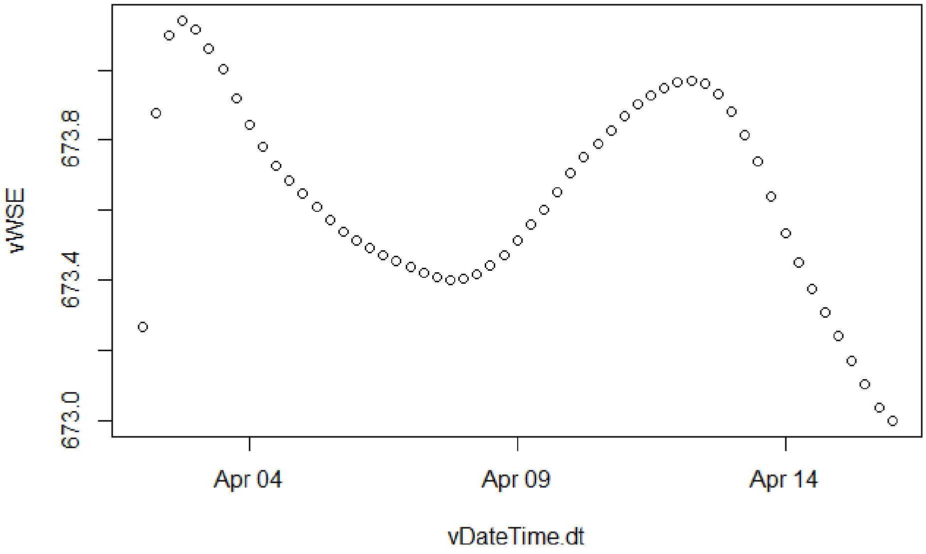
One way to convert the HEC-RAS date format is:

```
vDateTime.dt<-strptime(vDateTime(),"%d%b%Y %H:%M:%S")
```

where vDateTime() is the **Time Date Stamp** vector extracted from the HDF file.

Then you can plot against these absolute dates, for example:

plot (vDateTime.dt,vWSE)



Reading HEC-RAS HDF5 Results with Python

Dysarz (2018)[2] includes sample code that accessed sediment HDF5 data from Python.

Legacy Output

Moving to the new sediment plotter is highly recommended. However, because some users are comfortable and familiar with the old viewers, and because they may have workflows that depend on them, HEC has made them available in the recent release.

Table 1-6: Comparative Advantages and Disadvantages of the two legacy Sediment Plots

5.0 Legacy Output	4.x Legacy Output
Reads from HDF5, so it can read very large output files (tested on files >64GB) quickly. Reads all unsteady sediment output at any interval.	Will not open files greater than 2GB or unsteady sediment files with more than 1 computation increment per profile. Large files that do open, are sluggish. There are simply some files that the old output cannot read, making the new output the only option.
Recording animation requires external software (e.g. Snagit).	Built in video recording.
Default line color and weight.	More control over line color and weight.
Only plots one reach and variable at a time.	Plots multiple variables and reaches on the same plot.
Better cross section and profile selection tools.	Users can only create new geometry files from the old sediment cross section editor.
Plots water surface elevation and BSTEM nodes (Toe and Movable Bed Limits) with Cross Sections	
Available at the end of a simulation. No intermediate output if the simulation crashes.	Output available as the simulation run. Allows troubleshooting if the model crashes.
Stores favorites.	

---

[2] Dysarz, T. (2018) Application of Python Scripting Techniques for Control and Automation of HEC-RAS Simulations, *Water*, 10(10):1382, doi: 10.3390/w10101382.

The main utility of the legacy output is that users can open the the 4.x output during a run and review results before the simulation completes.

The 4.x cross section viewer also has a feature that used to be the only way to generate new geometry files from updated cross sections. However, current versions of HEC-RAS has a tool available in the Sediment Output Options menu to **Create Geometry Files From Sediment Results** so users can create new geometry files without using the legacy output viewers.

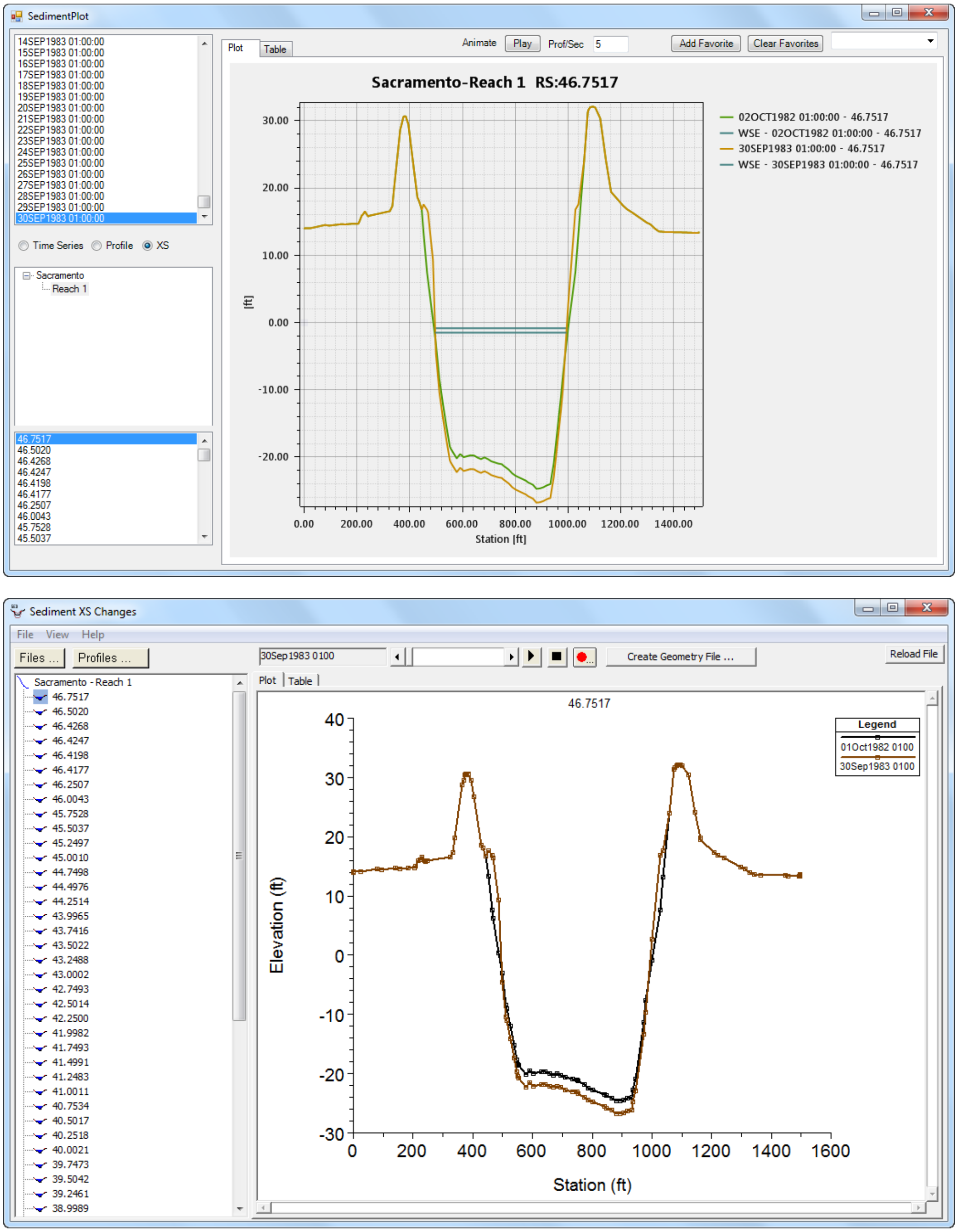
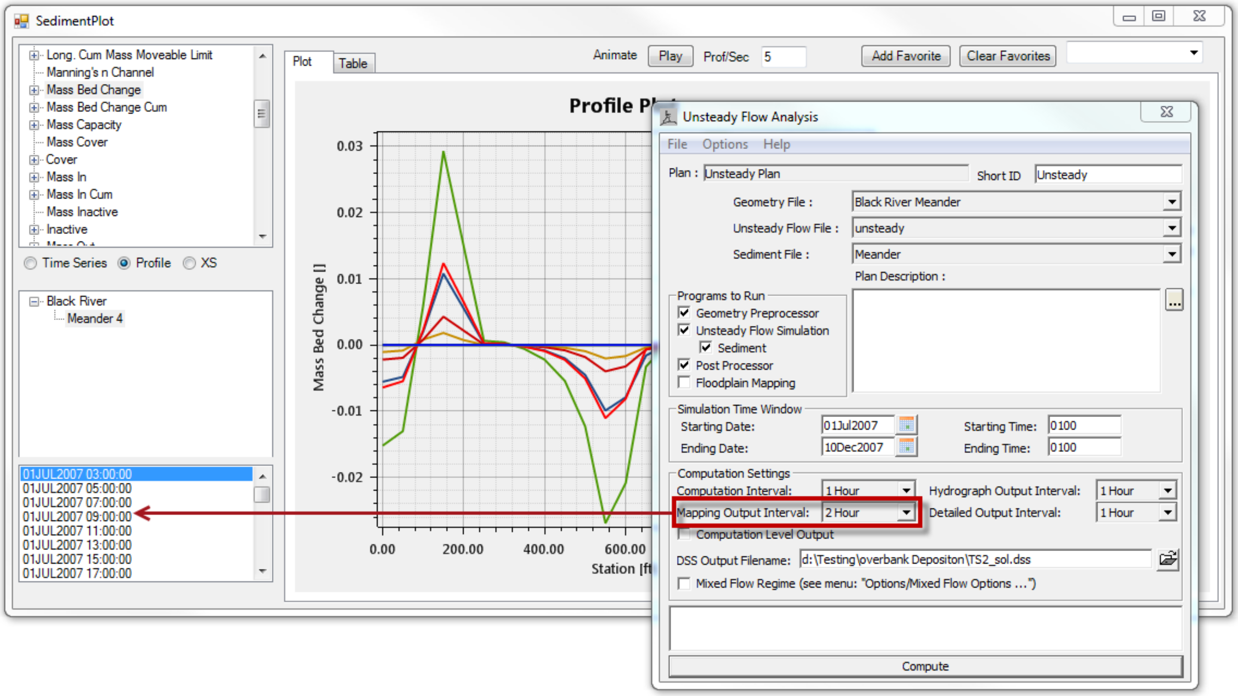


Figure 1-148: Cross section shape for a single station after four different simulation times with the new HDF5 plotter (top) and the legacy editor (bottom).

Unsteady Sediment Output

The new HDF5 *unsteady* sediment output is controlled by the but the **Mapping Output Interval** in the **Unsteady Flow Analysis** window (Figure 1-149), not the **Sediment Output Options** editor, (Figure 1-114). The legacy ("old") time series and profiles generally do not work for unsteady sediment runs. However, setting the output interval to 1 (**Error! Reference source not found.**) will often get HEC-RAS to write these data files for unsteady transport.

The **Computational Level Output** is generally very useful for trouble shooting unsteady sediment simulations. However, HEC-RAS can only write Unsteady Computation Output or the legacy sediment data. HEC-RAS will not write the legacy sediment output if the **Computational Level Output** is selected. View sediment output with the new HDF5 viewer.



Plan : Unsteady Plan Short ID Unsteady

Geometry File : Black River Meander

Unsteady Flow File : unsteady

Sediment File : Meander

Plan Description :

Programs to Run
- ☑ Geometry Preprocessor
- ☑ Unsteady Flow Simulation
  - ☑ Sediment
- ☑ Post Processor
- ☐ Floodplain Mapping

Simulation Time Window

Starting Date: 01Jul2007 Starting Time: 0100

Ending Date: 10Dec2007 Ending Time: 0100

Computation Settings

Computation Interval: 1 Hour Hydrograph Output Interval: 1 Hour

Mapping Output Interval: 2 Hour Detailed Output Interval: 1 Hour

☐ Computation Level Output

DSS Output Filename: d:\Testing\overbank Depositon\TS2_sol.dss

☐ Mixed Flow Regime (see menu: "Options/Mixed Flow Options ...")

Figure 1-149: The Unsteady Mapping Output Interval controls the HDF5 sediment output interval in unsteady sediment transport models.

Favorites Plot

Sediment modeling work flow often involves accessing the exact same plot or table after each simulation. Selecting the same variables, cross sections and time step form the long lists of available options each time can be time consuming. To improve this work flow, the new HDF5 **Sediment Output** viewer includes a favorite option. Select the commonly accessed plot and then press the **Add to Favorites** button. Name the plot. HEC-RAS will add this name to the Favorites drop down box, and will automatically reconstruct the plot (and table) when it is selected.

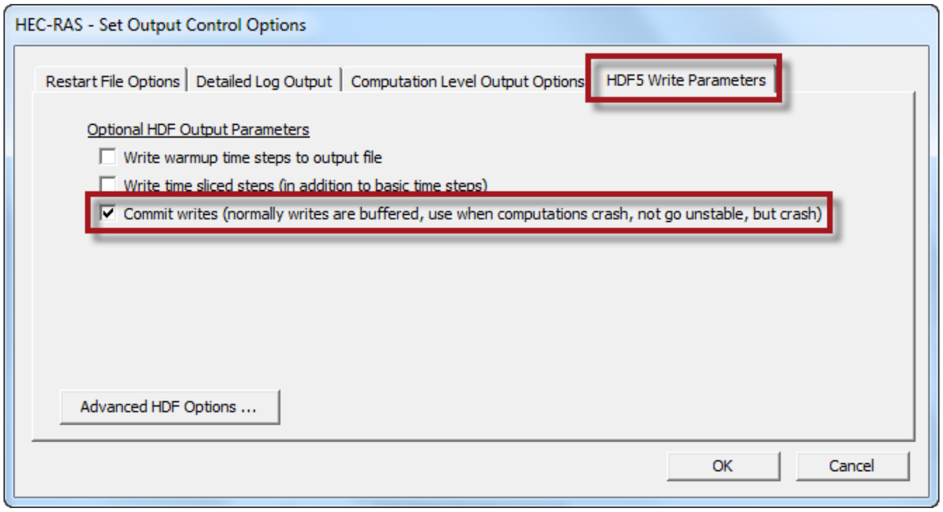
Trouble shooting

Get Unsteady HDF5 Output if Model Crashes

One of the liabilities of the new HDF5 output is that HEC-RAS does not release these until the end of the simulation. Users cannot view these files until the run is complete. Additionally, if the model crashes, it will not generate a final output file to help troubleshoot the simulation.

Users can request HEC-RAS to write intermediate results, so results will be available if the model crashes. This will create stable HDF5 output file when HEC-RAS crashes, but it involves saving and closing the file each time step, so this feature will increase run times substantially and is off by default.

To request intermediate HDF5 writes to access output after a crash, go to **Options→Output Options** in the **Unsteady Flow Analysis** editor. Select the **HDF5 Write Parameters** and check the **Commit Writes** box.



Optional HDF Output Parameters

☐ Write warmup time steps to output file

☐ Write time sliced steps (in addition to basic time steps)

☑ Commit writes (normally writes are buffered, use when computations crash, not go unstable, but crash)

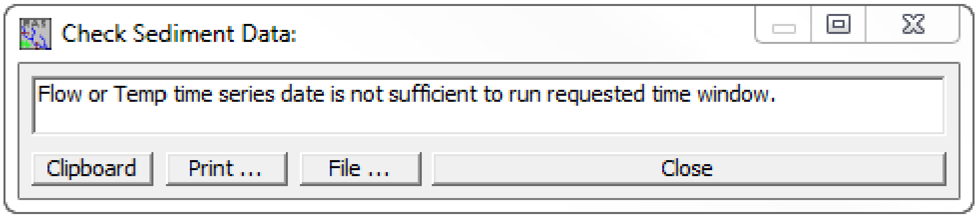
Figure 1-150: Select final HDF5 writes after each time step to access HDF5 output after an HEC-RAS crash (this will increase run times).

Common Error Messages

There are several common error messages users encounter when modeling sediment in HEC-RAS. These fall in two basic categories: Pre-Run errors (those that HEC-RAS throws before it starts computations, usually alerting users to incomplete data) and Runtime Errors (those written in the computational window during a run).

Flow or Temp Time Series Date is Not Sufficient to Run Requested Time Window

The most common pre-run error message alerts users that there is not enough flow or temperature data to run the simulation (Figure 1-151).



Flow or Temp time series date is not sufficient to run requested time window.

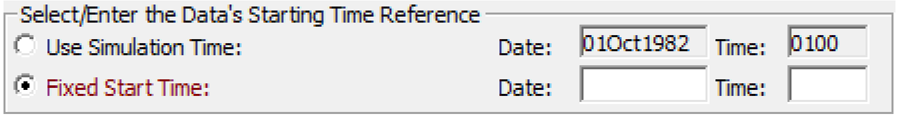
Figure 1-151: Insufficient Flow or Temp series not sufficient pre-run error message.

This message indicates that one of the flow, temperature, or sediment time series in the quasi-unsteady or sediment data do not span the computational interval. Check to make sure that all the time series start at or before the simulation start time and end at or after the simulation end time.

However, other data errors, which can be harder to find can generate this error. Here are three common culprits:

1. <u>No Temperature Data</u>: Temperature data is mandatory, but requires pressing a button on the quasi-unsteady flow editor. Blank temperature data will return this error.

2. <u>Blank or mistaken **Fixed Start Time**:</u>



Select/Enter the Data's Starting Time Reference

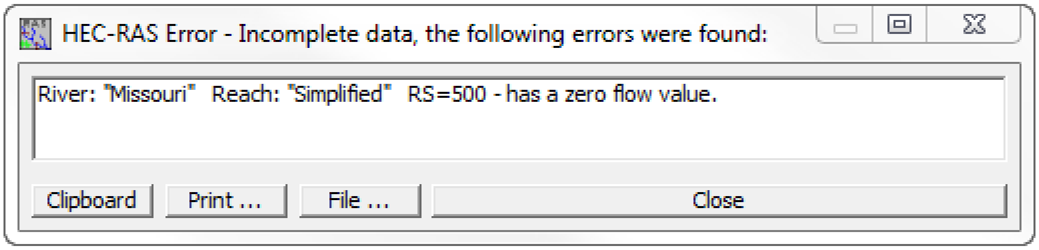
○ Use Simulation Time: Date: 01Oct1982 Time: 0100

● Fixed Start Time: Date: Time:

3. <u>Missing Computation Increments</u>. A quasi-unsteady time series can span the entire simulation time window, but if one or more flows lack computation increments HEC-RAS will return this error. If the **Automated Computation Increment** tool does not span the range of flows, it will leave Computation Increments blank and return this error.

Incomplete data: "Zero flow value"

Another common pre-Run error indicates that a flow boundary condition has a zero flow value (Figure 1-152).



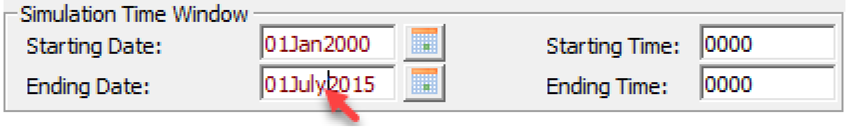
River: "Missouri" Reach: "Simplified" RS=500 - has a zero flow value.

Figure 1-152: Zero Flow Value pre-run error message.

HEC-RAS cannot specify a zero flow external boundary condition. However, more often, this error is the result of:

1. <u>Mis-formatted Date</u>: If the Fixed Start Time or the simulation time window is defined with a date that does not conform to the HEC-RAS DDMMMYYYY convention the date will not register correctly.

An example of a common error is:

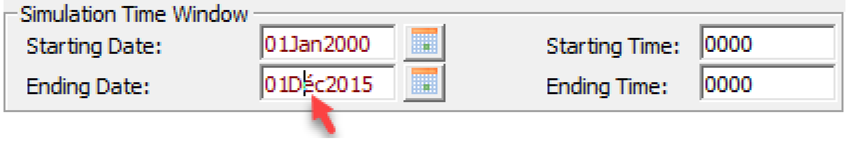


Simulation Time Window
Starting Date: 01Jan2000
Ending Date: 01July2015
Starting Time: 0000
Ending Time: 0000

2. Non-English Settings, Months, or Special Characters: The months also have to be in English. The following table includes the only MMM abbreviations RAS accepts.

JAN	FEB	MAR	APR	MAY	JUN
JUL	AUG	SEP	OCT	NOV	DEC

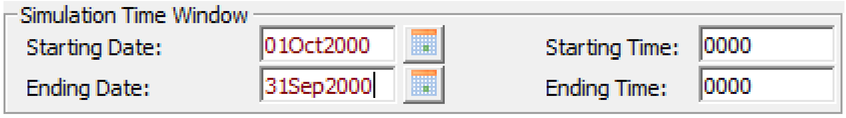
An example of a common error is:



Simulation Time Window
Starting Date: 01Jan2000
Ending Date: 01Dec2015
Starting Time: 0000
Ending Time: 0000

Additionally, in order to accept dates, the Microsoft language settings on your computer must be set to English (US).

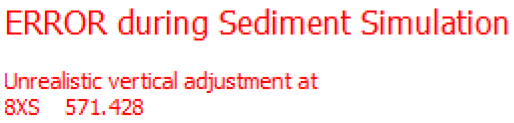
3. End Date earlier than the Start Date: Another common error includes specifying an end date later than the start date (e.g. setting up a water year run but failing to change the second date):



Simulation Time Window
Starting Date: 01Oct2000
Ending Date: 31Sep2000
Starting Time: 0000
Ending Time: 0000

Unrealistic Vertical Adjustment

The **Unrealistic Vertical Adjustment** error is the most common sediment runtime error. This error indicates that the cross section eroded or deposited too much sediment in a time step, potentially destabilizing the simulation.



ERROR during Sediment Simulation

Unrealistic vertical adjustment at
8XS 571.428

Figure 1-153: The Unrealistic Vertical Adjustment Runtime Error.

This error occurs most often at the upstream cross section. If the transport function, load, bed gradation, and load gradation are not in quasi-equilibrium at the beginning of the simulation, the upstream cross section will often deposit until it is full.

If the model deposits unrealistically at the upstream cross section, one-or-more of three factors are likely:

1. Load is too large. (Sediment boundary condition)
2. Capacity is too small. (Transport Function)
3. Load is too coarse. (Boundary condition gradation)

Other less-common causes include:

1. Large Computational Increment: Large computation increments (or moderate computation increments during large flows) are the most common source of sediment model instability and, therefore, this error. Users can often resolve this error by reducing the computation increment.

2. Model Should Deposit Outside the Movable Bed Limits: If the modeled system deposits significant sediment in the floodplain, an HEC-RAS model that forces all bed change in the channel (by confining the movable bed limits to the channel and selecting the default bed change method that only modifies the cross section within the channel) can force too much deposition in the channel, causing unrealistic bed change. In systems (or reaches) with significant floodplain deposition, change the **Bed Change Options** to allow deposition outside the movable bed limits (or extend the movable bed limits).

3. Bed Material is Too Fine: If the bed material is too fine for the transport function, or if the transport function over predicts transport in the reach, the mismatch can lead to large, rapid bed changes, destabilizing the mode

4. Equilibrium Load: If the upstream gradation associated with an equilibrium load boundary condition includes substatnial silt or clay, the equilibrium load condition can compute enormous fine grained sediment loads at the boundary. Small decreases in transport downsteam can cause large bed changes. User defined rating curves are almost always better sediment boundary condition options, even if they are speculative.

Sediment Rating Curve Extrapolation

Users sometimes enter flow-load rating curves that do not cover the entire range of flows. Users often develop a flow-load curves for their measured data - collected over a more narrow range of flows than the simulated flow range, so the model that includes a much wider variety of flows.

HEC-RAS will produce two errors if it encounters flows lower or higher than the maximum and minimum rating curve flows:

If HEC-RAS encounters flows below the lowest flow-load rating curve point it will generate the error:

> The sediment boundary condition(s) include(s) a flow that is lower than the maximum flow in the sediment rating curve. HEC-RAS extrapolated between the lowest load and zero.

This error is blue because it is not critical. Because it is reasonable to assume that 0 flow is associated with 0 load, HEC-RAS will extrapolate below the lowest flow in the rating curve by interpolating between that point and 0, 0 (cfs-T/d, cms-T/d, cfs-mg/L, or cms-mg/L).

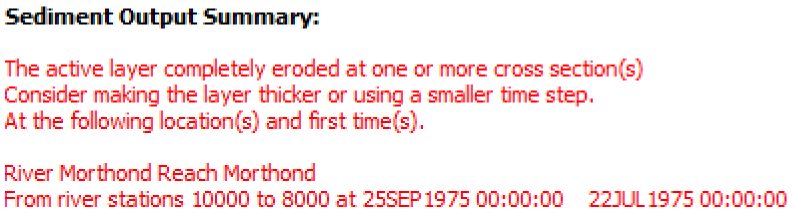
If the flow series includes flows higher than the highest flow-load point, HEC-RAS will report:

The sediment boundary condition(s) include(s) a flow that is higher than the maximum flow in the sediment rating curve. HEC-RAS used the highest load in the rating curve.

This error is red, because HEC-RAS will not extrapolate beyond the highest flow point on a sediment rating curve. Results will be very sensitive to loads associated with high flows and it is important for the user to make this site-specific decision explicitly. Therefore, HEC-RAS will only use the highest specified load for all flows that are larger than the highest flow point in the flow-load curve, and will produce this error message in the runtime window to ask the user to increase the max flow in the flow-load curve.

Active Layer Exhaustion

If the model erodes all the sediment in the active layer during a bed mixing time step, it can artificially limit erosion. For small active layers or large time steps, eroding the entire active layer during some or most of the high transport time steps can artificially reduce erosion significantly. Therefore, HEC-RAS generates an error if the active layer is completely eroded and indicates which cross sections empty at which times.

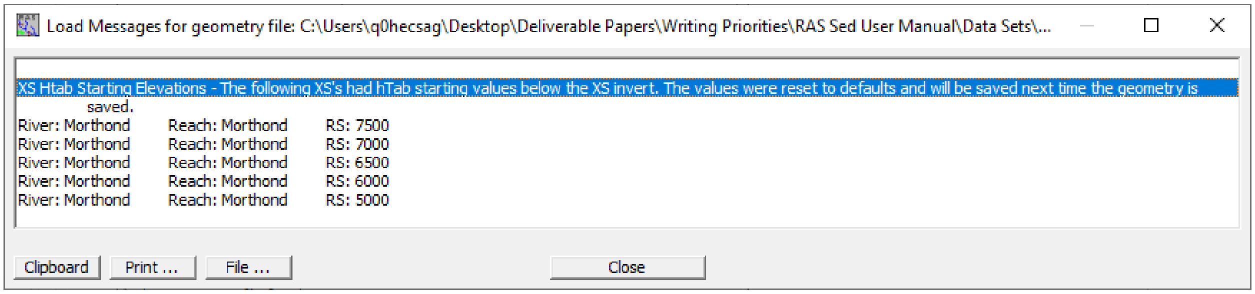


```
Sediment Output Summary:

The active layer completely eroded at one or more cross section(s)
Consider making the layer thicker or using a smaller time step.
At the following location(s) and first time(s).

River Morthond Reach Morthond
From river stations 10000 to 8000 at 25SEP1975 00:00:00    22JUL1975 00:00:00
```

Increasing the active layer thickness, using the **Minimum Active Layer Thickness** feature, or increasing the number of bed mixing time steps for each computation increment are common fixes for this error, particularly for fine sediment beds.

XS Htab Starting Elevations – The Following XS's had HTab starting values below the XS invert.

This error is often the result of using a geometry file created from a sediment result and there is a simple fix. Re-set the starting elevations in the HTab editor to the invert. This work flow is described here (Figure 1-136: Workflow to fix the HTab starting elevation error.).



Load Messages for geometry file: C:\Users\q0hecsag\Desktop\Deliverable Papers\Writing Priorities\RAS Sed User Manual\Data Sets\...

```
XS Htab Starting Elevations - The following XS's had hTab starting values below the XS invert. The values were reset to defaults and will be saved next time the geometry is
         saved.
River: Morthond      Reach: Morthond      RS: 7500
River: Morthond      Reach: Morthond      RS: 7000
River: Morthond      Reach: Morthond      RS: 6500
River: Morthond      Reach: Morthond      RS: 6000
River: Morthond      Reach: Morthond      RS: 5000
```

CHAPTER 2 1D SEDIMENT TRANSPORT TECHNICAL REFERENCE

Sediment transport modeling is notoriously difficult. Sediment data are uncertain and transport theory is empirical and highly sensitive to a broad array of physical variables and model parameters which are difficult to measure and estimate. However, with good data, a skilled modeler can use a calibrated sediment model to predict regional, long term trends that can inform planning decisions and evaluate project alternatives. HEC-RAS includes mobile boundary, sediment transport modeling capabilities which route sediment and adjust channel cross sections in response to sediment dynamics. This chapter describes the theory and assumptions used for this analysis.

Hydrodynamics in a Sediment Model

Sediment transport models require hydraulic parameters. Therefore, HEC-RAS computes hydraulics each time step before it routs sediment or updates cross sections. HEC-RAS 5.0 couples sediment transport computations with either quasi-unsteady hydraulics or unsteady hydraulics. The User's Manual offers pros and cons of both approaches. Unsteady flow is not unique to sediment studies. HEC-RAS can simulate unsteady flow without sediment data and Chapter 2 documents the unsteady equations in detail.

Quasi-unsteady hydraulics, on the other hand, are only used for sediment studies. Therefore, the quasi-unsteady approach is described below.

Quasi-Unsteady Flow

The quasi-unsteady flow model simplifies hydrodynamics, representing a continuous hydrograph with a series of discrete steady flow profiles. HEC-RAS keeps flow constant for each flow record, computing transport over flow record duration. The steady flow profiles are more stable than the matrix solution of the unsteady Saint-Venant equations, but approximating a hydrograph with a series of steady flows does not conserve flow or explicitly account for volume.

The quasi-unsteady flow model has divides time into three time step. HEC-RAS divides each discrete steady flow profile (**Flow Duration**), over which HEC-RAS holds flow constant, into **Computational Increments**, which are the hydraulic and sediment transport time step. HEC-RAS updates the hydraulics and cross sections every **Computational Increment**, but further subdivides this time step into **Bed Mixing Time Steps**, updated bed gradation accounting for each bed layer several times each **Computational Increment**.

Duration

The Duration is the coarsest time step. HEC-RAS assumes that flow, stage, temperature, or sediment are constant over the Duration (Figure 2-1). For example, enter daily flow data (e.g. from a USGS day) with twenty-four hour Flow Durations.

Computational Increment

The **Computational Increment** is the primary quasi-unsteady hydraulic and sediment time step. The **Computation Increment** usually subdivides the **Duration** (Figure 2-1), though it can be equal (but not larger) to the duration. While flow remains constant over the entire flow duration, HEC-RAS updates the bed geometry and hydrodynamics after each computational increment. If cross sections change, particularly if they change rapidly, sediment sensitive hydraulic parameters can change even if the flow does not.

Model stability can be sensitive to the **Computation Increment**, because HEC-RAS assumes that hydraulics and bed geometry are constant. If the bed changes rapidly, large computation increments decouple the feedbacks between sediment and hydraulic processes, leading to unreasonable deposition or erosion, which can cause the model to crash. If HEC-RAS computes erratic bed change, experiment with **Computation Increment** sensitivity.

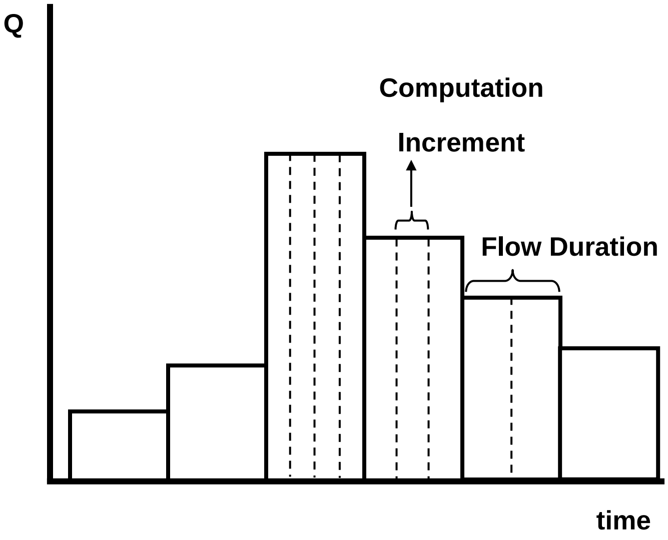


Figure 2-1. A Quasi-Unsteady Flow Series with time step.

Bed Mixing Time Step

Finally, HEC-RAS also subdivides Computational Increments into the bed mixing time step (sometimes called the SPI parameter). Bed gradation can evolve very quickly, so HEC-RAS updates the bed gradation accounting (running the bed sorting and armoring routines) several times during each computation increment.

HEC-RAS holds hydraulic parameters and cross section elevation constant over all mixing time step in a computation increment throughout the **Computation Increment**. However, the model updates the composition of the bed mixing layers (e.g. the active, cover and/or inactive layers) at the **Mixing Time Step**, revising the grain class accounting in these layers several times between hydraulic and sediment capacity computations. The vertical gradational profile changes response to the deposition or erosion even though the bed does not change until the end of the **Computation Increment**. Tighter accounting of bed gradation affects transport. HEC-RAS computes transport capacity base on the active layer gradation, so while the hydraulics (and transport potential, see below) remain constant throughout the **Computation Increment**, transport capacity can change between **Bed Mixing Time Steps**.

Sediment Continuity

The HEC-RAS sediment routing routines solve the sediment continuity equation also known as the Exner equation:

$$(1-\lambda_p)B\frac{\partial \eta}{\partial t} = -\frac{\partial Q_s}{\partial x}$$

where:
B = channel width
η = channel elevation
λ_p = active layer porosity
t = time
x = distance
Q_s = transported sediment load

Like most continuity equations, the Exner equation simply states that the difference between sediment entering and leaving a control volume must be stored or removed from storage. The unique feature of the Exner equation is that sediment storage is stored in the bed in a multi-phase mixture with water, requiring porosity to translate mass change into volume change. The Exner equation translates the difference between inflowing and outflowing loads into bed change, eroding or depositing sediment.

HEC-RAS solves the sediment continuity equation by computing a sediment transport capacity for control volume ($Q_{s\text{-}out}$) associated with each cross section, comparing it to the sediment supply ($Q_{s\text{-}in}$) entering the control volume from the upstream control volume or local sources (e.g. lateral sediment loads). If capacity is greater than supply, HEC-RAS satisfies the deficit by eroding bed sediments. If supply exceeds capacity, HEC-RAS deposits the sediment surplus.

Computing Transport Capacity

The right-hand side of the continuity equation, the sediment gradient across the control volume, compares the sediment inflow with the sediment outflow. Sediment inflow is simply the sediment entering the control volume from the upstream control volume(s) and any local sources (lateral sediment inflows). Computing the sediment leaving the control volume is more difficult, a measure of the sediment mass the water can move, which is a complex function of the hydrodynamics and sediment properties. **Sediment transport capacity** is a measure of the control volume competence to pass sediment, computing the maximum sediment it can transport by grain class.

Grain Classes

HEC-RAS divides the sediment material into multiple grain classes. Default grain classes sub-divide the range of transportable material, (0.002 mm to 2048 mm) into 20 grain classes or bins, each including adjacent, non-overlapping fractions of the grain size spectrum. Default grain classes follow a standard log base 2 scale where the upper bound of each class is twice its lower bound, the upper bound of the smaller, adjacent class. The gain class represents all particles they contain with a single, representative grain size. HEC-RAS uses the geometric mean of the grain class to represent the grain size for each bin. Grain boundaries (and labels) are editable.

Sediment Transport Potential

Sediment **transport potential** is the transportable mass of a *particular* grain class in response to cross channel hydraulic parameters. HEC-RAS computes **transport potential** for each grain class with one of the sediment transport equations available in the program.

The sediment transport equations are empirical equations or algorithms that translate hydrodynamics into transport. However, most of these equations were developed for a single representative grain size.

To apply these equations to sediment mixtures, with multiple discrete grain classes, HEC-RAS computes **transport potential**, allying the transport function independently to each grain class present in the system, as if it were the only grain class in the system. Later **transport potential** is prorated by the prevalence of the grain class, to compute the **transport capacity** (see discussion below), which is the transport used in the Exner equation. But first HEC-RAS applies the transport function to each available grain class *independently*, computing a **transport potential** for each.

HEC-RAS includes eight 1D sediment transport potential functions. The three 2D (Wu, van Rijn, and Soulsby-van Rijn) functions are not available in 1D yet. Since sediment transport is sensitive to so many variables, transport potentials computed by the different equations can vary by orders of magnitude, depending on how the material and hydrodynamics compare to the parameters over which the transport function was developed. As much as possible, select a transport function developed for similar gradations and hydraulic parameters as the project reach. Appendix E in this document include the actual equations and algorithms. This section includes brief, qualitative notes on the use, applicability, and sensitivity of each equation.

Most sediment transport functions are based either on shear stress or stream power. They usually use an excess-shear or excess-power form, which compare the actual shear or power to a threshold. HEC-RAS does not compute any transport for that grain class if it is below the threshold (i.e. the grain class is not "competent"). The stream power equations use two different versions of stream power, the product of velocity and slope (VS) and the product of velocity and shear stress (τV). The six shear stress or stream power equations are:

Table 2-1: Transport functions based on excess shear stress and stream power.

Excess Shear Stress	Stream Power
Meyer-Peter Muller	Ackers-White (τV)
Laursen-Copeland	Englund-Hansen (τV)*
Wilcock and Crowe	Yang (VS)

*Engulend-Hansen is not an excess form of the stream power equation, but just a function of stream power.

Ackers and White

Ackers and White (1973) is a total load function, developed from flume data for relatively uniform gradations ranging from sand to fine gravels. Ackers and White derived the equation dimensional analysis and did not include a grain shear partition. They fit coefficients to the equation based on experiments that included a range of bed configurations including ripples, dunes, and plane bed conditions.

This function does not have an intuitive shear stress, excess shear stress, or excess stream power formulation that drives most of the other equations. But it is built on a very similar excess "mobility" power function. The sediment flux is a function of a "Transport Parameter":

$$\overset{\text{Sediment Flux}}{X} = \frac{\overset{\text{Transport Parameter}}{\boxed{G_{gr}}}\,sd}{D\left(\frac{u_*}{V}\right)^{n}}$$

Where:
s = sediment specific gravity
d = median particle size
D = effective depth
u_* = Shear Velocity $(\tau)^{½}$
V = Average Channel Velocity
n = transition exponent
(based on sediment size)

Which is just a simple, dimensionless, power function, of excess "Mobily" with empirical coefficients and an empirical mobility threshold:

$$\overset{\text{Transport Potential}}{\boxed{G_{gr}}} = \underbrace{\boxed{C}\left[\frac{\overset{\text{Sediment Mobility}}{\boxed{F_{gr}}} - \overset{\text{Threshold Mobility}}{\boxed{A}}}{\boxed{A}}\right]^{\boxed{m}}}_{\text{Empirical Power Coefficients}}$$

e.g. for
d>2mm
A=0.17
m=1.78
C=0.25

HEC-RAS exposes the threshold mobility (A) and the coefficients (C and m) so users can calibrate them. However, these are not fixed parameters. They are dynamic, changing with sediment properties and flow. Molders who chose to calibrate Ackers-White should use scaling factors instead.

Mobility in this transport approach is a function of the Bagnold version of stream power (τV) where τ is represented by u*):

$$\overset{\text{Sediment Mobility}}{\boxed{F_{gr}}} = \frac{u_*^n V^{1-n}}{\sqrt{g(s-1)d}\left(\sqrt{32\log(\alpha d/D)}\right)^{1-n}}.$$

Engelund-Hansen

Engelund-Hansen (1967) is a total load transport equation, developed from flume data, using relatively uniform sand sizes between 0.19 mm and 0.93 mm. England Hansen is the simplest transport equation, an explicit function of stream power ($V^2\tau^{3/2}$) and the d50 of the material. It is not an "excess" stream power equation, so it does not control for competence and often can, therefore, compute low transports for large grain classes. Engelund-Hansen should usually be restricted to sand systems.

The equation is:

$$g_s = V^2\left(\frac{\tau_b}{(\gamma_s-\gamma)d_{50}}\right)^{\frac{3}{2}}\sqrt{\frac{d_{50}}{g\left(\frac{\gamma_s}{\gamma}-1\right)}} = V^2(\tau^*)^{\frac{3}{2}}\sqrt{\frac{d_{50}}{g\left(\frac{\gamma_s}{\gamma}-1\right)}}$$

Where:

g_s = Sediment transport by unit width
γ = Unit weight of water
γ_s= Unit weight of sediment
V = Average channel velocity
τ_b= Bed shear stress
τ^*= Dimensionless Shields Number $(\tau_b/(\gamma_s-\gamma)d_{50}))$
d_{50} = Median particle size

Laursen-Copeland

Laursen (1968) developed a total-load, excess-shear transport function with the form:

$$C = 0.01\gamma\left(\frac{d}{D}\right)^{\frac{7}{6}}\left(\frac{\tau^{\prime}}{\tau_c}-1\right)f\left(\frac{u_*}{\omega}\right)$$

This equation makes Concentration (C) a function three dimensionless parameters, the ratio of the representative particle size (d) to the water depth (D), the rouse number (ratio of the shear velocity ($u*$) to the fall velocity (ω) - and the dimensionless form of excess shear stress. Instead of making shear stress dimensionless with the Shields number, this equation makes the excess shear relationship dimensionless (similar to the dimensionless excess shear in the Partheniades equation):

$$\left(\frac{\tau'}{\tau_c}-1\right)or\left(\frac{\tau'-\tau_c}{\tau_c}\right)$$

Where τ' is the grain shear stress and τ_c is the critical shear stress. Laursen and Madden modified the transport function in 1963, to data from the Arkansas River. They updated the graphical function of the Rouse number based on additional data from the Arkansas River.

In the late 1980s, Ron Copeland[3] updated the equation again, including three significant developments. The Laursen-Copeland version of this function:

1. Expanded the empirical Rouse function $f\left(\frac{u_*}{\omega}\right)$ to include additional data over a wide range of grain classes.
2. Replaced the total shear stress with a grain shear stress based on a hydraulic grain roughness.
3. Computed a dynamic, critical shear stress based on a variable Shields parameter.

Copeland's most significant update was the new empirical $f\left(\frac{u_*}{\omega}\right)$ function. The Laursen transport approach builds the empiricism into this function which Laursen and Madden fit to a handful of available measurements in the 1960s. Copeland fit this empirical kernel to to flume results from seven gravel studies and two sand studies, and transport from six large sand or sand and gravel rivers (Figure 2-2). This expanded the applicable range of the transport function in both directions, including gravel and coarse silt, giving it the larges applicable range of the equations in HEC-RAS.

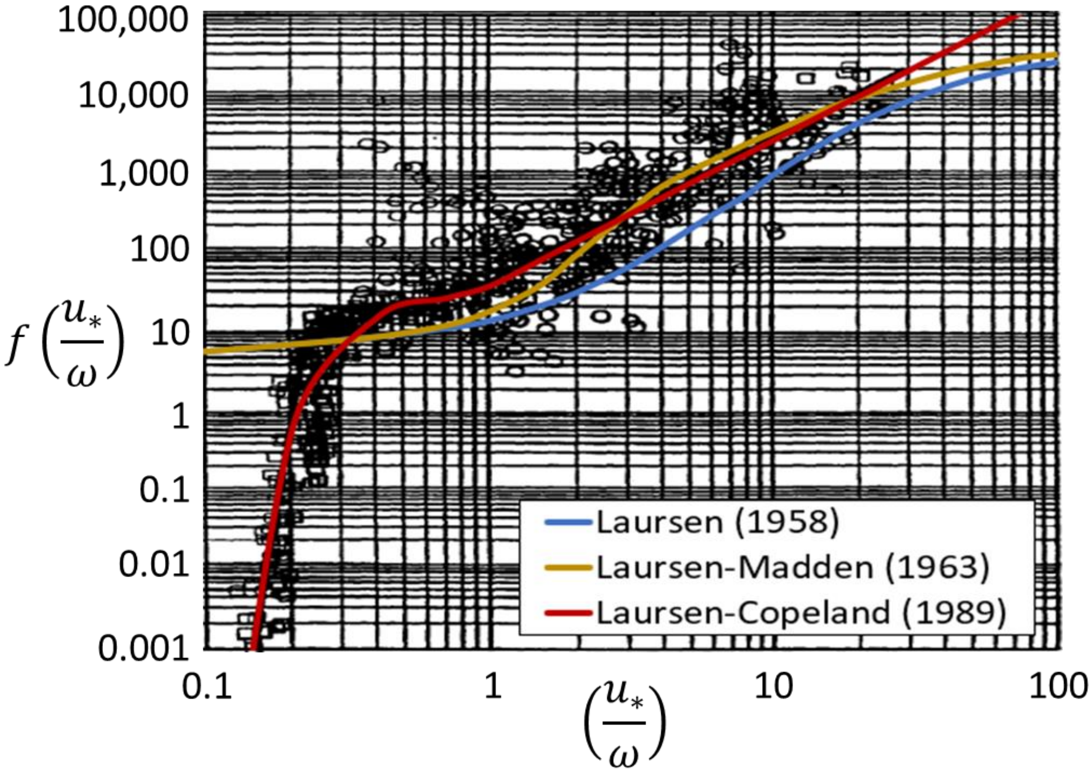


Figure 2-2: The Rouse number function from the three versions of the Laursen equation.

---

[3] Copeland, R. (1993) Numerical Modeling of Hydraulic Sorting and Armoring in Alluvial Rivers, Dissertation, University of Iowa, 284p (Appendix B).

Second, Copeland exchanged total bed shear stress for grain shear stress by replacing depth (*D*) in Laursen's shear (τ') equation with the hydraulic radius due to grain roughness (*R'*), such that:

$$\tau' = \frac{\rho V^2}{58}\left(\frac{d}{D}\right)^{\frac{1}{3}} \text{ becomes } \tau' = \frac{\rho V^2}{58}\left(\frac{d}{R'}\right)^{\frac{1}{3}}$$

where R' comes from the Limerinos equation (Burkham and Dawdy, 1976):

$$\frac{V}{u_*} = \frac{V}{\sqrt{gR'S}} = 3.28 + 5.75log\left(\frac{R'}{d_{84}}\right).$$

The hydraulic radius appears in both sides of this equation, so the transport function iterates to solve for R'.

Finally, the Laursen equation computes the dimensional critical shear stress from a stipulated dimensionless Critical Shields number (0.03). Copeland implemented Paintal's (1971) conclusion that the Shields parameter adjusts in response to the applied Shields stress. Therefore, the Laursen-Copeland equation adjusts the critical Shields parameter based on the dimensionless shear stress, such that:

$$\tau_c^* = \begin{cases} 0.039 & x > 0.05 \\ 0.647\tau^* + 0.0064 & 0.05 > \tau^* > 0.02 \\ 0.02 & \tau^* < 0.02 \end{cases}$$

The wide range of materials used to develop the Copleand version of Laursen's equation gives it the widest range of potential applicability of the transport functions included in HEC-RAS. It is the only transport function developed over the coarse silt range and unpublished work at Colorado State (Watson, personal communication) demonstrated that this equation outperformed other transport functions in the very fine sand and very coarse silt range.

Meyer-Peter Müller

The Meyer-Peter and Müller (MPM) equation (1948) was one of the earliest equations developed and is still one of the most widely used. It is a simple excess shear relationship. Parker (2006)[4] casts MPM in its simplest, dimensionless, volumetric form as.

$$q_b^* = 8(\tau^* - \tau_c^*)^{3/2} \quad , \quad \tau_c^* = 0.047$$

Where q_b^* and τ^* are dimensionless transport and mobility parameters respectively, where:

$$\tau^* = \frac{\tau}{(\gamma_s - \gamma)d_m} \text{ and } q_b^* = \frac{q_b}{\sqrt{Rgd_m}d_m}$$

---

[4] Parker (2006) 1D Sediment Transport Morhodynamics with applications to River and Turbidity Currents, e-book.

Modeling Note: Dr. Gary Parker's ebook is an excellent place to start for anyone new to sediment transport theory.

MPM is strictly a bedload equation developed from flume experiments of sand and gravel under plane bed conditions. The MPM experiments mostly examined uniform gravel, making the transport function MPM most applicable in gravel systems. MPM tends to under predict transport of finer materials.

HEC-RAS uses the version of MPM from Vanoni (1975), ASCE Manual 54, the version used in HEC 6.

$$\left(\frac{k_r}{k_r'}\right)^{\frac{3}{2}}\gamma RS = 0.047\left(\gamma_s - \gamma\right)d_m + \left(\frac{\gamma}{g}\right)^{\frac{1}{3}}\left(\frac{\gamma_s - \gamma}{\gamma_s}\right)^{\frac{2}{3}} g_s^{\frac{2}{3}}$$

where:

g_s = Unit sediment transport rate in weight/time/unit width
k_r = A roughness coefficient
k_r' = A roughness coefficient based on the grains
γ = Unit weight of water
γ_s = Unit weight of sediment
g = Acceleration of gravity
d_m = Median particle diameter
R = Hydraulic radius
S = Energy gradient

Solving for transport, this equation starts to take the familiar dimensionless, form:

$g_s \propto 8\left(\left(\frac{k_r}{k_{r'}}\right)^{\frac{3}{2}}\tau^* - 0.047\right)^{\frac{3}{2}}$ with an additional term in the excess shear equation. The full derivation of Parker's simple dimensionless, volumetric form from the Vanoni version used in HEC-RAS is included in the transport appendix. This version includes a form drag correction, $(kr/k_{r'})^{1.5}$, based on the roughness element ratio computed from the Darcy – Weisbach bed fiction factor. This form drag partitions bed shear stress, isolating grain shear. By imbedding the form shear correction, this version of the equation computes transport based on the bed shear component acting only on the particles.

The form drag correction should be unnecessary in plane-bed conditions, so some versions of MPM exclude it. Wong and Parker (2006) demonstrate that using MPM without the form drag correction over-predicts bed load transport.

Therefore, HEC-RAS offers the Wong Parker correction to MPM based on their 2006 paper. The Wong Parker correction changes MPM in *two* ways. First, it sets the form drag correction to unity ($kr/k_{r'}=1$), effectively removing it from the equation. Second, it sets the MPM coefficients to those Wong and Parker (2006) computed using the *plane-bed* data sets from the original MPM analysis recasting:

$$q_b^* = 8(\tau^* - \tau_c^*)^{3/2} \quad , \quad \tau_c^* = 0.047$$

As

$$q_b^* = 3.97(\tau^* - \tau_c^*)^{3/2} \quad , \quad \tau_c^* = 0.0495$$

Where: q^*_b is the Einstein bedload number (correlated with bedload), τ^* is the Shield's stress which is compared to, τ^*_c which is the 'critical' Shields stress.

The effects of these changes can push transport higher or lower than MPM based on the magnitude of the form drag correction. Removing the form drag correction can increase transport (if it was computing a partition) and changing the coefficients decreases transport.

Wong and Parker (2006) based their work on the *plane-bed* data sets MPM analyzed, those without appreciable bed forms. Therefore, their correction is directly applicable only to lower-regime plane-bed conditions.

Toffaleti

Toffaleti (1968) is a total load function developed primarily for sand sized particles, which followed the basic principles of the Einstein approach, replacing some of the empirical assumptions. Toffaleti is usually applied to 'large rivers', since most of the data used to develop it were from large, suspended load systems. The function is not driven by excess shear velocity or bed shear. Instead, it describes the relationship between sediment, hydraulics, and water temperature with a set of regressions.

Toffaleti divides the water column down into four vertical zones and computes the concentration of each zone with a simple approximation of a Rouse concentration profile. The four zones are based on theoretical inflection points and transitions in the vertical velocity profile. The function then computes transport in each of the zones (Figure 2-3) based on a "reference unit sediment discharge" (M_i):

$$M_i = \frac{g_{ssLi}(1 + n_v - 0.756z_i)}{\left(\frac{R}{11.24}\right)^{1+n_v-0.756z_i} - (2d_{si})^{1+n_v-0.756z_i}}$$

Where g_{ssLi} is the "nucleus load"

$$g_{ssLi} = \frac{0.600p_i}{\left(\frac{T_T A k_4}{V^2}\right)^{\frac{5}{3}}\left(\frac{d_{si}}{0.00058}\right)^{\frac{5}{3}}}$$

and the two exponents are:

$$z_i = \frac{\omega V}{(260.67 - 0.667T)rS}$$

$$n_v = 0.1198 + 0.000048T$$

In these equations, T is temperature, V is the 1D, depth averaged water velocity, r is the full, average water depth, S is the river slope, d_{si} and ω_i are the particle size and fall velocity of the particular grain class (i) and p_i is the fraction of that grain class. Because of the dimensionality of this equation, all units are US customary, and HEC-RAS converts SI units before and after calculating Toffaleti transport.

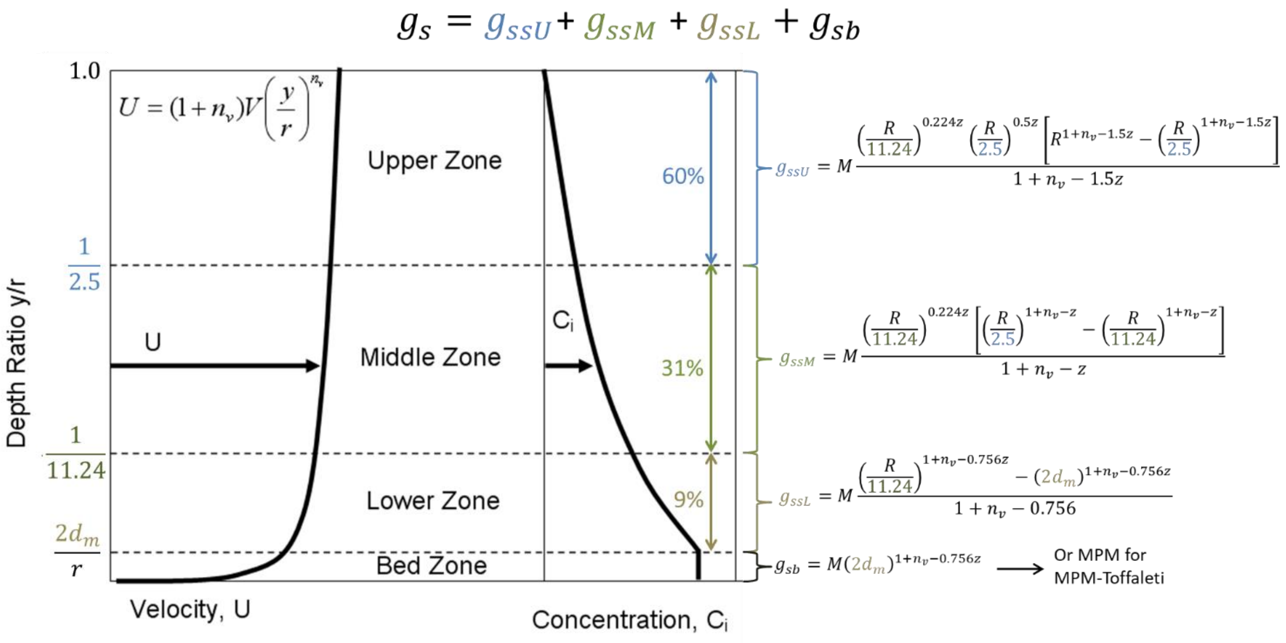


Figure 2-3: Toffaleti' s equations for each vertical transport zone.

Modeling Note: Toffaleti temperature sensitivity - Temperature appears in both the *z* and n_v exponents, which can make Toffaleti more sensitive to temperature than excess shear equations.

The USACE has applied the function successfully to large systems like the Mississippi, Arkansas, Sacramento, and the Atchafalaya Rivers. However, it performs particularly poorly for gravel size particles. Additionally, the Toffaleti equation uses two different grain sizes, a d_{50} and a d_{65}, to quantify transport dependence on the gradational deviation from the mean. This made more sense when the equation was used to compute the transport of the bulk gradational material. When HEC-RAS applies it to the individual grain classes, it will use the d_{50} and d_{65} for the given grain class, stretching the original intent of the d_{65} parameter.

HEC-RAS can output transport for each zone separately, approximating the vertical concentration profile. Sometimes modelers will use this feature to calibrate to suspended load measurements, comparing the measurement to the computed flux from the upper three zones.

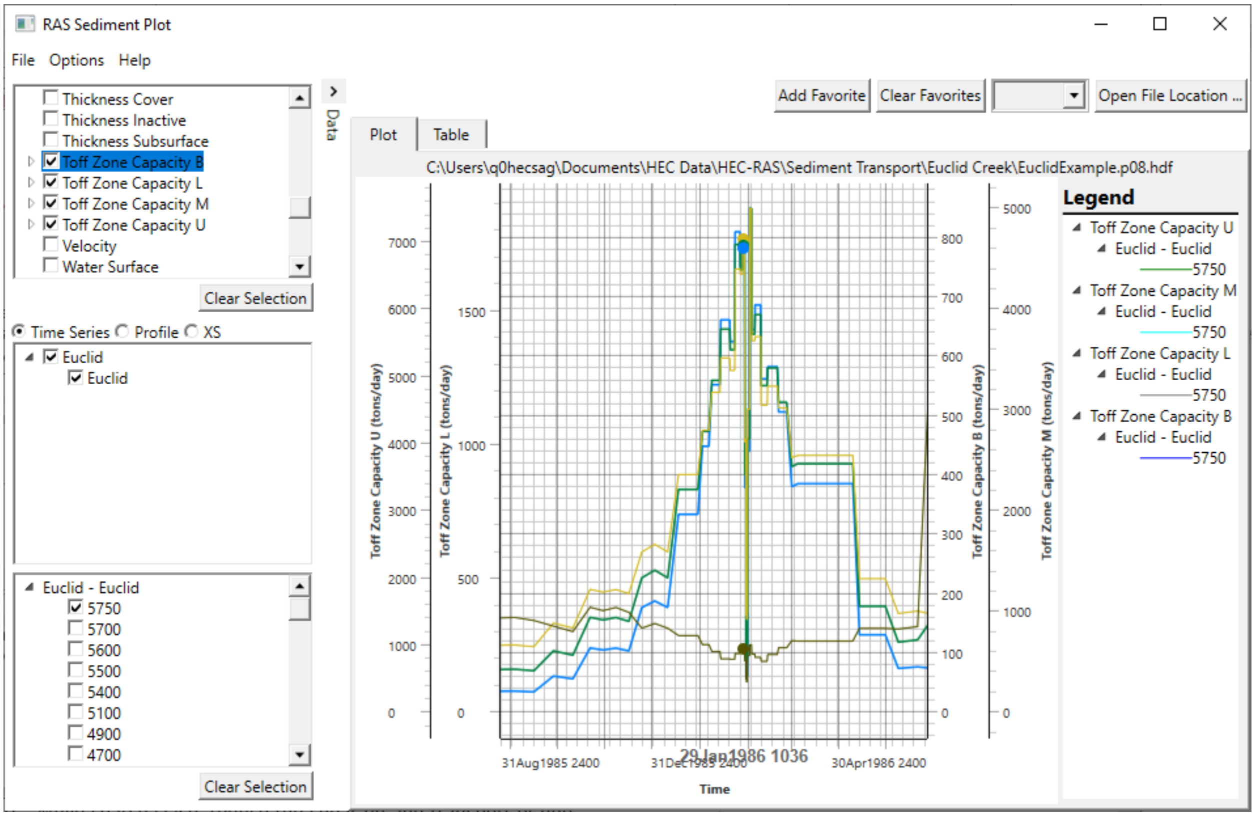


Figure 2-4: Zone Specific Capacity computed for each Toffaleti transport zone.

Toffaleti-MPM

The Toffaleti equation was developed for large, sand bed river, and does not perform well for coarse particles (Williams and Julian, 1989).[5] But some large domain models include large sand-bed rivers as well as coarser tributaries. Because HEC-RAS requires user to select one transport function, these models have to use the same equation for both. HEC 6 addressed systems where Toffaleti was appropriate for down-gradient rivers that have coarse bed-load up-gradient, but integrating the Toffaleti and the Meyer-Peter Muller equations. This combined function replaces the bed component of Toffaleti with the MPM bed load equation which is more appropriate for coarse material.

Toffaleti Limiter

The Toffaleti transport function was not developed for these large particles or high gradient systems and has a numerical artifact that can arise under these conditions. Yaw et al. (2019) demonstrated a load discontinuity, under certain shallow, large particle settings. This discontinuity is native to the Toffaleti equation so it can show up in the original formula or its hybrid with MPM which was designed to extend the approach to larger particle sizes.

---

[5] Williams, D. T., and Julien, P. Y. (1989). "Applicability index for sand transport equations." Journal of Hydr. Eng., 115(11), 1578– 1581.

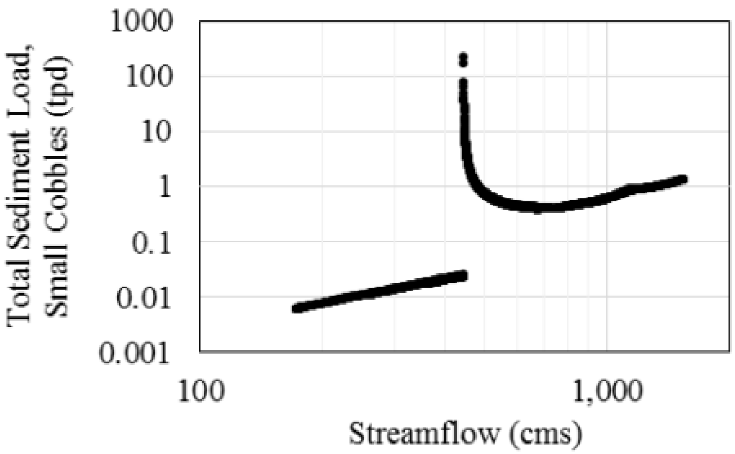


Figure 2-5: Discontinuity between flow and transport for cobbles in a high gradient Toffaleti model.

As long as the hydraulic radius is roughly an order of magnitude larger than twice the particle size the form of the Toffaleti equation works. But as $2d_{si}$ approaches $R_h/11.24$ the denominator of the reference unit sediment discharge (see *Mi* equation in Toffaleti Section) goes to zero (generating infinite transport) and then negative as grain size continues to increase relative to shallow depths.

But particles that invert the Toffaleti transport denominator are unlikely to be suspended. These particles will almost always be limited to bed load. So HEC-RAS added a “Toffaleti limiter” that uses Julian’s (2002) Rouse number, suspension test, that a grain class is likely to be suspended if the fall velocity (ω) is less than 40% of the shear velocity (u_*) ($u_*/\omega>0.4$). Therefore, HEC-RAS checks the Rouse number (u_*/ω) of each grain class in each time step and sets the transport capacity to zero for all transport ones where Rouse number is less than or equal to 0.4,

Yang

Yang (1973, 1984) is a total load transport equation which bases transport on Stream Power, the product of velocity and shear stress. The function was developed and tested over a variety of flume and field data. The equation includes two separate relations for sand and gravel transport. Yang tends to be very sensitive to stream velocity, and it is more sensitive to fall velocity than most.

Yang is fundamentally a power law equation where Concentration (C_t) is a function of excess stream power (VS-VS_{cr}):

$$C_t = a(VS - VS_{cr})^b$$

The log-transformed version of that equation is:

$$\log C_t = b + \log a\left(\boxed{\overset{\text{Stream Power}}{\boxed{VS}} - VS_{cr}}\right) \quad \text{Critical Stream Power}$$

The actual form of the Yang (1973) sand (particle size, d<2mm) equation is:

$$\log C_t = \boxed{5.435 - 0.286\log\frac{\omega d_m}{\nu} - 0.457\log\frac{u_*}{\omega} +}\ \mathbf{b}$$

$$\mathbf{a}\ \boxed{\left(1.799 - 0.409\frac{\omega d_m}{\nu} - 0.314\log\frac{u_*}{\omega}\right)}\log\left(\frac{VS}{\omega} - \frac{V_{cr}S}{\omega}\right)$$

Where the power and coefficient are functions that include dimensionless parameters (e.g. the classic ratio of shear velocity and fall velocity that is often used to determine if a grain class can be suspended.

The variables are:

C_t = Total sediment concentration
ω = Particle fall velocity
d_m = Median particle diameter
ν = Kinematic viscosity
$u*$ = Shear velocity
V = Average channel velocity
S = Energy gradient

This transport function switches to Yang's (1984) gravel equation for grain classes larger than 2 mm.

$$\log C_t = 6.681 - 0.633\log\frac{\omega d_m}{\nu} - 4.816\log\frac{u_*}{\omega} +$$

$$\left(2.784 - 0.305\frac{\omega d_m}{\nu} - 0.282\log\frac{u_*}{\omega}\right)\log\left(\frac{VS}{\omega} - \frac{V_{cr}S}{\omega}\right)$$

The transition between the sand and gravel equations is not always smooth. If results have counter intuitive results around the sand-gravel boundary, investigate the computed potential across that transition.

Wilcock and Crowe

Wilcock and Crowe (2003) is a bedload equation designed for well-graded (poorly-sorted) rivers containing both sand and gravel. It is a "surface" transport method based on the theory that transport depends on the material in direct contact with the flow and it is the bed surface that modulates bed mobility. It was developed based on the *surface* gradations of flumes and rivers and sediments with bulk sand contents between 6-34%. The beds were often armored with much lower sand content on the surface than in the subsurface. Therefore, users should choose active layer algorithms and gradations should reflect the bed surface properties. Always use this function with the **Active Layer** bed mixing method and consider defining separate, initial active layer gradations to reflect the cover layer.

The Wilcock and Crowe equation is based on the ratio of the shields number (τ^*) to a "reference shields" number (τ_{ri}^*), making it a sort of excess shear stress. The reference shields parameter is comparable to the critical Shields parameter in MPM or Laursen-

Copeland, but recognizes that rivers transport trace sediment volumes at very low shear stresses. Therefore, instead of defining a "critical" shear stress, below which no particles move, this function uses a refence shear stress where transport is trivial. The factor 0.002 in the transport equation below corresponds to the reference transport rate.

They define transport W_i^* as two functions of the dimensionless shear ratio $\frac{\tau^*}{\tau_{ri}^*}$:

$$W_i^* = \begin{cases} 0.002\left(\frac{\tau^*}{\tau_{ri}^*}\right)^{7.5} & if\ \frac{\tau^*}{\tau_{ri}^*} < 1.35 \\ 14\left(1 - \frac{0.894}{\sqrt{\frac{\tau^*}{\tau_{ri}^*}}}\right)^{4.5} & if\ \frac{\tau^*}{\tau_{ri}^*} \geq 1.35 \end{cases}$$

The Wilcock and Crowe approach is distinct from the other transport functions because include a hiding equation that accounts for grain class inter-dependence. When a single grain size is used to represent the sediment mixture, the transport equation assumes the same reference shear stress will mobilize all the sizes. This is accurate for very well mixed sediments but becomes less accurate as a sediment grain size distribution develops. In Figure 2-6, the grain size distribution of the bed sediment shown in brown (Figure 2-6A) is well mixed (or poorly sorted) and the grain size distribution of the bed sediment shown in brown (Figure 2-6B) is poorly mixed (well sorted). Both are representative of natural gravel and sand river systems. The influence of mixture on grain inter-dependence causes the sizes in the brown mixture to mobilize at a similar critical shear stress for all but the largest grains. In Figure 2-6C, the critical shear stress curve is near flat until the largest size fractions. In contrast, the green sediment, which is poorly mixed / well sorted, has a much larger range of critical shear stresses at which the different grain size fractions mobilize. Transport of the brown sediment could be reasonably approximated using the d_{50} grain size and a single critical shear stress value. Transport rates for the green sediment require grain size specific calculations. The Wilcock and Crowe model accounts for this inter-dependence and sensitivity of critical shear stress on grain size mixture through a hiding factor that explicitly incorporates grain size.

The last two decades of graded sediment transport research suggests that gravel and cobbles affect sand transport and visa versa. Wilcock and Crowe quantify grain class dependence with hiding and sand dependent gravel transport equations:

Hiding: Wilcock and Crowe computes the inter-dependence of grain sizes and the influence on mobility and transport with a hiding function. The hiding function relates the transport potential of bed surface to the distribution of finer and larger sizes.

Where there is a small amount of sand on the surface, sand nestles between larger gravel clasts, which reduces the bed shear it experiences. In this way coarse clasts reduce the transport of fine particles to occurring only when a large grain is mobilized. In contrast, gravel transport increases with sand content. As sand content of the bed surface increases, it 'lubricates' the bed, depositing between surface gravels and reducing the framework integrity. Once mobilized, the gravels are transported more easily over the sandier bed surface.

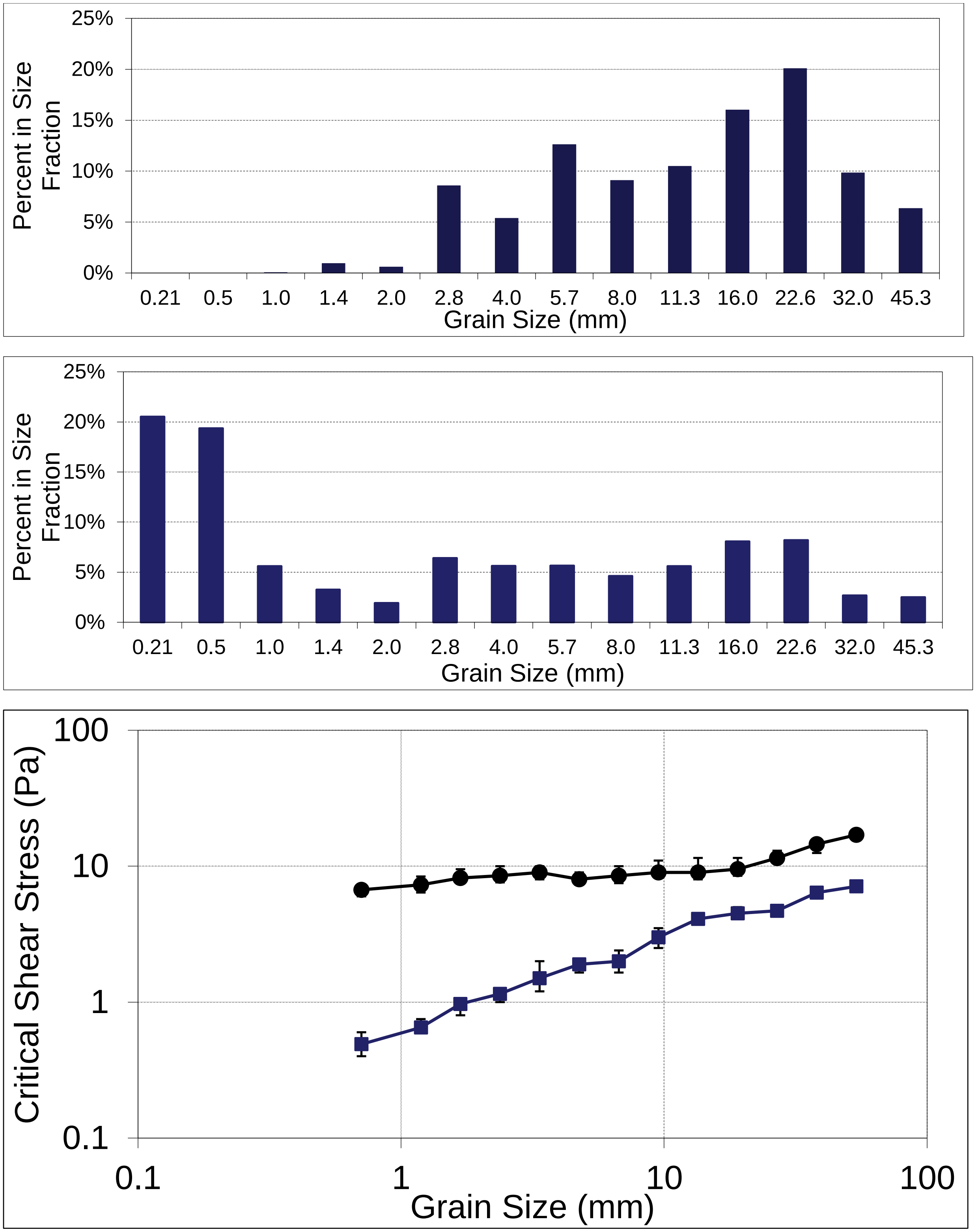


Figure 2-6: A) bed surface with a well-mixed grain size distribution and small amount of sand on the surface. B) bed surface with a poorly mixed grain size distribution and larger amount of sand on the surface. C) measured critical shear stresses for each grain size fraction in the two mixtures.

Wilcock and Crowe adjusts the reference shear (τ_{ri}^{*}) for the specific grain size class using the base reference shear (τ_{rm}^{*}) for the median grain class, the ratio of the grain class particle size (d_i) on the surface to the median mixture surface grain size (d_{sm}), and the hiding factor, b:

$$\tau_{ri}^{*} = \tau_{rm}^{*} \left(\frac{d_i}{d_{sm}}\right)^{b} \text{ and } b = \frac{0.67}{1+exp\left(1.5-\frac{d_i}{d_{sm}}\right)}$$

Modeling Note: HEC-RAS version 6.0 included hiding features independent of the transport functions. Because Wilcock and Crowe includes a hiding algorism, modelers should not use it with the generic hiding features in the Bed Mixing Options. Adding a hiding feature to this transport function would double-count the process.

Wilcock and Crowe also include this effect in the base reference shear stress (τ_{rm}^{*}). The reference shear is a function of the sand content (FS) of the bed surface (in percent):

$$\tau_{rm}^{*} = 0.021 + 0.015 \cdot e^{-20 \cdot FS}$$

The equation for base reference shear stress is derived using the surface sand content, as shown in Figure 2-7. The reduction in reference shear stress occurs for both sand content on the bed surface and in the subsurface. However, the equations in the Wilcock and Crowe model are fit to the surface sand.

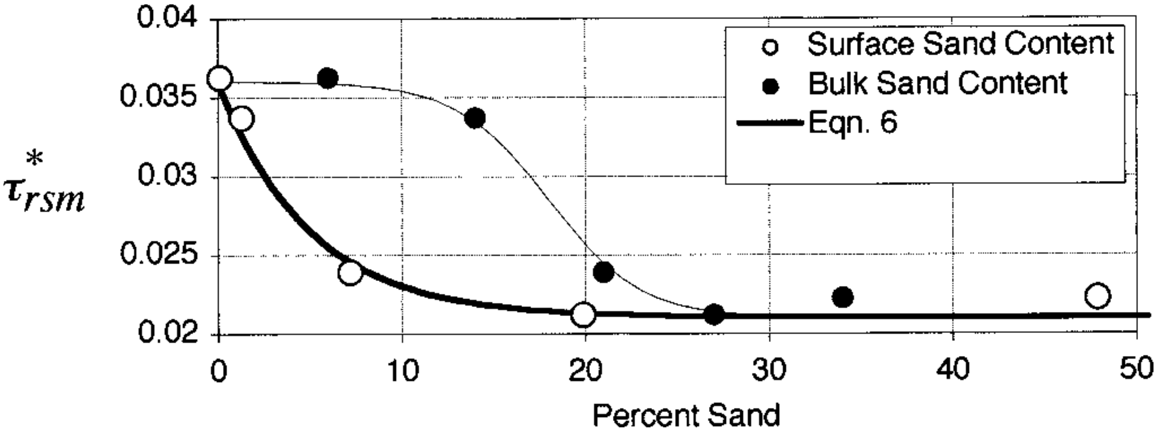


Figure 2-7: The influence of the surface and subsurface sand content on the reference shear stress for a sediment mixture.

Figure 2-8 illustrates the influence of the sand content on the bed surface over the reference shear stress for the sand and gravel fractions. As the sand content increases and sand becomes able to transport independent of gravel movement, the reference shear stress for sand decreases from a maximum of 0.8 to a minimum of 0.04. At the same time the reference shear stress for the gravel fraction decreases from 0.04 to 0.01 as the increase in sand on the bed surface makes it easier to transport.

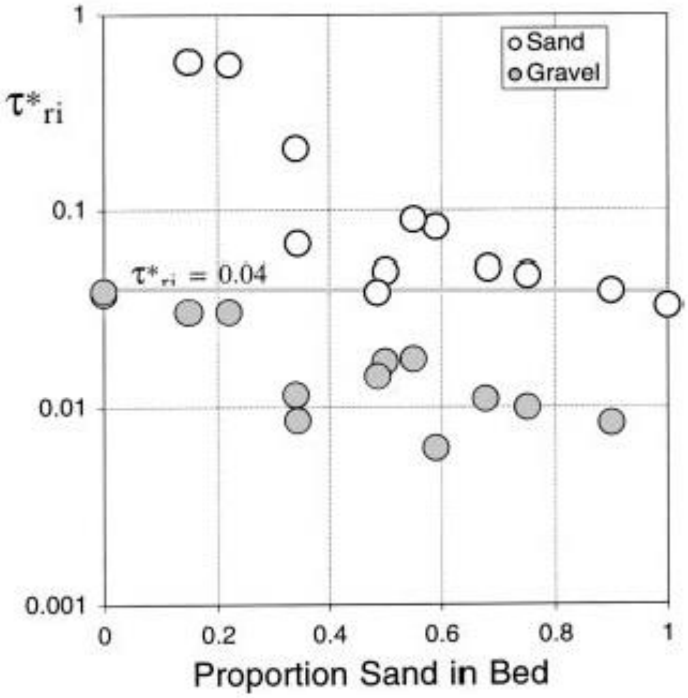


Figure 2-8: Influence of sand content on the reference shear stresses of sand and gravel fractions.

As the sand content increases: the reference shear decreases, increasing the excess bed shear, and total transport. This equation is very sensitive to this sand content parameter, making field data collection of a separate gravel count and surface sand content estimate very important.

Modeling Note - Calibrating Wilcock and Crowe: To calibrate Wilcock & Crowe (2003), adjust the mobility scaling factor, which will be allied to τ^*_{rm}. Adjusting τ^*_{rm} corrects error in the drag partition or other site-specific mobility factors while preserving both the hiding function and the transport function. Choosing to specify τ^*_{rm} directly, overwrites the mobility parameter and loses the sand dependence from the τ^*_{rm} equation above

Modeling Note[6] - Sensitivity to Surface Grain Size Distribution Bias: Surface gradations are usually measure with Wolman pebble counts or photoseiving. Numerous studies have shown that manual particle count surveys tend to be biased against the largest and smallest size fractions, particularly random walk methods in the water.7 The gravel count should be truncated at 8 mm at the finer end and 128 mm at the courser end. When truncating, sampled grains are grouped together as 'finer than' or 'greater than' and a visual estimate is made of the percent bed surface cover by the fractions. A grid-based sampling system reduces the error associated with random

---

[6] This modeling note is based on recommendations from transport function developer Dr. Joanna Curran (Crowe).

7 See Bunte and Abt (2001) Sampling surface and subsurface particle-size distributions in wadable gravel- and cobble-bed streams, for a discussion of common surface gradation sample biases and best practices.

walks and selection by touch. Particles as small as 4 mm may be counted when using a grid. Pebble counts also bias the percent of sand on the bed. Therefore, the sand component should be estimated by eye. "Photoseiving" also includes biases. Overlapping or buried particles tends to underrepresent the coarser grain classes by as much as 20%. Surface based transport methods are sensitive to these gradations and will be affected by biased measurements.

Transport Capacity

Once HEC-RAS computes **transport potential**, applying the transport equation to each grain class, (i.e. as if the system was composed of 100% of that grain class) the model must translate that into the actual grain class transport, as a function of the composition of the sediment mixture. The **transport capacity** prorates the **transport potential**, reducing the transport of each grain class based on its prevalence in the bed.

Classic Bed Partitioning

The **transport capacity** for each grain class is the **transport potential** multiplied by the percentage of that grain class in the bed. Therefore, the total transport capacity is:

$$T_c = \sum_{j=1}^{n} \beta_j T_j$$

Where: T_c is Total transport capacity, n is the number of grain size classes, B_j is the percentage of the active layer composed of material in grain size class "j", and T_j is the Transport potential computed for the material in grain class "j". Partitioning capacity based on the gradation of the active layer is a classic assumption based Einstein's (1950), who proposed sediment discharge of a size class is proportional to the fractional abundance of that size class in the bed (Vanoni, 1975).

Modeling Note – Partition Gradations for Empty Sediment Control Volumes: As long as the sediment control volume has bed sediment, it can partition the transport potential into capacity. However, if the active layer thickness = 0, either because it is a concrete channel with no starting sediment thickness (Initial Max Depth = 0) or because it scoured through the entire erodible depth, the bed partitioning assumption will run into trouble. If the active layer has no sediment, the fraction of each grain class is zero (β_j=0 in the previous equation). Therefore, regardless of the computed potential, this approach will compute no transport capacity over a fixed bed. If the model computes no transport capacity, it will deposit all of the sediment in one time step, and erode in the next, causing oscillating errors and decreasing transport in half, because it only transports every other time step.

To offset this numerical artifact, recent versions of HEC-RAS uses the initial bed gradation to partition potential into capacity if the control volume has no bed sediment. This is also why HEC-RAS requires bed gradations for concrete channels. It uses the gradation to compute capacity.

Capacity Sensitivity to Bank Stations and Movable Bed Limits

The first consideration when selecting movable bed limits should be which section of the cross section the river is likely to adjust vertically. However, the placement of the movable bed limits can also affect sediment transport capacity. Most transport equations compute transport capacity per unit width. HEC-RAS converts this transport-per-unit-width to total transport by multiplying the unit rate by the distance between the movable bed limits. Therefore, though there are complicating feedbacks between cross section shape, channel bank placement, and movable bed limits, movable bed limits that are farther apart, often generate more transport capacity.

Continuity Limiters

The continuity equation compares the transport capacity to the supply (i.e. inflowing sediment load) for each grain class for each time step. If the capacity exceeds the supply HEC-RAS computes a sediment deficit. If the supply exceeds capacity the model computes a sediment surplus. In general, the model converts surplus into deposition and deficit into erosion. However, HEC-RAS applies some physical constraints to the continuity equation, checking if computed deficit or surplus can actually erode or deposit. HEC-RAS models these constraints with three basic limiters: a temporal deposition limiter, a temporal erosion limiter, and the sorting and armoring algorithms that provide an additional constraint on erosion.

Temporal Deposition Limiter

The temporal constraint on deposition is the limiter based on the simplest and most robust theory. Fall velocity controls how fast particles can drop out of the water column and deposit. By comparing the vertical distance a particle has to travel to reach the bed surface and the vertical distance a particle can travels in a time step (fall velocity * time), HEC-RAS computes the percentage of a sediment surplus can actually deposit in a given control volume in a given time step. The model computes a **deposition efficiency coefficient** for each grain class (i):

$$C_d = \frac{V_s(i) \cdot \Delta t}{D_e(i)}$$

Where: C_d is the deposition efficiency coefficient, $V_s(i)$ is the fall velocity for the grain class, Δt is the time step, and D_e is the effective depth of the water column over which the grain class is transported.

The coefficient is a fraction, which will reduce deposition if the product of the fall velocity and the time step is less than the effective depth. If the time and fall velocity are sufficient for the grain class to fall the entire effective depth (i.e. the numerator is greater than the denominator), all of the surplus sediment deposits. This ratio requires two parameters (in addition to the time step, which HEC-RAS provides automatically): fall velocity and the effective transport depth.

Fall Velocity

Most fall velocity derivations start with balancing the gravitational force and the drag force on a particle falling through the water column. The free body diagram is included in Figure 2-9.

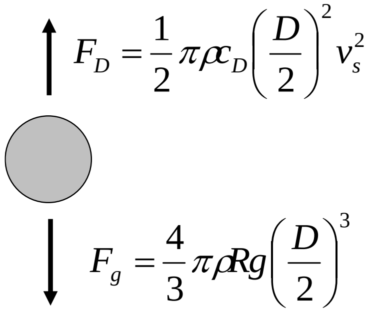


Figure 2-9. Free body diagram used for computing fall velocity.

However, the resulting equation is circular because fall velocity is function of the drag coefficient C_D, which is a function of the Reynolds number, which is itself a function of fall velocity. This self-referential quality of the force balance requires either an approximation of the drag coefficient/Reynolds number or an iterative solution. The fall velocity options in HEC-RAS are detailed in Chapter 12, pages 12-30 to 12-32, but a few brief comments on how each of these methods attempts to solve this equation (fall velocity dependence on fall velocity) are given below.

Rubey assumes a Reynolds number to derive a simple, analytical function for fall velocity. Toffaleti developed empirical, fall velocity curves that, based on experimental data, which HEC-RAS reads and interpolates directly. Van Rijn uses Rubey as an initial guess and then computed a new fall velocity from experimental curves based on the Reynolds number computed from the initial guess. Finally, Report 12 is an iterative solution that uses the same curves as Van Rijn but uses the computed fall velocity to compute a new Reynolds number and continues to iterate until the assumed fall velocity matches the computed within an acceptable tolerance.

Fall velocity is also dependent upon particle shape. The aspect ratio of a particle can cause both the driving and resisting forces in Figure 2-9 to diverge from their simple spherical derivation. All of the equations assume a shape factor or build one into their experimental curve. Only Report 12 is flexible enough to compute fall velocity as a function of shape factor. Therefore, HEC-RAS exposes shape factor as a user input variable but only uses it if the Report 12 method is selected.

Effective Transporting Depth

The deposition limiter works by comparing how far a particle can fall in a time step versus the distance available for it to travel. The fall velocity computes how far the particle can fall in a time step, but the temporal limiter equation also requires an average vertical distance that the grain class can fall. That distance depends on the concentration profile of the grain class in the flow field (i.e. sediment is not uniformly distributed in the water column).

Rouse (1963) developed the classic concentration profile theory (Figure 2-10). The Rouse number z is higher for larger particles and lower for higher shear velocities. Smaller particles and higher shears distribute suspended particles over more of the water column. Grain classes with higher Rouse numbers have to fall farther to deposit.

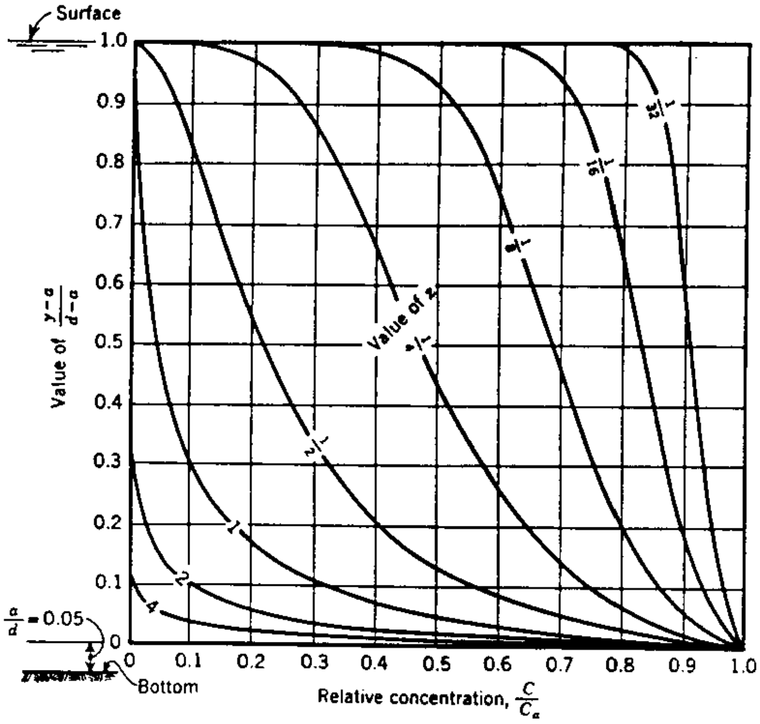


Figure 2-10. Rouse concentration profiles.

Toffaleti (1968) subdivided the \water column into four zones, computing transport separately for each zone (Figure 2-11). HEC-RAS uses these zones as a (coarse) integration of vertical concentration profiles. HEC-RAS adopts these four zones as the effective transporting depth for different grain sizes, assuming that the grain class is evenly mixed and in equilibrium in the zone. The model distributes grain classes smaller than fine sand throughout the entire water column (Effective Depth = 1). The model distributes fine sand over the middle, lower, and bed zone which compose the lower 40% of the water column. All coarser particles (≥Medium Sand) transport relatively close to the bed, in the lower zone and bed zone, the deepest 9%of the water column.

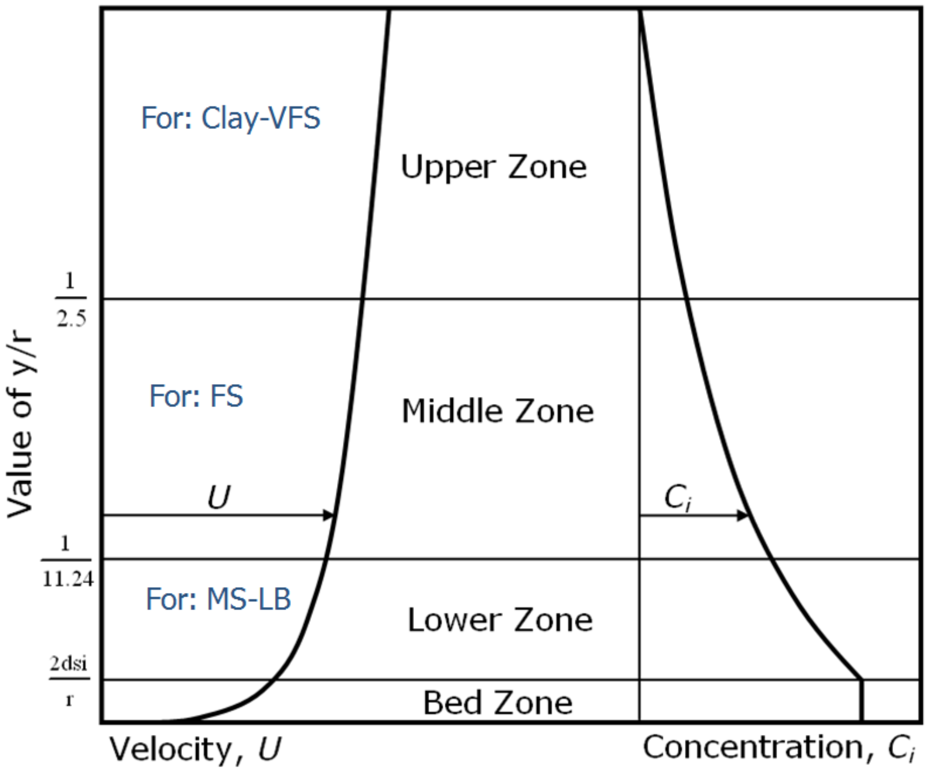


Figure 2-11. Toffaleti' s zones for computing transport (after Vanoni, 1954)

This approach has limitations. It distributes sediment evenly throughout the zone at the beginning of each time step. This assumption simplifies the concentration gradients depicted in Figure 2-10. Additionally, assuming the effective depth (based on the transporting depth) is on only a function of grain size ignores the Rouse dependence on shear velocity. Finally, the algorithm mixes the transporting zone fully at the beginning of each time step, retaining no memory of how far material settled in the previous time step. Despite the limitations, however, the temporal deposition limiter improves the continuity approach, limiting the deposition with physical process.

Temporal Erosion Limiter

Like deposition, erosion is also a temporal process. Physical processes delay erosion, potentially limiting the continuity surplus to a smaller erosion mass. Therefore, erosion also requires a temporal limiter. Unfortunately, the physical processes that delay erosion are more diverse, site specific, and difficult to quantify than those that limit deposition. The equations used are more empirical and generally less accurate.

HEC-RAS adopted its erosion limitation equation from HEC 6. It is similar to 'Characteristic Flow Length' principles, but predates them. The governing assumption, based on undocumented flume experiments, is that an unarmored reach requires thirty times the water depth for erosion to fulfill the capacity. This assumption is reflected in the equation for the entrainment coefficient:

$$C_e = 1.368 - e^{-\left(\frac{L}{30 \cdot D}\right)}$$

Where: C_e is the entrainment coefficient, D is flow depth, and L is length of control volume. This equation produces the relationship between the entrainment coefficient and length/depth ratios in Figure 2-12. HEC-RAS multiplies the sediment deficit by this entrainment coefficient to calculate erosion.

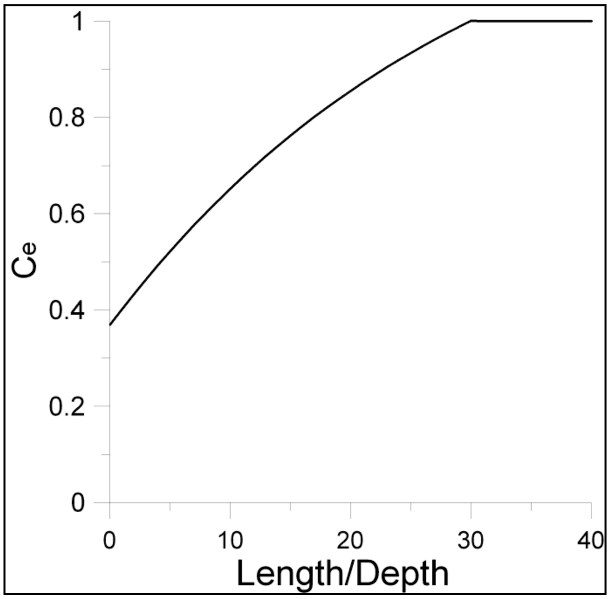


Figure 2-12. The calculated entrainment coefficients for a range of control volume length to depth ratios.

If the length exceeds the flow depth by thirty times or more, the entrainment coefficient goes to one and HEC-RAS erodes the full deficit. In the lower limit, as the length approaches the depth, the second term of the C_e equation goes to 1 leaving a minimum entrainment coefficient of 0.368. Therefore, the program will always allow at least 36.8% of the deficit to erode.

Sorting and Armoring

Erosion can also be supply limited. In many well graded rivers, a coarse armor layers forms on top of a subsurface layer, composed of the representative reach gradation. Rivers form these coarse armor layers by static or dynamic armoring (Parker, 2008). Static armoring comes from differential transport of finer materials, where finer particles transport, leaving the coarse particles behind until the immobile coarse particles armor the bed, precluding future erosion. Static armoring processes often dominate downstream of dams, where attenuated flow regimes are competent to move finer particles but not coarser particles. Dynamic armoring can also form armor layers in systems where large flows are competent to move all grain classes. Dynamic armoring forms coarse cover layers while all grain classes are mobile because equilibrium transport of graded material requires over representing coarse particles at the surface, compensating for their lower transportability by increasing their availability (Parker, 2008).

In either case, armor layers decrease total transport because the surface particles available for transport tend to be coarser and more difficult to move. This is also a physical limiter on the transport capacity.

HEC-RAS includes three algorithms to simulate bed sorting and armoring. All three algorithms divide the bed into an active layer and an inactive layer. The active layer is a surface layer that represents actively transporting material (or material that could be transported). The active layer gradation evolves independently and material is moved between it and the parent material in the inactive layer below it. HEC-RAS computes transport capacity based on the gradation of the active layer, not the entire bed.

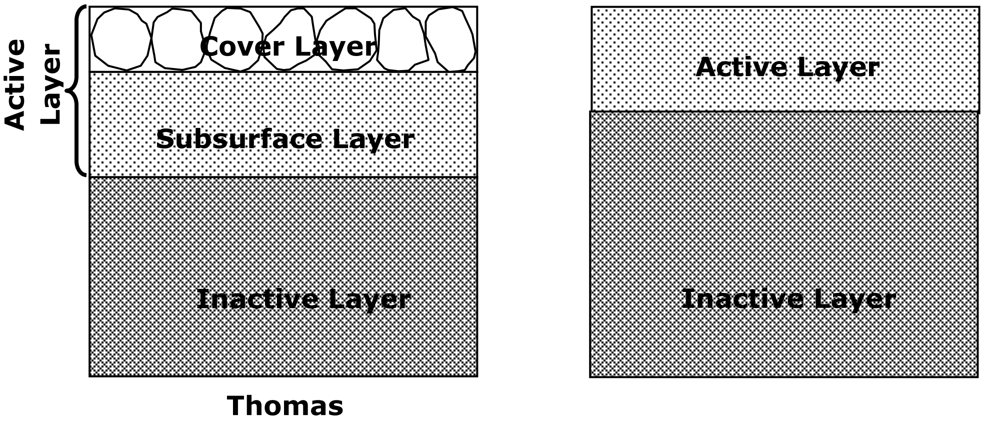


Figure 2-13. Schematic of the mixing layers in HEC-'AS' sorting and armoring methods.

Thomas Mixing Method (Exner 5)

The **Thomas** method (formerly Exner 5) is the default sorting and armoring method in HEC-RAS. This is a three-layer bed mixing algorithm (Figure 2-13), which was designed to account for the influences of static armoring. Tony Thomas developed this method (Thomas, 1982), which was the default method in HEC-6. It subdivides the active layer into a cover layer and a subsurface layer, allowing a thin cover layer to coarsen and regulate erosion, while maintaining the more broadly graded active layer. HEC-RAS computes transport capacity computation based on the gradation of the entire active layer, which includes the combined cover and subsurface layers. Sediment deposits into and erode from the cover layer. Thomas developed this mixing algorithm based on the photograph in Figure 13-8 and the data in Harrison (1950).

If finer grain classes erode faster than coarser glasses (relative to their abundance) the cover layer coarsens, regulating the sediment that transport capacity can remove from the active layer. HEC-RAS can erode a grain class long as it is available in the cover layer. But once the model strips a grain class from the cover layer it will try to satisfy the grain class transport capacity with subsurface layer sediment. The cover layer can reduce or preclude erosion from the subsurface layer, leaving capacity unfulfilled.

Figure 2-14. Static Armor layer below Fort Randall Dam (Livsey, 1963)

The Copeland (1992) method followed the basic approach and architecture of the Thomas method made a few critical changes. The discussion that follows generally applies to both methods, then the algorithm elements particular to Copeland are discussed in the next section.

Active Layer and Equilibrium Depth:

The Thomas method computes the Active Layer (cover layer + subsurface layer) at the beginning of each time step by computing the **Equilibrium Depth** (D_{eq}). Equilibrium Depth is the smallest water depth at which surface sediment does not move, where hydraulic forces are too small to move bed particles. Alternately, it is the maximum potential scour depth. Then it adjusts the active layer to the equilibrium depth (Figure 2-15).

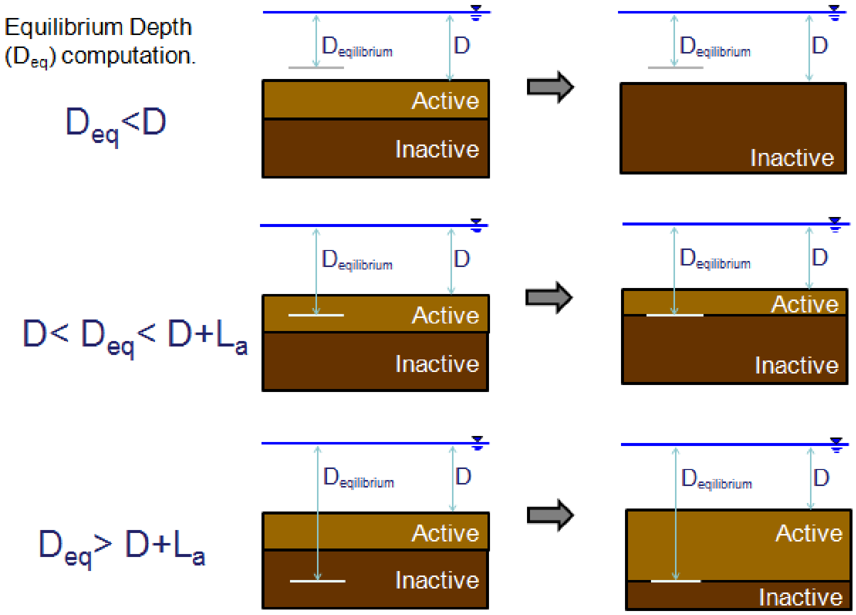


Figure 2-15: Active layer adjustment to the equilibrium depth for three conditions: equilibrium depth less than water depth (top), equilibrium depth within the current active layer (middle), and equilibrium depth deeper than current active layer (after Copeland, 1992).

Equilibrium Depth (D_{eq}) is based on a relationship between hydraulic energy, bed roughness and sediment transport intensity. The Thomas method combines Manning's equation for flow velocity, Strickler's equation for grain roughness, and Einstein's Transport Intensity equation to compute equilibrium depth:

Manning's Equation

$$V = \frac{1.49}{n} R^{\frac{2}{3}} S_f^{\frac{1}{2}}$$

Strickler's Roughness Equation

$$n = \frac{d^{\frac{1}{6}}}{29.3}$$

Einstein's Transport Intensity Equation

$$\Psi = \frac{\rho_s - \rho_w}{\rho_w} \cdot \frac{d}{D \cdot S_f}$$

Where:

V = Velocity
R = Hydraulic Radius
S_f = Friction Slope
n = Manning's n value
d = representative particle size
ρ_s = grain density
ρ_w = water density

D = Depth

The Einstein Equation assumes particle erosion when the transportability $\Psi \geq 30$. Submerged particle density $(\rho_s - \rho_w / \rho_w)$ is 1.65. Substitution reduces the Einstein's Transport Intensity equation to:

$$S_f = \frac{d}{18.18D}$$

HEC-RAS solves these three equations for unit water discharge by replacing the sub-sectional hydraulic radius in the Manning equation with the panel depth, D, and the n-value with Strickler's equation such that:

$$q = \frac{1.49}{\left(\frac{d^{\frac{1}{6}}}{29.3}\right)} \cdot D^{\frac{5}{3}} \cdot \left(\frac{d}{18.18D}\right)^{\frac{1}{2}}$$

or

$$q = 10.21 \cdot D^{\frac{7}{6}} \cdot d_i^{\frac{1}{3}}$$

Where: q = water discharge in cfs per ft of width
di = the particle diameter and
D = is the depth that does not transport the grain class, or the equilibrium depth D_{eq}.

Solving for D_{eq} yields:

$$D_{eq} = \left(\frac{q}{10.21 \cdot d_i^{\frac{1}{3}}}\right)^{\frac{6}{7}}$$

Where: D_e = Equilibrium depth for particle size, i

The Thomas method solves the equilibrium depth equation for each grain class, and sets the active layer thickness to the larges, which is the maximum possible scour.

Splitting the Active Layer: Cover and Subsurface Layers

Thomas' main innovation was dividing the active layer into two sub layers: a **cover layer** and a **subsurface layer**. The algorithm computes transport capacity based on the entire active layer, but he cover layer coarsens independently and regulates erosion from the rest of the active layer (the subsurface layer).

At the beginning of the bed mixing stage, HEC-RAS computes a new active layer thickness – based on the equilibrium depth. HEC-RAS carries the cover layer over from the previous time step but re-creates the sub-surface layer each time based on the new active layer thickness computed by equilibrium depth.

Equivalent Particle Diameter:

The Thomas function (and the Copeland method after it) computes cover layer armoring based on an **equivalent particle diameter** principle. This **equivalent particle diameter** can be difficult to conceptualize, but is central to understanding the algorithm.

The **equivalent particle diameter (d_{eq})** converts the mass of each grain class into an equivalent *thickness*, expressed as a fraction or multiple of the grain class diameter. For example, if the large (grey) grain class in Figure 2-16 were spread evenly over the control volume, it would form a layer approximately half the particle diameter thick (half an equivalent particle diameter or $0.5d_{eq}$). Likewise, if the medium (brown) grain class in the cover layer (Figure 2-16) would form a layer approximately 40% of its diameter thick if spread evenly over the entire control volume (d_{eq}=0.4). The **equivalent particle diameter** converts the cover layer mass of each grain class into a thickness, normalized to the grain class diameter.

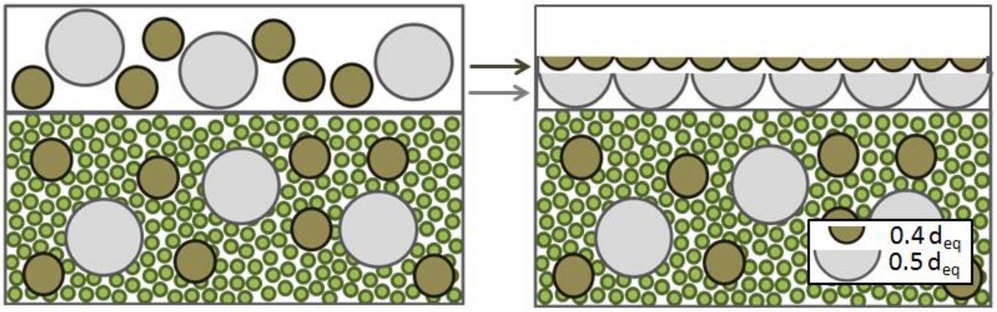


Figure 2-16: Example, idealized, three grain class cover and subsurface layer demonstrating the equivalent particle size principle

Armoring Ratio:

The Thomas and Copeland methods both use the equivalent particle diameter to compute an ***Armor Ratio***. The Armor Ratio is a coefficient between 0 and 1, which reduces the sediment deficit HEC-RAS will erode from the sub-surface layer, if the cover layer includes enough coarser material.

The Thomas algorithm has five basic steps:

1. Compute Sediment Deficit by Grain Class: First HEC-RAS computes transport capacity for each grain class and compares it to supply. If capacity exceeds supply, it tries to erode the deficit from the bed.

2. Remove the Grain Class Mass from the Cover Layer: If the cover layer contains the enough of the grain class, HEC-RAS removes the entire deficit from the cover layer. If the cover layer does not have enough of the grain class to satisfy the deficit, HEC-RAS removes all of the grain class from the cover layer, and then tries to remove the balance from the sub-surface layer.

3. Sum the Equivalent Particle Diameters of all coarser grain classes in the cover layer: Before HEC-RAS removes any sediment from the sub-surface layer, it computes the

equivalent particle diameter of every *coarser* grain class in the cover layer, and then sums them.

For example, in the simplified substrate in Figure 2-16, if HEC-RAS tried to remove the smallest grain class (green), it would sum the equivalent diameter of the two coarser grain classes. HEC-RAS uses the sum of the equivalent grain diameters for cover layer grain classes, coarser than the eroding grain class ($\Sigma d_{eq}=0.9$ in Figure 2-16) to compute armor layer regulation (i.e. reduce the amount of deficit the model can erode from the sub-surface layer).

4. Compute an Armoring Ratio: The Thomas method computes an armor ratio from the cumulative coarser equivalent diameter according to the relationship in Figure 2-17. This relationship interpolates between a low bound, where the cover layer has no effect on erosion and an upper bound where the armor layer totally prevents erosion from the subsurface layer.

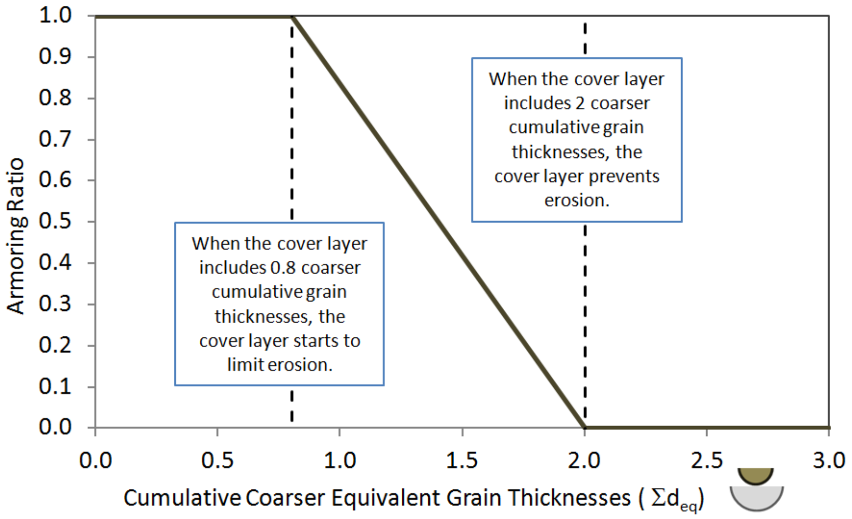


Figure 2-17: Armor ratio relationship used in the Thomas method.

Low Bound: If there is less than one total cumulative equivalent diameter of coarser material in the cover layer ($\Sigma d_{eq}<1$), then the cover layer can't be continuous. For $\Sigma d_{eq}<0.8$, 20% of the subsurface layer is exposed. At this thickness, the method assumes the cover layer has too many gaps to regulate the subsurface layer. The Thomas method does not reduce erosion for this case.

High Bound: On the other extreme, if the sum of the equivalent grain diameters of coarser grain classes is greater than 2 ($\Sigma d_{eq}>2$) the cover layer will not allow any erosion of that grain class from the sub surface layer. This end point comes from broad empirical evidence that flow cannot 'suction' fine sediment through more than two grain diameters of immobile armored layer.

The Thomas method interpolates linearly between these end points:

No Armoring (Armor Ratio = 1 →erosion =deficit) for $\Sigma d_{eq}<0.8$

and

No Erosion (Armor Ratio = 0 → erosion =0) for $\Sigma d_{eq}>2$.

5. Erode the grain class from the sub-surface layer, reducing the deficit by the Armor Ratio: HEC-RAS multiplies the sediment deficit for each grain class by the armor ratio such reducing erosion for each grain class (i) according to the expression:

   $$\text{Erosion}_{(i)} = \text{Armor Ratio}_{(i)} * \text{Sediment Deficit}_{(i)}$$

   For the example in Figure 2-16, where $\Sigma d_{eq}=0.9$, the Thomas method returns an armor ratio of 0.91, and HEC-RAS would remove 91% of the deficit of the fines grain class from the subsurface layer.

Cover Layer Reset: Destruction or Burial

The cover layer evolves during the simulation, coarsening or fining in response to capacity and upstream load. However, there are two situations which cause the cover layer to 'reset,' which introduce bed gradation non-linearity. Understanding these processes will help interpret bed gradation results.

Cover Layer Destruction:

The cover layer can erode until it is too thin to regulate the bed. At that point, the Thomas method resets the layer, mixing it with the rest of the active layer, and cutting a new, thicker cover layer from the mixed active layer bed material.

At the beginning of *each* computation time step, HEC-RAS computes the **stratification weight** of the cover layer. The **stratification weight** is simply the combined **equivalent particle diameter** of *all* grain classes in the cover layer. If the stratification weight, the total cumulative equivalent particle diameter is less than 0.5, HEC-RAS destroys the cover layer. Thomas based the 0.5 threshold on Harrison's (1950) experiments, which demonstrated that equilibrium sediment transport dropped when 40% of the bed surface was covered in his flume experiments.

Cover layer destruction can generate gradation results that are difficult to interpret, like those in Figure 2-18. This model eroded monotonically, and the capacity was high enough that the cover layer periodically slowed erosion but never stopped it. Therefore, as the bed eroded, the cover layer periodically coarsened, but as it coarsened it also thinned. When the cover layer thinned to less than 0.5 d_{eq}s, it reset, instantly fining as it adopted the gradation of the parent material. So, while the cover layer algorithm can form a static armor layer and keep the model from over-predicting erosion in graded sediment systems, cover layer dynamics also make it difficult to track gradation temporally or longitudinally (Gibson and Pridal, 2015).

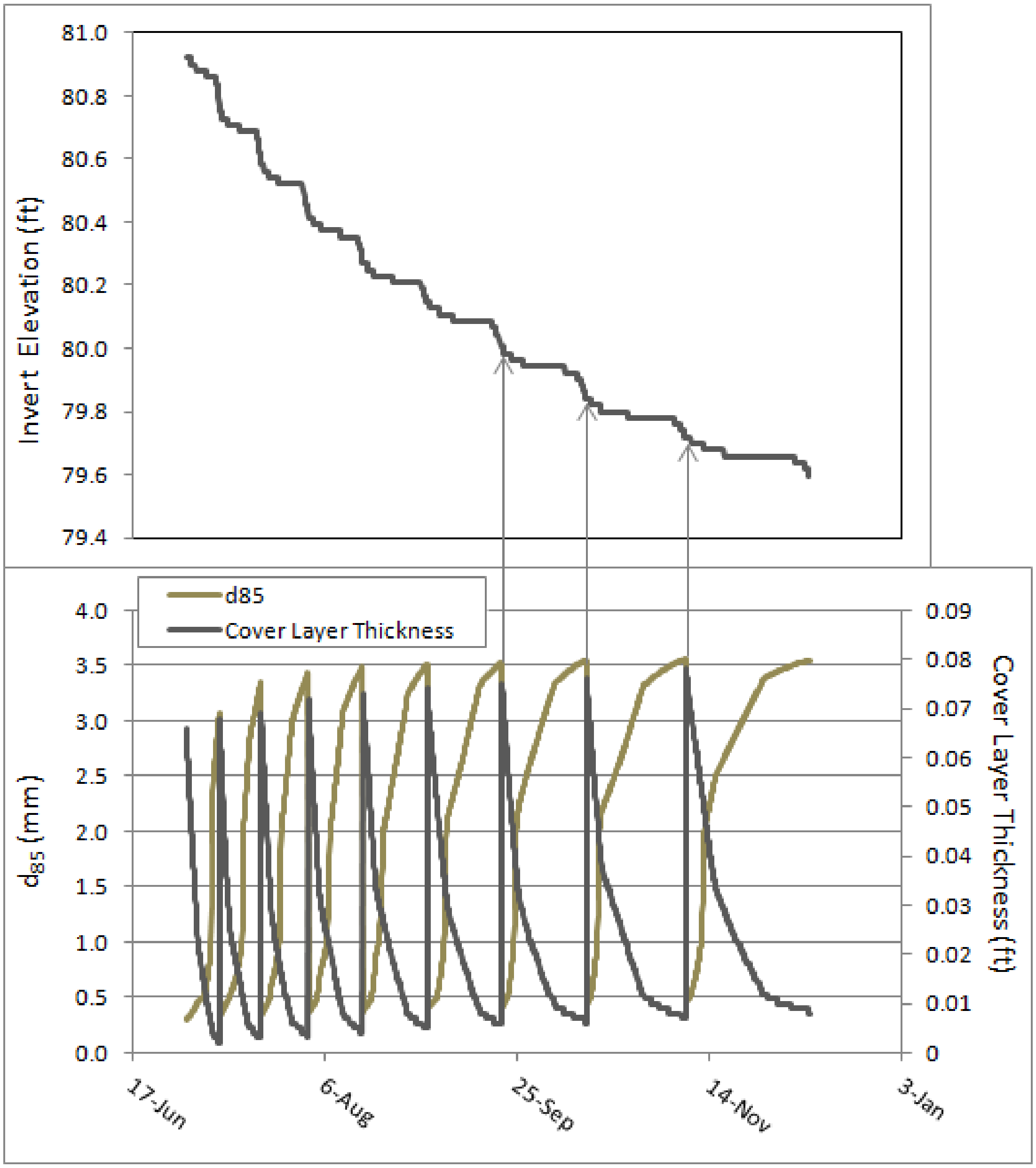


Figure 2-18: Degrading bed computed with the Thomas method which coarsens, thins and resets, never completely armoring. The periodic armor layer resets causes gradational oscillations.

Cover Layer Burial:

HEC-RAS also resets the cover layer if deposition buries it. If the cover layer grows to 2 ft thick, the Thomas method assumes that the cover layer no longer exists as a distinct stratigraphic layer, and mixes the bed, resetting the cover layer with sediment from the mixed substrate. This feature is helpful in rapidly changing environments that alternate between deposition and armoring erosion, but can also introduce non-linear shifts in the gradation output.

The HEC-6 User's Manual includes more discussion on this mixing method, calling it Method 2 (p. 25)

Copeland Mixing Method (Exner 7)

The Thomas method was developed for coarse, well graded systems. It was initially developed for the Snake River, then generalized for other systems. But it tended to over predict armoring, and, therefore, under predict erosion on finer systems (USACE, 1993, Thomas, 2010). Copeland (1992) adjusted the method, to make it more applicable to sand beds. The Copeland method follows the Thomas method in concept and approach. It subdivides the active layer into cover and subsurface layers, allowing the gradation of the former to regulate erosion from the later. The Copeland method adds a "bed source" layer, but is still, practically, a three layer method, like the Thomas method. It computes an **armor ratio** based on the **equivalent particle diameters** of coarser grain classes. But the Copeland method changes some of the equations and assumptions, and generally allows more scour, making it popular for large, sand bed rivers.

There are three main differences between the Copeland and Thomas methods:

1. The Copeland method doesn't compute active layer thickness with the **equilibrium depth** concept. Instead it starts at the maximum or 2 d90 or 15% of the water depth.

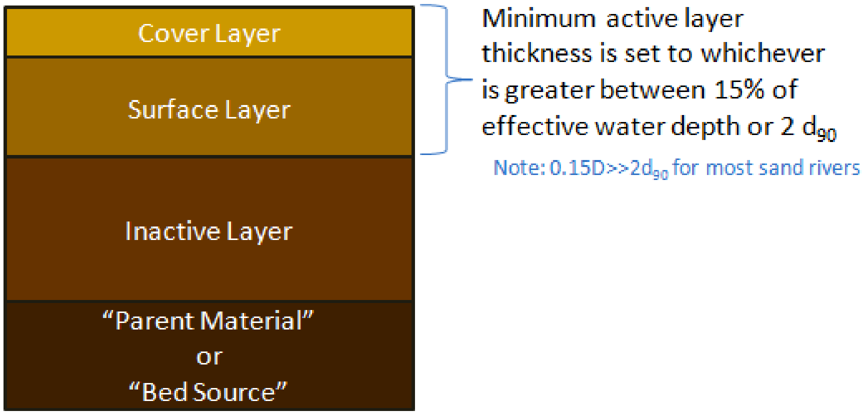


Figure 2-19: Schematic of the Copeland (1992) method.

2. The Copleand method replaces the linear interpolation between $0.8 < \Sigma d_{eq} < 2$ (from Figure 2-17) with a polynomial.

$$AR = -0.026*(\Sigma d_{eq})^3+0.28*(\Sigma d_{eq})^2-1.07*(\Sigma d_{eq})+1.40$$

   This relationship has the same basic trend as the Thomas relationship but (Figure 2-20) starts armoring at a smaller Σd_{eq} ($0.4 < \Sigma d_{eq}$, following the Harrison observation) but not fully preventing subsurface erosion until Σd_{eq} is much higher ($\Sigma d_{eq} > 4$).

3. The cover layer is limited to a maximum thickness of $3d_{90}$. However, burial does not reset the cover layer.

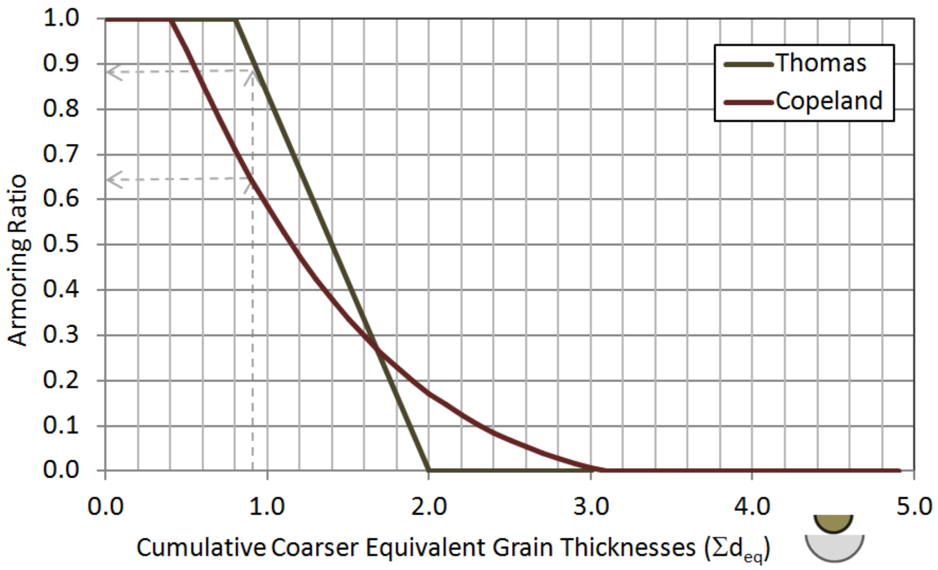


Figure 2-20: Armor ratio equations for the Thomas and Copeland armoring methods.

The main differences between the Thomas and Copeland methods are summarized in Table 2-2.

Table 2-2: Differences Between the Thomas and Copeland Armoring Methods.

Thomas (Ex 5)	Copeland (Ex 7)
Active Layer (L_a) thickness based on Equilibrium Depth (D_{eq})	Active Layer (L_a) thickness based on 15% of Water Depth or $3d_{90}$.
Linear Armor Ratio	Polynomial Armor Ratio.
Armors more rapidly, ↓ erosion	Armors more gradually, ↑ erosion

Active Layer Mixing Method

The Thomas and Copeland methods are sophisticated, multi-layer approaches to bed mixing and armoring. They are also complicated, doing a lot of math behind the scenes, providing results that can be difficult to interpret. Because HEC-RAS computes transport capacity for each grain class independently, these methods limit erosion while computing transport that reflects the subsurface gradation, which is generally observed in rivers.

However, a simplified two-layer active layer method (Figure 2-13) is also included in HEC-RAS. A simple active layer approach has obvious disadvantages including less vertical resolution and no explicit armoring factor. Use it with caution. However, it is a more intuitive and transparent method, it can form a coarse or fine active layer, and, with an appropriate exchange increment, it may be preferable in some cases for modeling mobile armor systems (Gibson and Piper, 2007).

Hirano (1971) is often credited with introducing the "active layer" approach for sediment transport modeling, though HEC was doing similar work at the same time. This approach divides the substrate into an active (mixing or surface) layer, available for transport, and an inactive layer that has no influence on the computations for a given time step.

Selecting an Active Layer Thickness

Active Layer Exchange Incremnts

As the bed aggrades and degrades the sediment passes the active layer resets to a specified thickness (e.g. the d_{90}), and the layers pass material between them. If the bed erodes, the inactive layer sends sediment, an "**exchange increment**" to the active layer, to restore it. If the bed deposits, the active layer resizes and sends an **exchange increment** to the inactive layer.

The gradational composition of the erosion exchange increment is straight forward. The material the inactive layer sends to the active layer has the gradation of the inactive layer, and is mixed with the active layer sediment.

The depositional case is more complicated because the deposited material has a different gradation than the active layer. Three basic options have been proposed.

1. Mixed active Layer/Deposition Gradation. Adds the deposited material to the active layer, mix them, and send an exchange increment with the fully mixed gradation to the inactive layer. This method assumes the depositing material and the active layer are mixing fully at tight temporal scales.

2. Ambient Active Layer Gradation: Remove the exchange increment from the active layer and send it to the inactive layer first, then add the deposited material to the active layer and mix them. This method assumes static stratigraphy, that the deepest material, which would have the active layer gradation, would become inactive.

3. Deposited Material Gradation: Early work on dynamic armoring recognized that actively transporting channels maintain an armor layer even in depositional environments. But the previous two methods would cause depositing beds to fine, burying the cover layer (Parker *et al.* 1991a,b). So this method sends the deposited material directly to the inactive layer. This maintains a coarse cover layer, but does not allow any gradational evolution in the active layer.

Toro-Escobar *et al* (1996) tested these hypotheses and found that the was not composed entirely of the active layer or bed load gradations, but it also wasn't proportional (e.g. fully mixed). They found that method 3 was closer to their observations than method 2, but was not sufficient. So they proposed a depositional exchange increment during deposition was composed of 30% active layer material and 70% deposited material. This maintains a coarse cover layer better than methods 1 and 2 above, but also allows gradational evolution.

HEC-RAS follows this approach, passing depositional exchange increments to the inactive layer that are 30% active layer material and 70% depositional material. For example, if HEC-RAS deposited 10 tons of material in a time step (assuming the active layer remained the same thickness) it would transfer 3 tons from the active layer to the inactive layer and add 7 tons of the deposited material directly to the inactive layer. It would then mix the remaining 3 tons of the deposited material into the active layer.

Surface Based Transport Equations and the Active Layer Method: The Thomas and Copeland methods subdivide the active layer to address competing principles in sediment transport:

1. Transporting sediment generally has the same gradation as the subsurface layer, so transport capacity must be computed based on subsurface gradations.

2. The cover layer regulates erosion.

These bed mixing and armoring algorithms allow HEC-RAS to attribute the transport potential of classic transport functions based on subsurface gradations, computing transport capacity based on these gradations, without over predicting erosion.

In the years since these algorithms were developed, a different conceptual approach to graded bed transport has emerged: surface-based transport functions. Parker (2008) suggested that basing transport functions on surface gradations automatically account for dynamic armoring processes.

Wilcock and Crowe (2003), which is included in HEC-RAS, is a **surface-based** equation in this tradition. It accounts for inter-particle interactions like hiding and sand-dependent gravel transport explicitly, but builds the armor layer regulation into the equation implicitly, by basing transport on armor layer gradations. Therefore, when using the Wilcock and Crowe (2003) equation in HEC-RAS, always use the active layer Mixing algorithm. Using Thomas or Copeland with a surface-based transport equation double counts armoring and miss-matches conceptual frameworks.

Bed Change

HEC-RAS computes sediment mass balance. Therefore, final erosion or deposition computations are masses. It is relatively straight forward to convert mass to volume (multiply by the unit weight or use porosity and density). However, converting volume change in a control volume to area change is not trivial. And then, applying the area change to the cross section to get a new cross section shape that makes physical sense requires additional assumptions and algorithms.

Volume Change → Area Change Conversions

The simplest way to convert volume change to cross section change is to consider each cross section and its control volume independently (this is called the Single CV method in HEC-RAS). However, when distributing the volume longitudinally, it is advantageous to spread the volume out over the control volume in a way that transitions between the cross sections.

The other bed changes methods in HEC-RAS follow HEC6, assuming that the volume change is not equally distributed over the control volume. In order to compute a smooth transition between cross sections, HEC-RAS assumes the mass is distributed in a “wedge”, tapering out between the maximum volume change at the central cross section, to zero at the upstream and downstream cross sections Figure 2-21. This assumption allows HEC-RAS to use a couple common numerical approximations to compute volume from irregular areas and, in this case, the inverse.

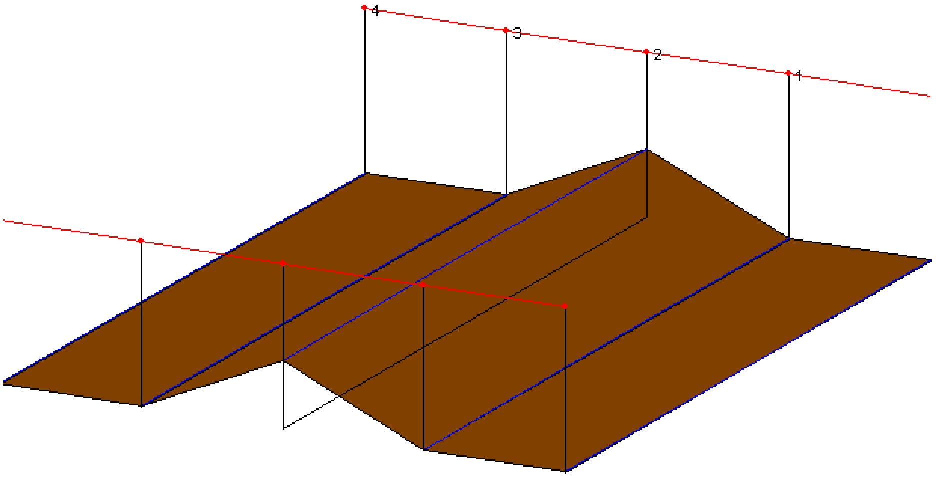


Figure 2-21: "Wedge" used to distribute erosion or deposition volume longitudinally over the control volume.

Single Control Volume Method (Single CV)

The Single Control Volume Method (Single CV) is the simplest method to convert volume change to cross section area change. It simply ignores the upstream and downstream cross sections. So the area change is simply the volume change divided by the length of the control volume (the half the downstream distance of the upstream and current evaluated cross sections) and the wetted, mobile, cross section width, such that:

$$\Delta Area = \frac{\Delta Volume}{W_2 * \left(\frac{L_{32}}{2} + \frac{L_{21}}{2}\right)}$$

Where:

W_2 = the wet, mobile, width of the cross section or the top width of the water within the movable bed limits,

L_{32} = the downstream distance associated with the upstream cross section (XS_1), and

L_{21} = the downstream distance associated with the cross section evaluated (XS_2).

Simpson's Rule

Simpson's rule(s) approximate of a function by fitting a polynomial through representative points. They are particularly useful for approximating the volume between three irregular shapes, when no other information is available on the transition between them. Because the length-volume relationship along a river is an irregular, but continuous function with periodic observations (cross sections), hydrographers often use Simpson's rule to compute the volume associated with a three-cross sections sequence. The simple insight of Simpson's result is that a parabolic fit weights the central observation (e.g. XS_2) in a simple ratio to the bounding observations (the upstream and downstream cross sections). The version of Simpson's rule used in HEC-RAS (following HEC6) is sometimes calls Simpson's

Second rule or the 3/8ths. It is actually designed to find the volume from four equally spaced observations, but is modified to account[8] for three irregular spaced cross sections.

$$\Delta Area = \frac{\Delta Volume}{\left(\frac{1}{8}(W_3 * L_{32}) + \frac{3}{8}(W_2 * L_{32}) + \frac{3}{8}(W_2 * L_{21}) + \frac{1}{8}(W_1 * L_{21})\right)}$$

End Area Method

The end area method uses the wedge concept, distributing the volume longitudinally along the cross section, tapering upstream and downstream to zero ∆Area points at the bounding cross sections. But unlike Simpson's rule, the end-area method just assumes linear transitions. So:

$$\Delta Area = \frac{\Delta Volume}{\left(\frac{(W_3 + W_2)}{2}\frac{L_{32}}{2} + \frac{(W_2 + W_1)}{2}\frac{L_{21}}{2}\right)}$$

Incidentally, did you ever spend any time in the 1D Simpson's rule code? I'm documenting it

The model converts mass to volume and spreads the volume change upstream and downstream from the cross section in a "wedge", to determine the area change at the cross section. An exaggerated bed change is shown at river station 2, in Figure 2-21. HEC-RAS then converts the area change into cross section change.

Once HEC-RAS computes sediment surplus or deficit and applies the limiters, it computes a final mass to erode or deposit from the control volume. HEC-RAS adds or removes mass by adjusting the cross-section station/elevation points.

Combining Area-Volume Methods

HEC-RAS computes volume from cross section area change or vice versa in two places. It uses these methods to compute the cross-section change, and also bed material accounting. Earlier versions of HEC-RAS followed HEC 6, using Simpson's rule for the cross section change and a rectangular, single cross section, control volume (Single CV) for bed mixing. This sometimes generated volume errors and numerical artifacts, which could include cross section deposition (↑A) while the Exner routines computed negative mass.

Recent versions of HEC-RAS are backward compatible, maintaining the legacy computational approach. But new models use Simpsons' rule by default. Additionally, users can select to apply any of the three approaches to both bed change and mixing, or select the legacy method ("Backward Compatible" – not recommended)

---

[8] This approach was adopted from HEC6 and was developed by W. Tony Thomas.

Modifying the Cross Section

Veneer Method

By default, HEC-RAS uses the "veneer method" to change cross sections. The veneer method changes all the wetted nodes within the movable bed limits the same vertical distance. Currently the only method available for translating erosion or deposition into changes in the cross-section shape is to deposit or erode each wetted, movable cross section station/elevation point equally. Following these guidelines, an example of a cross section update for erosional or depositional cases is included in Figure 2-22. The points that move are both within the erodible bed limits and beneath the water surface elevation. For the erosion case, a duplicate point is generated if the mobile bed limit is wet.

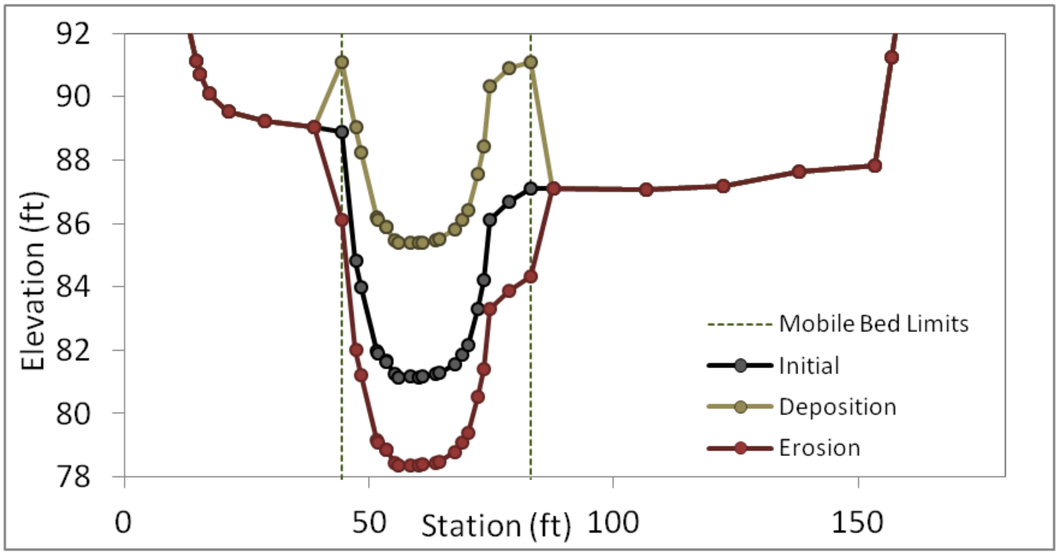


Figure 2-22: Example of veneer method, the standard bed change approach. HEC-RAS raises or lowers all wet nodes within (and including) the movable bed limits the same increment to reflect deposited or eroded mass.

HEC-RAS will not erode any node included in an ineffective flow area regardless of the bed change method or where the erodible bed limits are placed. Water velocity in an ineffective flow area is, by definition, zero. Therefore, scour cannot occur at the cross section points in an ineffective flow area. However, HEC-RAS will allow deposition in ineffective flow areas.

There are a couple of exceptions to these basic rules however. First, an alternate method which allows overbank deposition is available. This option handles erosion in precisely the same way as the default method, confining erosion to the movable bed limits. For the depositional case, however, HEC-RAS distributes bed change equally between all of the wetted points regardless of whether they are between the erodible bed limits or not (Figure 2-23). The principle behind this method is that eroding velocities or shears are limited to the channel, but deposition can occur in the floodplain where slowly moving water allows material to settle out.

Finally, HEC-RAS includes a depositional method that preferentially deposits in deeper parts of the cross section (Figure 2-24). This method can be useful in reservoirs, particularly in the prograding delta, where sand fills the channel. However, use it with care. Shear is often highest where the water is deepest, so depth dependent deposition requires low energy-high supply conditions.

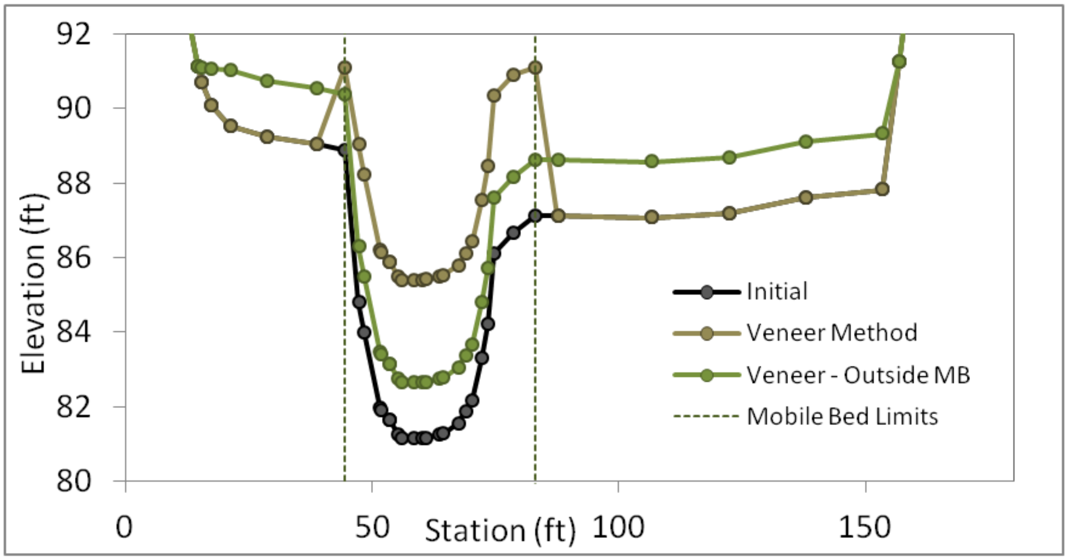


Figure 2-23: Deposition with the basic veneer method and the overbank deposition method.

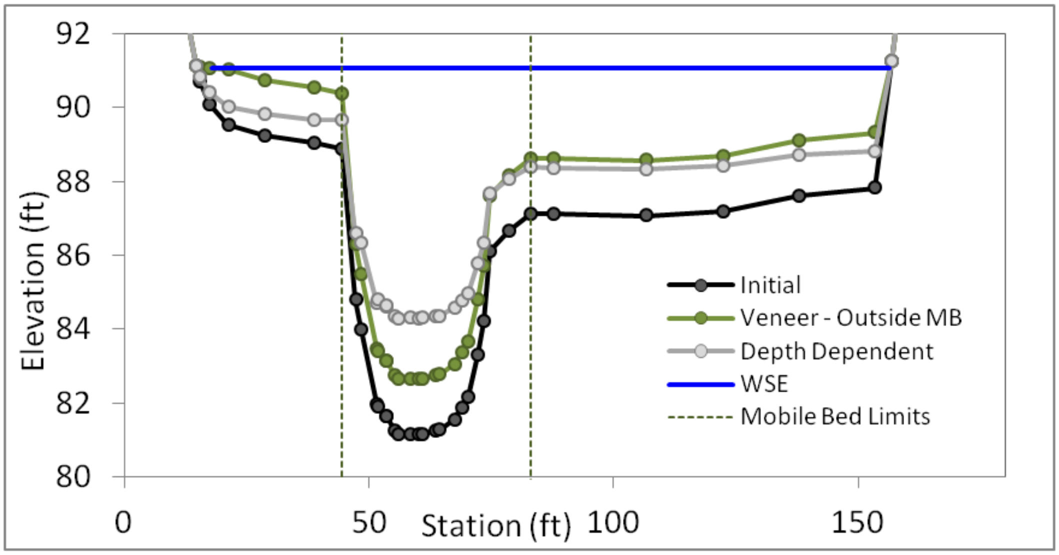


Figure 2-24: Alternate bed change method that confines erosion to the erodible limits but allows deposition at any wetted node.

Cohesive Transport

Most of the sediment transport equations were developed with sand and/or gravel data. Therefore, most silt and all clay particles are outside of the range of applicability of the sediment transport functions implemented in HEC-RAS. In most systems, these particles are *wash load,* material only found in the bed in trace amounts, because transport capacity always exceeds supply. Some modelers will just ignore fines as *throughput load*, arguing that if fines never interact with the bed in the model reach, the model is insensitive to them and they add unnecessary complexity and parameters to the model. However, sometimes fines must be modeled explicitly. In reservoirs and other backwater or low energy zones, silt and clay can deposit and clay lined channels, both natural and engineered, can erode, causing local and downstream problems.

Fine sediment transport is further complicated by electrostatic and electrochemical forces. These particles are not just outside of the empirical range of the equations, but they often erode and deposit by fundamentally different processes. These forces cause fine particles, particularly clay, and "stick" to the bed surface, so that fine erosion and deposition are often not primarily functions of sediment size. These processes make fine deposition and erosion fundamentally different than the cohesionless sand and gravel transport.

HEC-RAS considers the smallest five grain classes 'fine sediment.' HEC-RAS applies the **cohesive method** selected to these grain classes. In the default grain classes, these five grain classes are the clay and silt classes, and are all finer than 0.625 mm. If the user edits these, the cohesive methods will still apply to the first five grain classes, regardless of their size. However, if more than 20% of the active layer is cohesive, then the model considers the sediment 'matrix supported,' assuming cohesive sediment is abundant enough to fill the voids and regulate the erosion rate of all particles.

HEC-RAS includes three cohesive methods: applying the standard transport equations, or two different implementations of the Krone and Partheniades approach.

Standard Transport Equations

The default option for silt and clay simply applies the selected transport function for the fine material as well. The transport equation will extrapolate well outside its derived range and usually compute enormous (often unreasonable) transport potentials. These transport potentials should not be considered remotely representative. They can be useful, however, to model fine sediment as wash load. With huge transport potentials, even a tiny amount of silt and clay in the active layer will produce essentially unlimited sediment transport capacity. This method can route fine wash load through the system, treating fine material as throughput load.

Krone and Partheniades Methods

If the model objectives and systems morphology make cohesive erosion and deposition important, however, the standard transport equations are not sufficient. The Krone and Partheniades equations are simpler than the cohesionless transport functions, building much of the predictive power into several, site specific parameters.

Earlier versions of HEC-RAS included a version of the Krone and Partheniades cohesive approach. This approach differed from the algorithm implemented in HEC 6 and, subsequently HEC 6T. Both are defensible, taking alternate approaches applying the Partheniades scour relationship to a mixed bed. Therefore, the original HEC-RAS algorithm was retained but the HEC 6T algorithm was added as an option. Both methods apply the Krone and Partheniades equations to compute deposition and erosion rates in the same way.

HEC-RAS uses either the Krone equation to compute deposition or the Partheniades equations to compute erosion and selects between them based on the bed shear stress. Two user defined shear thresholds define three cohesive transport conditions: Deposition, Particle Erosion, and Mass Erosion. The user defined thresholds are:

τ_c: Critical shear threshold for particle erosion

τ_m: Critical shear threshold for mass erosion

where $\tau_c \leq \tau_m$. HEC-RAS computes a bed shear stress (τ_b) for each cross section and compares it to these two thresholds, determining the appropriate cohesive process, and applying the appropriate equation (Figure 13-9).

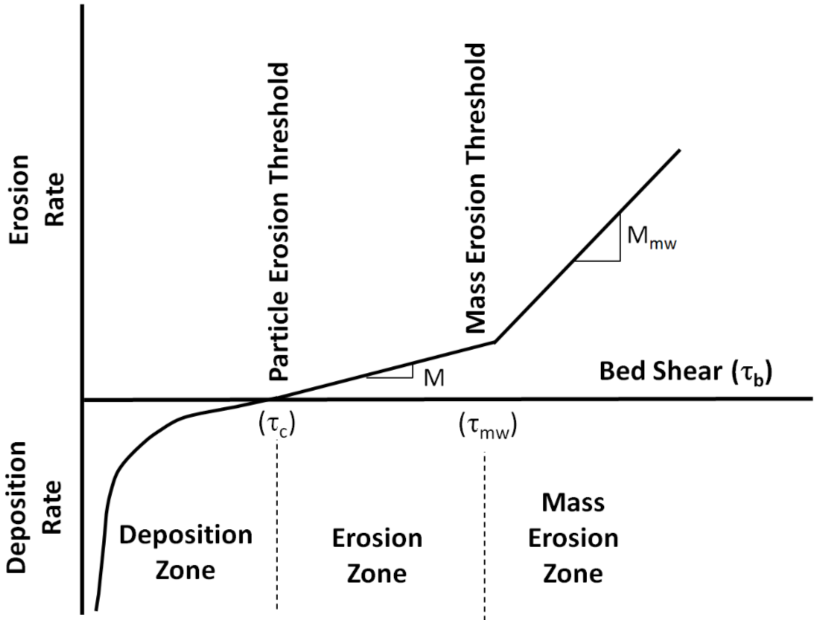


Figure 2-25. Schematic of cohesive sedimentation zones and processes as a function of shear.

Previous models often included a fourth zone, an equilibrium zone, which neither eroded nor deposited. This approach subdivided τ_c into deposition τ_d and erosion τ_e shears. In the intermediate zone between these ($\tau_d<\tau_b<\tau_e$) binding forces exceeded the erosion forces, but turbulence was sufficient to keep transported particles in suspension. This approach computed no bed change if bed shears fell in this equilibrium zone. More recent work has caused this concept to fall out of favor (Sanford and Halka, 1993). Therefore, HEC-RAS uses a single critical shear threshold (τ_c), above which particles erode and below which they deposit.

Deposition

HEC-RAS deposits cohesive sediment based on Krone (1962). Krone's observed that suspended sediment decreased logarithmically, in his experiments, for concentrations less than 300 mg/l, quantifying the deposition rate with the equation:

$$\left(\frac{dC}{dt}\right)_d = -\left(1-\frac{\tau_b}{\tau_c}\right)\frac{V_s C}{y}$$

where: C = sediment concentration
t = time
τ_b = bed shear stress
τ_c = critical shear stress for deposition

Vs = fall velocity
y = water depth (Effective Depth in HEC-6)

This equation yields an exponential deposition relationship, where the deposition rate increases non-linearly as bed shear drops farther below the critical shear:

$$\int \frac{dC}{C} = \int -\left(1-\frac{\tau_b}{\tau_c}\right)\frac{V_s}{y}dt \rightarrow C = C_o e^{\left(-\left(1-\frac{\tau_b}{\tau_c}\right)\frac{V_s t}{y}\right)}$$

Because of the logarithmic assumption the Krone equation only requires one empirical coefficient, the critical shear (τ_c).

If the calculated bed shear (τ_b) is less than the critical erosion shear (τ_c) HEC-RAS will deposit transporting cohesive sediment based on this equation. The equation is not applicable for shear stresses greater than the depositional threshold.

As Krone (1962) recognized, the cohesive deposition rate is also dependent on the flocculation rate, which is a function of the sediment concentration and the water chemistry. Many sophisticated coupled flocculation-deposition models account for these processes. However, HEC-RAS does not attempt to compute flocculation. Therefore, the grain size distribution should reflect the distribution of flocculants rather than discrete grains, even though standard particle sized distribution methods tend to report the latter.

Erosion

Erosion is more difficult to compute than deposition. The cohesive erosion equations are far more empirical. HEC-RAS computes cohesive erosion based on Partheniades (1962). Partheniades (1962) argued that the force resisting erosion is mainly electrostatic in nature, since the average electrochemical force exerted on a clay particle is a million times greater than the average weight of the particle. Therefore, cohesive erosion is not based on particle size, but an empirical 'erodibility' that accounts for the other binding processes.

Partheniades (1962) modeled cohesive erosion rates as a pair of linear functions of bed shear. When bed shear exceeds critical shear, particle erosion begins as the shear stress removes individual 'particles' or flocs are removed. This particle erosion rate increases, approximately, a linear function of shear.

However, if bed shear gets high enough, it begins to remove clods from the bed, introducing a non-linear inflection point (τ_{mw} in Figure 2-25) in the erosion rate. This has historically been called 'mass wasting' or 'mass erosion.' The terminology is ambiguous, but HEC-RAS retained it for continuity. Erosion rate above the mass erosion threshold is also linear, but increases as a function of shear at a different (usually higher) slope (Figure 2-26).

Particle Erosion ($\tau_c < \tau < \tau_{mw}$)

According to the Partheniades equation (1965):

$$\left(\frac{dm}{dt}\right)_e = M\left(\frac{\tau_b}{\tau_c}-1\right)$$

where: m = mass of material in the water column
t = time
τ_b = bed shear stress
τ_c = critical shear stress for erosion
M = empirical erosion rate for particle scour

Therefore:

$$\int dm = \int M\left(\frac{\tau_b}{\tau_c}-1\right)dt \rightarrow m = M\left(\frac{\tau_b}{\tau_c}-1\right)t + m_o$$

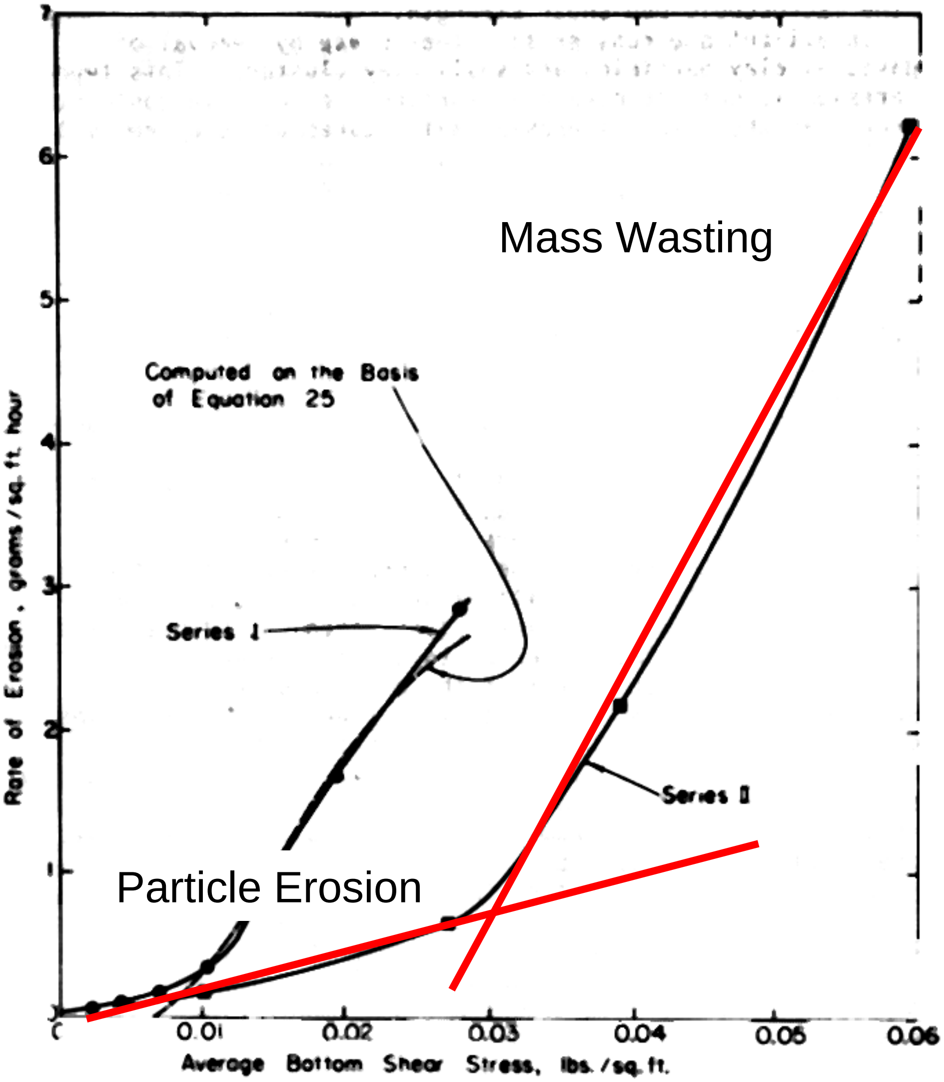


Figure 2-26. Shear stress - rate of erosion relationship from Partheniades (1965).

This equation essentially interpolates cohesive erosion between the lower and upper end of the particle erosion zone, based on an empirical, linear, user specified coefficient, the **Erodibility Coefficient (M)**.

Mass Erosion $(\tau_m<\tau)$

The Partheniades approach is a piece-wise linear erodibility model. Beyond the mass erosion threshold, the cohesive algorithm extrapolates erosion rates from the maximum computed particle erosion rate, with a similar linear extrapolation, based on a new **Mass Erosion Erodibility Coefficient M_{MW}.**

Therefore, the full piecewise-linear model, in three zones is:

$$Erodibility = \begin{cases} 0 & , \quad \tau_c < \tau \\ M\left(\frac{\tau_{MW} - \tau_c}{\tau_c}\right) & , \quad \tau_c < \tau \leq \tau_{MW} \\ M\left(\frac{\tau_{MW} - \tau_c}{\tau_c}\right) + M_{MW}\left(\frac{\tau - \tau_{MW}}{\tau_c}\right), & \quad \tau_{MW} < \tau \end{cases}$$

Where τ_c is the critical shear where erosion begins, τ_{mw} is the critical shear where the higher shear erosion rate ("mass wasting") starts, M is the base erodibility rate (between τ_c and τ_{MW}) and M_{MW} is the "mass wasting" erodibility rate, which is associated with shears greater than τ_{MW}.

Erodibiltiy has units of Mass/Area/Time, so this approach computes the mass eroded from each cross section in each time step with:

$$Mass = \begin{cases} 0 & , \quad \tau_c < \tau \\ M\left(\frac{\tau_{MW} - \tau_c}{\tau_c}\right) * A * \Delta t & , \quad \tau_c < \tau \leq \tau_{MW} \\ M\left(\frac{\tau_{MW} - \tau_c}{\tau_c}\right) * A * \Delta t + M_{MW}\left(\frac{\tau - \tau_{MW}}{\tau_c}\right) * A * \Delta t, & \quad \tau_{MW} < \tau \end{cases}$$

$$Mass = M\left(\frac{\tau_{MW} - \tau_c}{\tau_c}\right) * Area + M_{MW}\left(\frac{\tau - \tau_{MW}}{\tau_c}\right) * Area$$

Modeling Note: Some changes were made to this approach and conversion factors between versions 5.0.7 and 6.0.

K_d vs M

There are two main versions of the excess shear, erodibility equation. The one used in the Parthenaides (1965) (the "dimensonless" form) equation normalizes the excess shear by the critical shear, making the shear term dimensionless. This approach has the intuitive advantage of giving the erodibility coefficient (M) the same units (Mass/Area/Time) as the Erosion rate:

$$Erodibility = M\frac{(\tau - \tau_c)}{\tau_c}$$

However there is an alternate version of the excess shear equation (the "dimensional" form, where erodibility is directly proportional to the simple excess shear.

$$Erodibility = K_d(\tau - \tau_c)$$

The ratio of erodibility to excess shear (K_d) is also called the "erodibility coefficient", but is not the same value. This expression is more intuitive (erodibility is directly proportional to excess shear), but makes the units of the coefficient less intuitive.

Different disciplines and practitioners tend to favor the different forms of this equation. Make sure you know whether the "Erodibility Coefficient" provided is Kd or M. HEC-RAS includes the option to input either, but setting these equations equal to each other demonstrates a pretty simple conversion between the two coefficients, M is simply the product of Kd and τ_c:

$$M\frac{(\tau - \tau_c)}{\tau_c} = K_d(\tau - \tau_c)$$

$$M = K_d\tau_c.$$

The 1D sediment calculations in HEC-RAS use the dimensionless (M) form of the excess shear equation, so if users enter Kd, HEC-RAS converts it to M.[9]

Estimating Cohesive Thresholds and Rates

The Importance of Site Specific Measurements

Applying the Partheniades method successfully requires estimating the shear thresholds and the erosion rates well. These parameters are site specific and can differ by five orders of magnitude between sites. Even within the same reach, τ_c, τ_{mw}, M, and M_{mw} can vary significantly between samples or at different depths. Therefore, the parameters can be determined experimentally (e.g. with a SEDFLUME apparatus) or are calibration parameters, adjusted to replicate measured bed change. These parameters cannot be estimated *a priori. Briaud et al.* (2001) summarize the situation well:

> "Today, no widely accepted correlation could be found (between cohesive erodibility and bulk soil parameters) after extensive literature reviews. If a correlation is likely to exist on one hand, and if it has not been found after forty years of effort on the other hand, the correlation must be complex…Considering all the problems associated with correlations, a direct measurement with the (erodibility testing) is favored." Briaud *et al*. (2001) *Journal of Geotechnical and Geoenvironmental Engineering*

Others concur:

> "With the vast number of factors involved in the determination of the erodibility of cohesive soils, it becomes necessary to test cohesive soils for critical shear stress for erosion and deposition rather than using soil properties for predicting threshold values

---

[9] HEC-RAS converts *Kd* to *M* as it writes the data file, so if you open the HDF file the *Kd* parameters in the interface will not match those written.

or using methods similar to those for coarse sediments." Huang et al. (2006) Erosion and Sedimentation Manual

"Unfortunately, the erodibility of cohesive sediment cannot be predicted on the basis of environmental parameters. As a consequence, researchers have developed various test apparatus to empirically measure sediment erodibility." Ravens (2007) *ASCE Journal of Hydraulic Engineering*

The cohesive literature is full of pronouncements that these parameters must either be measured or calibrated including: Roberts et al. (1998), McNeil et al (1996), Jepsen et al., (1997), Hanson (1996), Julian and Torres (2006), Hansen and Simon (2001), Kapen et al. (2007), Sanford and Maa (2001). Therefore, HEC-RAS does not include default parameters.

In the absence of robust calibration data, the Parthenaides method requires experimental data for reliable results. The SEDFLUME is the most common apparatus used to measure the cohesive parameters, usually computing parameters from Shelby tube samples. This device pushes a core of the cohesive bed material through the bottom of the flume. The Corp's sediment lab in ERDC, and several universities, can perform these experiments. ERDC's has a portable SEDFLUME that can deploy to a project site, avoiding sample disturbance during transport.

Bed Roughness Predictors

Hydraulic computations are sensitive to bed roughness. Bed roughness is a dynamic property and changes in response to sediment dynamics. If a fine pulse covers a coarse substrate, bed roughness will drop. As flow increases on sand rivers, bed form amplitude increases, increasing bed roughness, until the river passes into a plane bed regime which results in substantial drops in n-values.

Mobile bed sediment models simulate changes in bed gradation, which the model can use to compute roughness, computing feedbacks between sediment transport and bed roughness. HEC-RAS includes three **bed roughness predictors**, equations and algorism that compute manning's-n from hydraulics and sediment properties, including: Limerinos, Brownlie, and Van Rijn. The **bed roughnes predictors**, compute new manning's n values each time step, as the bed gradation and cross section evolve, which the program uses to compute hydraulics in the next computational increment.

Limerinos:

The Limerinos equation computes bed roughness based on grain roughness. It is primarily applicable to channels without active bed forms, where grain roughness is the primary source of bed roughness. It is the simplest equation, computing bed roughness as a function of the hydraulic radiI(R) of the channel and the d_{84} particle size (the partial size diameter two standard deviations above the mean):

$$n = \frac{0.0926R^{1/6}}{1.16 + 2.0\log\left(\frac{R}{d_{84}}\right)}$$

Brownlie:

The Brownlie (1983) computes bed roughness in sand beds where form roughness (bed roughness from bed forms) is much more important than grain roughness. The Brownlie method computes bed roughness base on the median particle size (d_{50}), the hydraulic radiI(R), the bed slope (S), and the geometric standard deviation of the mixture (σ). Because the Brownlie method is based on bed form mechanics it can shift between upper and lower regime relationships, causing non-linear changes in n-value:

Upper Regime:

$$n = \left[1.6940\left(\frac{R}{d_{50}}\right)^{0.1374} S^{0.1112}\sigma^{0.1605}\right]0.034(d_{50})^{0.167}$$

Lower Regime:

$$n = \left[1.0213\left(\frac{R}{d_{50}}\right)^{0.0662} S^{0.0395}\sigma^{0.1282}\right]0.034(d_{50})^{0.167}$$

Where R is the channel hydraulic radius in ft, d_{50} is the meidian particle size in ft, σ is the geometric standard deviation of sediment mixture: $\sigma = 0.5\ (\frac{d_{84}}{d_{50}} + \frac{d_{50}}{d_{16}})$.

Brownlie defined S as the bed slope, HEC-RAS approximates this variable with the energy slope computed at the cross section.

To determine which equation to apply, HEC-RAS uses the Brownlie criteria to identify the regime.

If S>0.006, HEC-RAS always assumes the system is in the upper regime. Otherwise, Brownlie computes an empirical parameter $F_g{}'$

$$F_g' = \frac{1.74}{S^{1/3}}$$

which can be compared to the grain Froude number F_g:

$$F_g = \frac{V}{\sqrt{(S_s - 1)\ g\ d_{50}}}$$

(where V is the flow velocity, g is the gravitational constant andS_S is specific gravity of sediment particles).

HEC-RAS selects the lower regime flow if $F_g \leq F_g'$ and upper regime if $F_g \geq F_g'$. An example application of Brownlie in HEC-RAS, for a sand pulse arriving at a gravel cross section, is included in Figure 2-27.

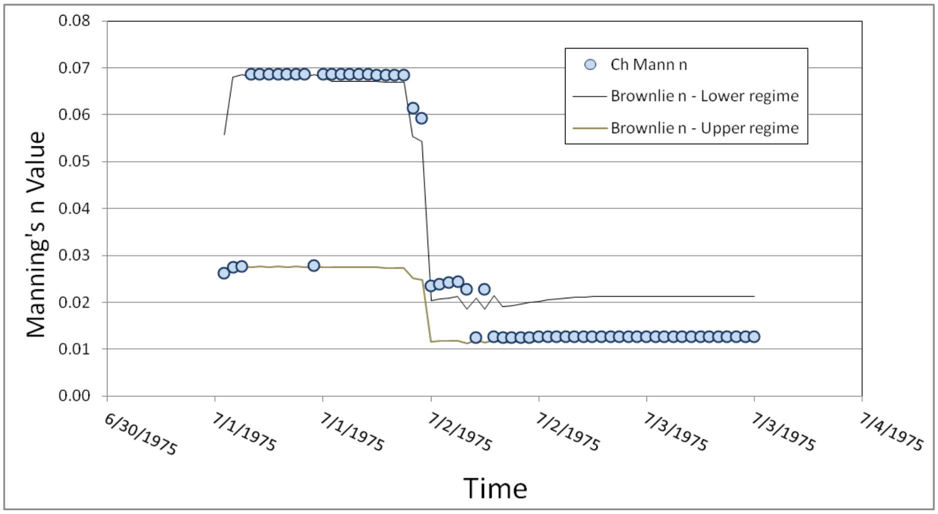


Figure 2-27: Bed roughness time series computed by Brownlie (in HEC-RAS) as a sand pulse passes through the cross section. First, when the sand pulse arrives at 7/2, the n value drops based on the gradation but stays lower regime. Eventually, the hydraulics change and it drops again, as the bed forms shift to upper regime.

van Rijn:

van Rijn *(1984)* is a more recent method based on the flume and field data, and it has a good predictive ability in the dune and plane bed regimes. Van Rijn computes bed forms dimensions and the equivalent bed roughness. It estimates a Chezy-coefficient, which HEC-RAS converts into a Manning n, from bed roughness from flow, sediment transport parameters. The van Rijn method computes four key dimensionless parameters to estimate bed-form roughness.

1. Particle Parameter:

$$d_* = d_{50}[\frac{(s-1)g}{\upsilon^2}]^{1/3}$$

Where d_{50} is the median particle size (ft), s is the specific gravity ratio ($s = \frac{\rho_s}{\rho}$),where ρ_s is sediment density, and ρ is the fluid density, g is gravitational acceleration and υ is kinematic viscosity.

2. Transport Stage Parameter:

$$T = \frac{(u_*^{'})^2 - (u_{*,cr})^2}{(u_{*,cr})^2}$$

Which $u_*^{'}$is grain bed-shear velocity:

$$u_*^{'} = \frac{g^{0.5}}{C'}\bar{u}$$

where $\bar{u}$ is mean flow velocity, C' is the Chezy-coefficient.

$$C^{'} = 18\log(\frac{12\,R}{3d_{90}})$$

where R is the hydraulic radius of the bed, $u_{*,cr}$ is the critical Shields parameter

$$u_{*,cr} = \sqrt{\frac{\tau_{cr}}{\rho}},$$

where τ_{cr} is the critical shear stress, and it is expressed as $\tau_{cr} = \tau_c^* \rho R g d_{50}$, and the dimensionless critical shear is computed with the equation

$$\tau_c^* = 0.5\,[0.22\,Re_p^{-0.6} + 0.06 * 10^{(-7.7\,Re_p^{-0.6})}],$$

where $R = \frac{\rho_s - \rho}{\rho}$, and $Re_p = \frac{\sqrt{gRD}\,D}{v}$, and ρ is the fluid density.

3. Bed-form dimensional parameters: The Bed-form parameter computes the bed form dimensions which the algorithm uses in the roughness computation:

$$\frac{\Delta}{h} = 0.11\,[\frac{d_{50}}{h}]\ \ [1 - e^{-0.5\,T}][25 - T]$$

$$\frac{\Delta}{\lambda} = 0.015\,[\frac{d_{50}}{h}]\ \ [1 - e^{-0.5\,T}][25 - T]$$

and it computes a ratio of the bed form height to the wavelength:

$$\psi = \frac{\Delta}{\lambda}$$

Where Δ is bed-form height, λ is bed-form length and is expressed as $\lambda = 7.3\,h$, and *h* represents flow depth. If $T \leq 0$ and $T \geq 25$, bed would be considered almost plane, and C′ calculated in step 2 will be used as Chezy-coefficient in step 4 for further calculation. ψ is bed-form steepness.

4. Equivalent roughness of bed forms: Finally, the algorithm uses the bed form height and height-to-wavelength ratio to compute a bed roughness.

$$k_s = 3d_{90} + 1.1\Delta[1 - e^{-25\psi}]$$

Van Rijn computes a Chezy-coefficient from the bed roughness:

$$C = 18\log\left(\frac{12\,R}{k_s}\right)$$

HEC-RAS converts the Chezy coefficient to a Manning's n (in English units) with the equation:

$$n = 1.49\,\frac{R^{1/6}}{C}$$

An example roughness time series, using van Rijn (in HEC-RAS unsteady sediment transport) for a sand delta rapidly prograding into a gravel cross section, is included in Figure 2-28.

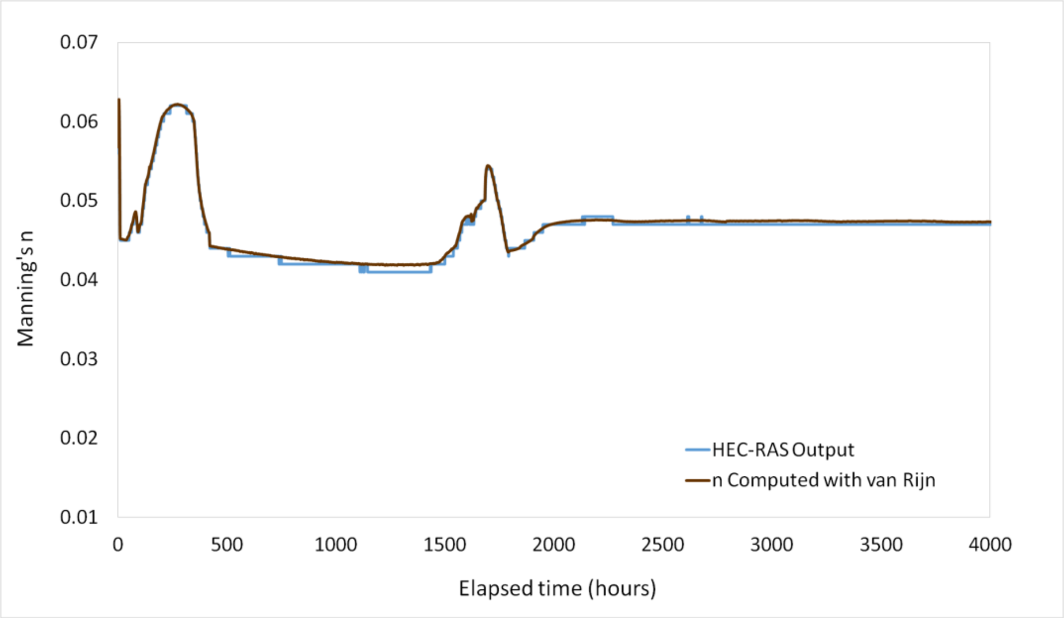


Figure 2-28: Bed roughness times series computed with HEC-RAS using the van Rijn predictor, compared to external computations.

Appendix A: Sample Transport Calculations

The following sample calculations were the basis for the algorism used in the HEC-RAS sediment functions. These example calculations use a single grain size. They were adapted in the HEC-RAS code for multiple grain sizes.

Ackers White

By Ackers-White (ASCE Journal of Hydraulics, 1973)

Input Parameters

Temperature, F $T = 55$ Average Velocity, ft/s $V = 2$

Kinetic viscosity, ft^2/s $\nu = 0.00001315$ Discharge, ft^3/s $Q = 5000$

Depth, ft $D = 10$ Unit Weight water, lb/ft^3 $\gamma_w = 62.385$

Slope $S = 0.001$ Overall d50, ft $d_{50} = 0.00232$

Median Particle Diamter, ft $d_{si} = 0.00232$

Specific Gravity of Sediment, $s = 2.65$

Constants

Acceleration of gravity, ft/s^2 $g = 32.2$

Solution

*note: Ackers-White required the use of d_{35} as the representative grain size for computations in their original paper. In the HEC-RAS approach, the median grain size will be used as per the 1993 update. The overall d_{50} is used for the hiding factor computations.

Hiding Factor from Profitt and Sutherland has been added for this procedure, but will be included as an option in HEC-RAS.

Computations are updated as per Acker's correction in Institution of Civil Engineers Water Maritime and Energy, Dec 1993.

Dimensionless grain diameter,

$$d_{gr} = d_{si}\left[\frac{g\cdot(s-1)}{\nu^2}\right]^{\frac{1}{3}} \qquad\qquad d_{gr} = 15.655$$

Shear velocity u

$$u_{star} = \sqrt{g\cdot D\cdot S} \qquad\qquad u_{star} = 0.567$$

Sediment size-related transition exponent n,

$$n = \left|\begin{array}{ll} 1 \quad \text{if } d_{gr} \le 1 & \\ \left(1-.056\cdot\log\left(d_{gr}\right)\right) & \text{if } 1 < d_{gr} \le 60 \\ 0 \quad \text{if } d_{gr} > 60 & \end{array}\right. \qquad\qquad n = 0.331$$

Initial motion parameter A,

$$A = \left|\begin{array}{ll} \left(\frac{0.23}{\sqrt{d_{gr}}}+0.14\right) & \text{if } d_{gr} \le 60 \\ 0.17 & \text{otherwise} \end{array}\right. \qquad\qquad A = 0.198$$

Sediment mobility number F_{gr},

$$\alpha = 10 \quad \text{(assumed value used in HEC6 and SAM)} \qquad\qquad \alpha = 10$$

$$F_{gr} = \frac{u_{star}{}^{n}}{\sqrt{g\cdot d_{si}\cdot(s-1)}}\cdot\left(\frac{V}{\sqrt{32}\cdot\log\left(\alpha\cdot\frac{D}{d_{si}}\right)}\right)^{1-n} \qquad\qquad F_{gr} = 0.422$$

Hiding Factor HF,

Shield's Mobility Parameter ▱

$$\theta = \frac{u_{star}{}^{2}}{g\cdot(s-1)d_{50}} \qquad\qquad \theta = 2.612$$

$$dRatio = \begin{vmatrix} 1.1 & \text{if } \theta \le 0.04 \\ (2.3 - 30 \cdot \theta) & \text{if } 0.04 < \theta \le 0.045 \\ (1.4 - 10 \cdot \theta) & \text{if } 0.045 < \theta \le 0.095 \\ 0.45 & \text{otherwise} \end{vmatrix}$$

dRatio = 0.45

$$\mathrm{dAdjust} = \mathrm{d}_{50} \cdot \mathrm{dRatio}$$

dAdjust = 1.044 x 10^{-3}

$$\mathrm{HFRatio} = \frac{\mathrm{d}_{si}}{\mathrm{dAdjust}}$$

HFRatio = 2.222

$$HF = \begin{vmatrix} 1.30 & \text{if HFRatio} \ge 3.7 \\ (0.53 \cdot \log(\mathrm{HFRatio}) + 1) & \text{if } 0.075 \le \text{HFRatio} < 3.7 \\ 0.40 & \text{otherwise} \end{vmatrix}$$

HF = 1.184

Adjust Sediment Mobility Number for Hiding Factor

$$\mathrm{F}_{gr} = \mathrm{HF} \cdot \mathrm{F}_{gr}$$

$F_{gr} = 0.5$

Check for too fine sediment based on F_{gr} and A,

$$\mathrm{Check} = \frac{\mathrm{F}_{gr}}{\mathrm{A}}$$

Check = 2.522

Sediment transport function exponent m,

$$\mathrm{m} = \begin{vmatrix} \left(\frac{6.83}{\mathrm{d}_{gr}} + 1.67\right) & \text{if } \mathrm{d}_{gr} \le 60 \\ 1.78 & \text{otherwise} \end{vmatrix}$$

m = 2.106

Check for too fine sediment based on m,

$$Check = \begin{vmatrix} 0 & \text{if } \mathrm{m} > 6 \\ Check & \text{otherwise} \end{vmatrix}$$

Check = 2.522

Sediment transport function coefficient C,

$$C = \begin{vmatrix} 10^{2.79 \cdot \log(d_{gr}) - 0.98(\log(d_{gr}))^2 - 3.46} & \text{if } d_{gr} \le 60 \\ 0.025 \quad \text{otherwise} \end{vmatrix} \qquad C = 0.0298$$

Transport parameter G_{gr},

$$G_{gr} = C \cdot \left(\frac{F_{gr}}{A} - 1 \right)^m \qquad G_{gr} = 0.072$$

Sediment flux X, in parts per million by fluid weight,

$$X = \frac{G_{gr} s d_{si}}{D\left(\frac{u_{star}}{V} \right)^n} \qquad X = 6.741 \text{ x } 10^{-5}$$

Sediment Discharge, lb/s

$$G = \gamma_w Q X \qquad G = 21.027$$

Sediment Discharge, tons/day

$$G_s = \frac{86400}{2000} \cdot G \qquad G_s = 908$$

Check to make sure particle diameter and mobility functions are not too low,

$$G_s = \begin{vmatrix} G_s & \text{if Check } > 1 \\ 0 & \text{otherwise} \end{vmatrix} \qquad G_s = 908$$

Engelund Hansen

From Vanoni (1975) and Raudkivi (1976)

Input Parameters

Temperature, F	$T = 55$	Average Velocity, ft/s	$V = 5.46$
Kinematic viscosity, ft^2/s	$\nu = 0.00001315$		
Depth, ft	$D = 22.9$	Unit Weight water, lb/ft^3	$\gamma_w = 62.385$
Slope	$S = 0.0001$		
Median Particle Diamter, ft	$d_{si} = 0.00232$	Channel Width, ft	$B = 40$
Specific Gravity of Sediment,		$s = 2.65$	

Constants

Acceleration of gravity, ft/s^2 $g = 32.2$

Solution

Bed level shear stress ☐

$$\tau_o = \gamma_w \cdot D \cdot S \qquad \tau_o = 0.143$$

Fall diameter d_f,

$$d_f = \begin{vmatrix} \left(-69.07 \cdot d_{si}^{\ 2} + 1.0755 \cdot d_{si} + 0.000007\right) & \text{if } d_{si} \le 0.00591 \\ \left(0.1086 \cdot d_{si}^{\ 0.6462}\right) & \text{otherwise} \end{vmatrix} \qquad d_f = 2.13 \times 10^{-3}$$

Sediment discharge lb/s,

$$g_s = 0.05 \cdot \gamma_w \cdot s \cdot V^2 \cdot \sqrt{\frac{d_f}{g \cdot (s-1)}} \cdot \left[\frac{\tau_o}{(\gamma_w \cdot s - \gamma_w) \cdot d_f}\right]^{\frac{3}{2}} \cdot B \qquad g_s = 32.82$$

Sediment discharge ton/day,

$$G_s = g_s \cdot \frac{86400}{2000} \qquad G_s = 1418$$

Laursen-Copeland

From Copeland (SAM Code, 1996)

Input Parameters

Temperature, F	T = 55	Average Velocity, ft/s	V = 5.46
Kinematic viscosity, ft^2/s	$\nu = 0.00001315$	Discharge, ft^3/s	Q = 5000
Depth, ft	D = 22.90	Unit Weight water, lb/ft^3	$\gamma_w = 62.385$
Slope	S = 0.0001	84% Particle diameter, ft	d_{84} = 0.00294
Median Particle Diamter, ft	d_{si} = 0.00232		
Specific Gravity of Sediment		s = 2.65	

Constants

Acceleration of gravity, ft/s^2 $g = 32.2$

Solution

*Note: the difference between the final result presented here and the result in SAM is due to the method for determining fall velocity. Rubey is used here, whereas SAM computes a value based on a drag coefficient determined from Reynolds number. Calculation routine taken from SAM.

Because the grain distribution is reduced to standard grade sizes representing each present grade class, the d_{84} will equal the standard grade size, d_{si}, in this procedure.

$$d_{84} = d_{si}$$

Grain-related hydraulic radius R

$$R' = \frac{0.0472 \cdot V^{\frac{3}{2}} \cdot (3.5 \cdot d_{84})^{\frac{1}{4}}}{(g \cdot S)^{\frac{3}{4}}} \qquad R' = 14.189$$

R’ = 15.248

$$u_*^{'} = \sqrt{g \cdot R' \cdot S} \qquad u_*^{'} = 0.222$$

$$FNRP = \left(\frac{V}{u_*^{'}} \right) - 3.28 - 5.75 \cdot \log\left(\frac{R'}{d_{84}} \right)$$

$$FNRP = 5.195 \times 10^{-4}$$

$$DFNRP = \frac{V + 5 \cdot u_*^{'}}{2.0 \cdot u_*^{'} \cdot R'} \qquad DFNRP = 0.972$$

$$\mathrm{RPRI2} = \mathrm{R}' + \frac{\mathrm{FNRP}}{\mathrm{DFNRP}} \qquad RPRI2 = 15.249$$

$$\Delta\mathrm{R} = \left| \mathrm{RPRI2} - \mathrm{R}' \right| \qquad \Delta R = 5.345 \times 10^{-4}$$

$$\mathrm{R}' = \left| \begin{array}{ll} \mathrm{R}' & \text{if } \Delta\mathrm{R} \le 0.001 \\ \mathrm{RPRI2} & \text{otherwise} \end{array} \right.$$

$$R' = 15.248$$

Grain-related bed shear stress τ'_b,

$$\tau'_b = R' \cdot \gamma_w \cdot S \qquad \tau'_b = 0.095$$

$$\tau_b = D \cdot \gamma_w \cdot S \qquad \tau_b = 0.143$$

$$\tau'_b = \left| \begin{array}{ll} \tau'_b & \text{if } \tau'_b < \tau_b \\ \tau_b & \text{otherwise} \end{array} \right. \qquad \tau'_b = 0.095$$

$$u'_* = \sqrt{\frac{\tau'_b \cdot g}{\gamma_w}} \qquad u'_* = 0.222$$

$$\mathrm{RRP} = \left(\frac{\mathrm{d_{si}}}{\mathrm{R}}\right)^{1.16667} \qquad RRP = 2.187 \times 10^{-5}$$

Dimensionless bed shear stress $\tau_b{}^*$,

$$\tau_b^* = \frac{\tau'_b}{\gamma_w \cdot (s-1) \cdot d_{si}}$$

$$\tau_b^* = 0.398$$

Shield’s parameter for course grains θ^*,

$$\theta^* = 0.647 \cdot \tau_b^* + 0.0064$$

$$\theta^* = \begin{vmatrix} 0.02 & \text{if } \theta^* < 0.02 \\ \theta^* & \text{otherwise} \end{vmatrix} \qquad \theta^* = 0.264$$

Critical shear stress, τ_{cr}

$$\tau_{cr} = \begin{vmatrix} \left[\theta^* \cdot \gamma_w \cdot (s-1) \cdot d_{si}\right] & \text{if } \tau_b^* \le 0.05 \\ \left[0.039 \cdot \gamma_w \cdot (s-1) \cdot d_{si}\right] & \text{otherwise} \end{vmatrix} \qquad \tau_{cr} = 9.315 \times 10^{-3}$$

Shear stress mobility parameter TFP,

$$\mathrm{TFP} = \frac{\tau'_b}{\tau_{cr}} - 1 \qquad \text{TFP} = 9.214$$

Fall velocity ω,

Use Rubey's equation, Vanoni p. 169

$$F_1 = \sqrt{\frac{2}{3} + \frac{36 \cdot v^2}{g \cdot d_{si}{}^3 \cdot (s-1)}} - \sqrt{\frac{36 \cdot v^2}{g \cdot d_{si}{}^3 \cdot (s-1)}}$$ $F_1 = 0.725$

$$\omega = F_1 \cdot \sqrt{(s-1) \cdot g \cdot d_{si}}$$ $\omega = 0.255$

Particle velocity ratio SF,

$$SF = \frac{u_*^{'}}{\omega}$$ $SF = 0.870$

Particle velocity ratio parameter Ψ,

$$\Psi = \left| \begin{matrix} \left[7.04 \cdot 10^{15} \cdot (SF)^{22.99}\right] & \text{if SF} \le 0.225 \\ (40.0 \cdot SF) & \text{if } 0.225 < \text{SF} \le 1.0 \\ \left(40 \cdot SF^{1.843}\right) & \text{if SF} > 1.0 \end{matrix} \right.$$ $\Psi = 34.804$

Sediment transport G_s, tons/day

$$G_s = 0.432 \cdot \gamma_w \cdot Q \cdot RRP \cdot TFP \cdot \Psi$$ $G_s = 945$

Meyer-Peter Muller

From Vanoni (1975) and Schlichting's Boundary Layer Theory (1968)

Input Parameters

Temperature, F	$T = 55$	Average Velocity, ft/s	$V = 5.46$
Kinematic viscosity, ft^2/s	$\nu = 0.00001315$	Discharge, ft^3/s	$Q = 5000$
Depth, ft	$D = 22.9$	Unit Weight water, lb/ft^3	$\gamma_w = 62.385$
Slope	$S = 0.0001$	Overall d50, ft	$d_{90} = 0.00306$
Median Particle Diamter, ft	$d_{si} = 0.00232$	Channel Width, ft	$B = 40$
Specific Gravity of Sediment,		$s = 2.65$	

Constants

Acceleration of gravity, ft/s^2 $g = 32.2$

Solution

Shear velocity u,

$$u_* = \sqrt{g \cdot D \cdot S} \qquad u_* = 0.272$$

Shear Reynold's number, R_s,

$$R_s = \frac{u_* \cdot d_{90}}{\nu} \qquad R_s = 63.189$$

Schlichting's B coefficient, Bcoeff

$$BCoeff = \begin{cases} (5.5 + 2.5 \cdot \ln(R_s)) & \text{if } R_s \leq 5 \\ \begin{bmatrix} 0.297918 + 24.8666 \cdot \log(R_s) - 22.9885 \cdot (\log(R_s))^2 \ldots \\ + 8.5199 \cdot (\log(R_s))^3 - 1.10752 \cdot (\log(R_s))^4 \end{bmatrix} & \text{if } 5 < R_s \leq 70 \\ 8.5 & \text{otherwise} \end{cases}$$

Friction factor due to sand grains f',

$$f' = \left(\frac{2.82843}{BCoeff - 3.75 + 2.5 \cdot \ln\left(2 \cdot \frac{D}{d_{90}}\right)} \right)^2$$

$f' = 9.565 \text{ X } 10^{-3}$

Nikaradse roughness ratio RKR,

$$RKR = \sqrt{\frac{f'}{8}} \cdot \frac{V}{\sqrt{g \cdot D \cdot S}}$$

$RKR = 0.695$

Sediment discharge lb/s,

$$g_s = \left[\frac{(RKR)^{\frac{3}{2}} \cdot \gamma_w \cdot D \cdot S - 0.047 \cdot (\gamma_w \cdot s - \gamma_w) \cdot d_{si}}{0.25 \cdot \left(\frac{\gamma_w}{g}\right)^{\frac{1}{3}} \cdot \left(\frac{\gamma_w \cdot s - \gamma_w}{\gamma_w \cdot s}\right)^{\frac{2}{3}}} \right]^{\frac{3}{2}} \cdot B$$

$g_s = 7.073$

Sediment discharge ton/day,

$$G_s = g_s \cdot \frac{86400}{2000}$$

$G_s = 306$

Derivation of the Dimensionless form of MPM from the Vanoni Form

Converting the HEC-RAS version of MPM (from Vanoni, 1975) to the dimensionless Form

$$\left(\frac{k_r}{k_r'}\right)^{\frac{3}{2}}\gamma RS = 0.047(\gamma_s-\gamma)d_m + 0.25\left(\frac{\gamma}{g}\right)^{\frac{1}{3}}\left(\frac{\gamma_s-\gamma}{\gamma_s}\right)^{\frac{2}{3}}g_s^{\frac{2}{3}}$$

Get transport (gs) on the left side of the equation and the shear terms on the right.

$$0.25\left(\frac{\gamma}{g}\right)^{\frac{1}{3}}\left(\frac{\gamma_s-\gamma}{\gamma_s}\right)^{\frac{2}{3}}g_s^{\frac{2}{3}} = \left(\frac{k_r}{k_r^{'}}\right)^{\frac{3}{2}}\gamma RS - 0.047(\gamma_s-\gamma)d_m$$

Divide by 0.25 and by $(\gamma_s-\gamma)d_m$ to convert shear to the dimensionless shields number and isolate the critical shear (0.047):

$$\frac{\left(\frac{\gamma}{g}\right)^{\frac{1}{3}}\left(\frac{\gamma_s-\gamma}{\gamma_s}\right)^{\frac{2}{3}}g_s^{\frac{2}{3}}}{(\gamma_s-\gamma)d_m} = 4\left(\left(\frac{k_r}{k_r^{'}}\right)^{\frac{3}{2}}\tau^* - 0.047\right)$$

Because the Shields number is:

$$\tau^* = \frac{\gamma RS}{(\gamma_s-\gamma)d_m}$$

The right side of this equation is already looking familiar.
Next raise everything to the 3/2 power to prepare to isolate transport (gs):

$$\frac{\left(\frac{\gamma}{g}\right)^{\frac{1}{2}}\left(\frac{\gamma_s-\gamma}{\gamma_s}\right)g_s}{((\gamma_s-\gamma)d_m)^{\frac{3}{2}}} = 8\left(\left(\frac{k_r}{k_r^{'}}\right)^{\frac{3}{2}}\tau^* - 0.047\right)^{\frac{3}{2}}$$

The Right side of the equation is in the final form, so simplify the left side of the equation into the dimensionless transport parameter (q^*):

$$q^* = \frac{{g_s}/{\gamma_s}}{\sqrt{Rg}\,d_m^{\frac{3}{2}}}$$

Where R is the difference between the specific gravity of the solids and liquid usually (S-1), (2.65-1) or 1.65 and g is the acceleration of gravity.

Simplify the expression until the dimensionless transport parameter emerges on the left side of the equation.

$$\frac{\left(\frac{\gamma}{g}\right)^{\frac{1}{2}}\gamma(R)g_s}{\gamma_s((\gamma_s-\gamma)d_m)^{\frac{3}{2}}}=8\left(\left(\frac{k_r}{k_r^{'}}\right)^{\frac{3}{2}}\tau^*-0.047\right)^{\frac{3}{2}}$$

$$\frac{(\gamma)^{\frac{1}{2}}\gamma(R)g_s}{(g)^{\frac{1}{2}}\gamma_s\gamma^{\frac{3}{2}}R^{\frac{3}{2}}d_m^{\frac{3}{2}}}=8\left(\left(\frac{k_r}{k_r^{'}}\right)^{\frac{3}{2}}\tau^*-0.047\right)^{\frac{3}{2}}$$

$$\frac{(\gamma)^{\frac{1}{2}}\gamma}{\gamma_s\gamma^{\frac{3}{2}}}\frac{g_s}{g^{\frac{1}{2}}R^{\frac{1}{2}}d_m^{\frac{3}{2}}}=8\left(\left(\frac{k_r}{k_r^{'}}\right)^{\frac{3}{2}}\tau^*-0.047\right)^{\frac{3}{2}}$$

At this point, most of the left side of the equation collapses to the dimensionless transport parameter

$$\frac{g_s}{(R)^{\frac{1}{2}}(g)^{\frac{1}{2}}(d_m)^{\frac{3}{2}}}=q^*$$

Leaving only the unit weight of the soil:

$$\frac{1}{\gamma_s}q^*=8\left(\left(\frac{k_r}{k_r^{'}}\right)^{\frac{3}{2}}\tau^*-0.047\right)^{\frac{3}{2}}$$

But the original MPM equation computes the unit transport by *weight* while the dimensionless transport parameter calculates unit *volume* transport, so the unit weight of the solids converts the volume flux to a mass flux. But to leave it in the volume flux format, we can drop this conversion, yielding:

$$q^*=8\left(\left(\frac{k_r}{k_r^{'}}\right)^{\frac{3}{2}}\tau^*-0.047\right)^{\frac{3}{2}}$$

Toffaleti

From Vanoni (1975) for a single grain size

Input Parameters

Slope,	S = 0.0001	Temperature, F	T = 55
Hydraulic Radius, ft	R = 10.68	viscosity, ft^2/s	$\nu = 0.00001315$
Width, ft	B = 40	Median Particle Size, ft	$d_{si} = 0.00232$
Velocity, ft/s		V = 5.46	65% finer Particle Size, ft $d_{65} = 0.00257$
		Fraction of Total Sediment	$p_i = 1$
		Unit Weight of Water, lb/ft^3	$\gamma_w = 62.385$

Constants

Acceleration of gravity, ft/s^2 $g = 32.2$

Solution

Nikaradse Roughness Value, using d_{65}, as per Einstein, 1950, p.

$$k_s = d_{65} \qquad k_s = 2.57 \times 10^{-3}$$

Grain-related shear velocity as per Einstein, 1950, p. 10

Guess $u'_{*try} = 0.199$

Assume hydraulically rough grain first.

$$r' = \frac{u'_{*try}{}^2}{g \cdot S}$$

r' = 12.298

$$u'_* = \frac{V}{\left(5.75 \cdot \log\left(12.27 \cdot \frac{r'}{k_s}\right)\right)}$$

Check $u'_* = 0.199$

Check for hydraulically rough or smooth grains…

Guess $u'_{*try} = 0.169$

$$r' = \frac{u'^{\,2}_{*try}}{g \cdot S}$$ r' = 8.87

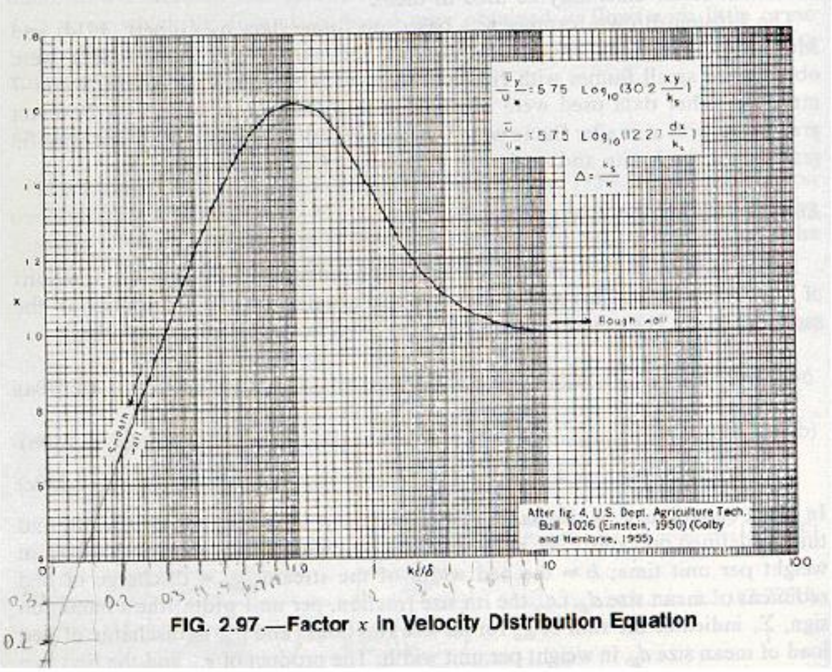
$$\delta' = \frac{11.6 \cdot \nu}{u'_{*try}}$$ $\delta' = 9.026 \times 10^{-4}$

Check = $\frac{\mathrm{k_s}}{\delta'}$ Check = 2.847 $\frac{k_s}{\delta'} = 2.847$

$$u'_* = \begin{vmatrix} \dfrac{V}{\left(5.75 \cdot \log\left(3.67 \cdot \dfrac{r' u'_{*try}}{\nu}\right)\right)} & \text{if Check} < 5 & \text{Smooth} \\ u'_* \quad \text{otherwise} & & \text{Rough} \end{vmatrix}$$

Check u'_* =0.169

Check for Transitional regime



After fig. 4, U.S. Dept. Agriculture Tech. Bull. 1026 (Einstein, 1950) (Colby and Hembree, 1955)

FIG. 2.97.—Factor x in Velocity Distribution Equation

$\Phi = \frac{k_s}{\delta'}$ $\Phi = 2.847$ $\Phi = 3.416$

x = 1.14 from figure 2.97, Vanoni, page 196

$$u'_* = \begin{cases} \dfrac{V}{5.75 \cdot \log\left(12.27 \cdot \dfrac{r' \cdot x}{k_s}\right)} & \text{if } 0.1 < \Phi < 10 \\ u'_* & \text{otherwise} \end{cases}$$

$\delta' = \frac{11.6 \cdot v}{u'_*}$ $\Phi = \frac{k_s}{\delta'}$ $\Phi = 3.416$

$u'_* = 0.203$

****Note: Einstein's method for determining u'^{*} was compared with Toffaleti's graphical approach.

Results showed that the two methods are in acceptable agreement, with differences on the order

of less than 3%. Einstein's approach was selected for its established reputation and its relative

simplicity.

Toffaleti coefficients, A and k_4,

$$A_{factor} = \frac{\left(10^5 \cdot \nu\right)^{\frac{1}{3}}}{10 \cdot u'_*}$$

$A_{factor} = 0.54$

$$A = \left| \begin{array}{l} \left(9.5987 \cdot A_{factor}{}^{-1.5445}\right) \quad \text{if } A_{factor} \le 0.5 \\ \left(39.079 \cdot A_{factor}{}^{0.481}\right) \quad \text{if } 0.5 < A_{factor} \le 0.66 \\ \left(221.85 \cdot A_{factor}{}^{4.660}\right) \quad \text{if } 0.66 < A_{factor} \le 0.72 \\ 48 \quad \text{if } 0.72 < A_{factor} \le 1.3 \\ \left(22.594 \cdot A_{factor}{}^{2.872}\right) \quad \text{if } A_{factor} > 1.3 \end{array} \right.$$

$A = 29.065$

$$k_{4Factor} = \frac{\left(10^5 \cdot \nu\right)^{\frac{1}{3}}}{10 \cdot u'_*} \cdot 10^5 \cdot S \cdot d_{65}$$

$K_{4Factor} = 0.014$

$$k_4 = \left| \begin{array}{l} (1.0) \quad \text{if } k_{4Facotr} \le 0.25 \\ \left(5.315 \cdot k_{4Factor}{}^{1.205}\right) \quad \text{if } 0.25 \langle k_{4Factor} \le 0.35 \\ \left(0.510 \cdot k_{4Factor}{}^{-1.028}\right) \quad \text{if } k_{4Factor} \rangle 0.35 \end{array} \right.$$

$k_4 = 1$

$$Ak_4 = A \cdot k_4$$

Check for too low values for the product Ak_4,

$$Ak_4 = \left| \begin{array}{l} 16 \quad \text{if } Ak_4 \langle 16 \\ Ak_4 \quad \text{if } Ak_4 \ge 16 \end{array} \right.$$

$Ak_4 = 29.065$

More Coefficients,

$$\mathrm{T_T} = 1.10 \cdot (0.051 + 0.00009 \cdot \mathrm{T}) \qquad \mathrm{T_T} = 0.062$$

$$\mathrm{n_V} = 0.1198 + 0.00048 \cdot \mathrm{T} \qquad \mathrm{n_V} = 0.146$$

$$\mathrm{c_z} = 260.67 - 0.667 \cdot \mathrm{T} \qquad \mathrm{c_Z} = 223.985$$

Fall Velocity for Medium Sand from Toffaleti Tables at 55 degrees F,

$$w_i = 0.340$$

$$\mathrm{z_i} = \frac{\mathrm{w_i} \cdot \mathrm{V}}{\mathrm{c_z} \cdot \mathrm{R} \cdot \mathrm{S}} \qquad z_i = 7.76$$

$$z_i = \begin{cases} (1.5 \cdot n_V) & \text{if } \mathrm{z_i} < \mathrm{n_V} \\ z_i & \text{otherwise} \end{cases} \qquad z_i = 7.76$$

Empirical Relationship for g_{ssLi},

$$\mathrm{g_{ssLi}} = \frac{0.600 \cdot \mathrm{p_i}}{\left(\frac{\mathrm{T_T} \cdot \mathrm{Ak_4}}{\mathrm{V}^2}\right)^{\frac{5}{3}} \cdot \left(\frac{\mathrm{d_{si}}}{0.00058}\right)^{\frac{5}{3}}} \qquad g_{ssLi} = 6.473$$

$$M_i = \frac{g_{ssLi}}{\left[\frac{\left(\frac{R}{11.24}\right)^{1+n_V-0.756 \cdot z_i} - (2 \cdot d_{si})^{1+n_V-0.756 \cdot z_i}}{1 + n_V - 0.756 \cdot z_i}\right]} \qquad \mathrm{M_i} = 2.948 \times 10^{-10}$$

Concentration,

$$C_{Li} = \frac{M_i}{43.2 \cdot p_i \cdot (1 + n_V) \cdot V \cdot R^{0.756 \cdot z_i - n_V}} \qquad C_{Li} = 1.425 \times 10^{-18}$$

Check for unrealistically high concentration and adjust $\mathrm{M_i}$ if necessary,

$$C_{2d} = C_{Li} \cdot \left(\frac{2 \cdot d_{si}}{R}\right)^{-0.756 \cdot z_i} \qquad C_{2d} = 75.536$$

$$C_{Li} = \left| \begin{array}{ll} C_{Li} & \text{if } C_{2d} < 100 \\ \dfrac{100}{\left(\dfrac{2 \cdot d_{si}}{R}\right)^{-0.756 \cdot z_i}} & \text{if } C_{2d} \geq 100 \end{array} \right. \qquad C_{Li} = 1.425 \text{ X } 10^{-18}$$

$$M_i = C_{Li} \cdot \left[43.2 \cdot p_i \cdot (1 + n_V) \cdot V \cdot R^{0.756 \cdot z_i - n_V}\right] \qquad M_i = 2.948 \text{ X } 10^{-10}$$

Bed Load Transport,

$$g_{sbi} = M_i \cdot (2 \cdot d_{si})^{(1 + n_V - 0.756 z_i)} \qquad g_{sbi} = 30.555$$

Lower Layer Transport,

$$g_{ssLi} = M_i \cdot \left[\frac{\left(\dfrac{R}{11.24}\right)^{(1 + n_V - 0.756 \cdot z_i)} - (2 \cdot d_{si})^{(1 + n_V - 0.756 \cdot z_i)}}{1 + n_V - 0.756 \cdot z_i} \right] \qquad g_{ssLi} = 6.473$$

Middle Layer Transport,

$$g_{ssMi} = M_i \cdot \frac{\left(\dfrac{R}{11.24}\right)^{0.244 \cdot z_i} \cdot \left[\left(\dfrac{R}{2.5}\right)^{1 + n_V - z_i} - \left(\dfrac{R}{11.24}\right)^{1 + n_V - z_i}\right]}{1 + n_V - z_i} \qquad g_{ssMi} = 5.674 \text{ X } 10^{-1}$$

Upper Layer Transport,

$$g_{ssUi} = M_i \cdot \frac{\left(\dfrac{R}{11.24}\right)^{0.244 \cdot z_i} \cdot \left(\dfrac{R}{2.5}\right)^{0.5 \cdot z_i} \cdot \left[R^{(1 + n_V - 1.5 \cdot z_i)} - \left(\dfrac{R}{2.5}\right)^{1 + n_V - 1.5 \cdot z_i}\right]}{1 + n_V - 1.5 \cdot z_i} \qquad g_{ssUi} = 1.72 \text{ X } 10^{-15}$$

Total Transport per Unit Width,

$$g_{si} = g_{sbi} + g_{ssLi} + g_{ssMi} + g_{ssUi} \qquad g_{si} = 37.027$$

Total Transport,

$$G = g_{si} \cdot B \qquad G = 1481 \text{ tons/day}$$

Yang

From Yang – ASCE Journal of Hydraulics (1975 and 1984)

Input Parameters

Temperature, F $T = 55$ Average Velocity, ft/s $V = 5.46$

Kinematic viscosity, ft^2/s $\nu = 0.00001315$ Discharge, ft^3/s $Q = 5000$

Hydraulic Radius, ft $R = 10.68$ Unit Weight water, lb/ft^3 $\gamma_w = 62.385$

Slope, $S = 0.0001$

Meidan Particle Diamter, ft $d_{si} = 0.00232$

Specific Gravity of Sediment $s = 2.65$

Constants

Acceleration of gravity, ft/s^2 $g = 32.2$

Solution

Shear Velocity, ft/s,

$$u_* = \sqrt{g \cdot R \cdot S} \qquad u_* = 0.185$$

Particle Fall Velocity, ft/s,

Use Rubey's equation, Vanoni p. 169

$$F_1 = \sqrt{\frac{2}{3} + \frac{36 \cdot \nu^2}{g \cdot d_{si}^{\ 3} \cdot (s-1)}} - \sqrt{\frac{36 \cdot \nu^2}{g \cdot d_{si}^{\ 3} \cdot (s-1)}}$$

$F_1 = 0.725$

$$\omega = F_1 \cdot \sqrt{(s-1) \cdot g \cdot d_{si}} \qquad \omega = 0.255$$

Shear Reynold's Number,

$$R_s = \frac{u_* \cdot d_{si}}{\nu} \qquad R_s = 32.717$$

Critical Velocity, ft/s,

$$V_{cr} = \begin{cases} \omega \cdot \left(\dfrac{2.5}{\log\left(\dfrac{u_* \cdot d_{si}}{\nu}\right) - 0.06} + 0.66 \right) & \text{if } 0 < \mathrm{R_s} < 70 \\ (\omega \cdot 2.05) \quad \text{if } \mathrm{R_s} \geq 70 \end{cases}$$

$$V_{cr} = 0.606$$

Log of Concentration,

$$\log C_t = \begin{cases} \left[5.435 - 0.286 \cdot \log\left(\dfrac{\omega \cdot d_{si}}{\nu}\right) - 0.457 \cdot \log\left(\dfrac{u_*}{\omega}\right) \ldots \\ + \left(1.799 - 0.409 \cdot \log\left(\dfrac{\omega \cdot d_{si}}{\nu}\right) - 0.314 \cdot \log\left(\dfrac{u_*}{\omega}\right)\right) \cdot \log\left(\dfrac{V \cdot S}{\omega} - \dfrac{V_{cr} \cdot S}{\omega}\right) \right] & \text{if } \mathrm{d_{si}} < 0.00656 \quad \text{Sand} \\ \left[\left(6.681 - 0.633 \cdot \log\left(\dfrac{\omega \cdot d_{si}}{\nu}\right) - 4.816 \cdot \log\left(\dfrac{u_*}{\omega}\right)\right) \ldots \\ + \left(2.784 - 0.305 \cdot \log\left(\dfrac{\omega \cdot d_{si}}{\nu}\right) - 0.282 \cdot \log\left(\dfrac{u_*}{\omega}\right)\right) \cdot \log\left(\dfrac{V \cdot S}{\omega} - \dfrac{V_{cr} \cdot S}{\omega}\right) \right] & \text{if } \mathrm{d_{si}} \geq 0.00656 \quad \text{Gravel} \end{cases}$$

$$\log C_t = 1.853$$

Concentration, ppm

$$C_t = 10^{\log C_t} \qquad C_t = 71.284$$

Sediment Discharge, lb/s

$$G = \frac{\gamma_w \cdot Q \cdot C_t}{1000000} \qquad G = 22.235$$

Sediment Discharge, tons/day

$$G_s = \frac{86400}{2000} \cdot G \qquad G_s = 961$$

CHAPTER 3 BSTEM: USDA-ARS BANK STABILITY AND TOE EROSION MODEL – TECHNICAL REFERNCE MANUAL

Background

The HEC-RAS (Hydrologic Engineering Center's (HEC) River Analysis System) software has included mobile bed capabilities since Version 4.0. These capabilities compute vertical bed changes in response to dynamic sediment mass balance and bed processes. However, many riverine sediment problems involve lateral bank erosion that does not fit in the current computational paradigm. There are many published methodologies that compute bank failure. The methodologies span a spectrum from basic angle of repose methods that require very few parameters but simplify bank processes considerably, to full blown geotechnical bank stability models that require a full suite of geotechnical parameters yet lack a framework for hydraulic toe feedbacks. The Bank Stability and Toe Erosion Model (BSTEM) developed by the National Sediment Laboratory, United States Department of Agriculture (USDA), Agricultural Research Station (ARS) is a physically based model that accounts for the dominant stream bank processes but requires an intermediate level of complexity and parameterization. This method was selected for implementation in HEC-RAS.

BSTEM (Simon, 2000; Langendoen, 2008; Simon, 2010) couples iterative, planer bank failure analysis based on a fundamental force balance, with a toe scour model that allows feedback between the hydraulic dynamics on the bank toe which could exacerbate failure risk (in the case of toe scour) or decrease failure risk (in the case of toe protection). The goal of coupling HEC-RAS with BSTEM is to build a model that simulates feedbacks between bed and bank processes. For example, if HEC-RAS computes a decrease in the regional base level or local channel scour it will decrease bank stability and increase the risk of a failure. Similarly, when a bank does fail, the bank material will be added to the sediment mass balance of the mobile bed model which will simulate the river's capacity to "metabolize" and transport these point sources.

Overview

As the name suggests, there are two major, interacting components to BSTEM:

1. **Bank Failure:** A geotechnical bank failure model that computes failure planes through the bank to determine if the gravitational driving forces exceed the frictional resisting forces (and the interactions of pore water pressure).

   Toe Scour: An erosion model that computes the progression of bank undercutting by hydraulic forces. As the toe scours, the bank becomes less stable, so toe scour can initiate bank failure.

These two processes also interact with a third process native to the classic sediment methodology in HEC-RAS computations:

2. **Vertical Erosion or Deposition:** The vertical adjustment of the cross section can also decrease the stability of the bank and interact with toe scour computations. Conversely, a large bank failure could add enough sediment mass to the system to deposit downstream and increase the stability of downstream banks.

Modeling the interactions and feedbacks between these three processes were the main motivation for including the USDA-ARS BSTEM algorithms into HEC-RAS. The science, methods and math of vertical erosion and deposition are covered in the HEC-RAS User's Manual (HEC, 2010) and the HEC-RAS Technical Reference Manual (HEC, 2010a).

Bank Failure

The bank failure methods employ classical, planar, analyses to compare gravitational driving forces of the soil, soil water and overburden, and frictional resisting forces (including the influences of pore water pressure) to determine the most likely failure plane through the bank and to compute whether that failure plane is stable. If the weakest failure plane is unstable, the bank fails and the sediment from the failed bank is added to the sediment transport model.

The bank stability model goes through a series of iterative computations to select potential failure planes, evaluate the factor of safety, and converge on the failure plane most likely to fail by following the steps below:

1. Find the critical Factor of Safety (FS_{cr}), the failure plane with the lowest Factor of Safety (FS) for nodes at several vertical locations up the bank.

2. Select the bounding Failure Planes (minimum and maximum angles) and compute a FS for each
3. Select a most probable critical failure plane ($FS_i \sim FS_{cr}$)
4. Compute the FS_i
5. Use that information to select a more likely critical failure plane (using the "bracket and Brent" optimization algorithm from Teukolsky et al., 2007) (set FS_{i+1} to updated estimate of FS_{cr})
6. Decide when the FS is close enough to FS_{cr} to stop
7. If FS_{cr} is less than one, fail the bank, update the cross section, and send the bank sediments to the routing model

The failure plane selection and optimization algorithms are covered below. Since computing a FS for each failure plane (Step 3) is the physical algorithm at the core of this process, the description below starts with the basic physics and then moves to the optimization scheme.

There are two basic computational approaches to computing the FS of a failure plane through the bank:

i. Layer Method
ii. Method of Slices

Layer Method

The Layer Method is based on Simon (2000) and it is the default method (Figure 3-1) in USDA-ARS BSTEM Version 5.4. This method was developed specifically for bank failure applications and is derived superficially to compute failure planes through vertically heterogeneous bank sediments. The layered configuration makes it easier to formulate a stability equation for bank sediments divided into discrete horizontal layers (which is the basic configuration of BSTEM stratigraphy). The Layer Method also eliminates one cycle of iteration required in the Method of Slices which reduces runtimes in long simulations.

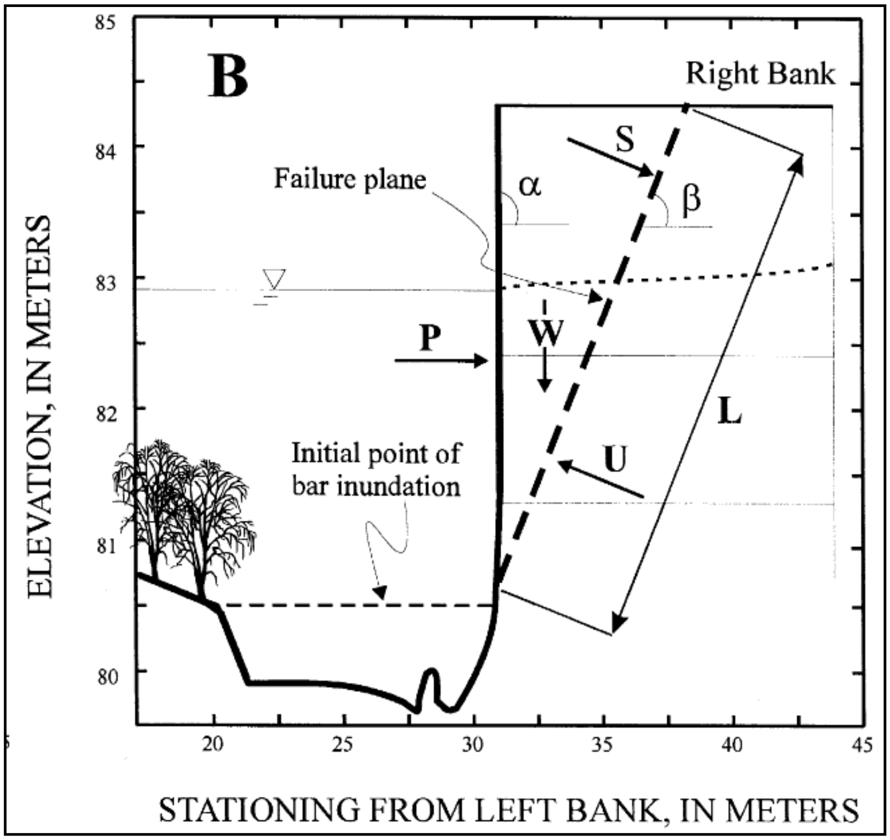


Figure 3-1: Force diagram for the "Layer Method" from Simon (2000).

The Layer Method solves a non-iterative equation (Equation 1, Layer Method Force Balance) for the FS that compares driving forces to resisting forces:

$$FS = \frac{\sum_{i=1}^{I}\left(c_i' L_i + S_i \tan\phi_i^b + \left[W_i \cos\beta - U_i + P_i \cos\left(\alpha - \beta\right)\right]\tan\phi_i'\right)}{\sum_{i=1}^{I}\left(W_i \sin\beta - P_i \sin\left[\alpha - \beta\right]\right)} \tag{1}$$

where:

i = layer
L = length of the failure plane
S = matrix suction force
U = hydrostatic uplift
P = hydrostatic confining force of the water in the channel’ ϕ' = friction angle
ϕ^b = relationship between matrix suction and apparent cohesion’ c' = effective cohesion
b = angle of the failure plane

However, Equation 1 combines the driving forces in the numerator and resisting forces in the denominator, because both the numerator and denominator have negative components. Equation 2 displays the components of the Layer Method Force Balance equation, with the driving forces indicated in red and resisting forces in green.

$$F_s = \frac{\sum_{i=1} \left(\overset{\text{Cohesion}}{\boxed{c_i' L_i}} + \overset{\text{Suction}}{\boxed{S_i \tan\phi_i^b}} + \left[\overset{\text{Weight of soil } \uparrow \text{ frictional resistance}}{\boxed{W_i \cos\beta}} \overset{\text{Hydrostatic } \downarrow \text{ frictional resistance}}{\boxed{-U_i}} + \overset{\text{Normal force of water } \uparrow \text{ frictional resistance}}{\boxed{P_i \cos(\alpha-\beta)}} \right] \tan\phi_i' \right)}{\sum^{I} \left(\underset{\text{Gravitational force along the inclination of the failure plane.}}{\boxed{W_i \sin\beta}} - \underset{\text{Hydrostatic confining force.}}{\boxed{P_i \sin[\alpha-\beta]}} \right)}$$

The forces in Equation 2 can be categorized into soil forces (weight of soil block, cohesion) and hydraulic forces (hydrostatic confining forces, pore water pressure). Equation 3 displays the hydraulic and soil forces of the Layer Method Force Balance equation:

$$F_s = \frac{\sum_{i=1} \left(\overset{\text{Soil}}{\boxed{c_i' L_i}} + \overset{\text{Water}}{\boxed{S_i \tan\phi_i^b}} + \left[\overset{\text{Soil}}{\boxed{W_i \cos\beta}} \overset{\text{Water}}{\boxed{-U_i}} + \overset{\text{Water}}{\boxed{P_i \cos(\alpha-\beta)}} \right] \tan\phi_i' \right)}{\sum^{I} \left(\underset{\text{Soil}}{\boxed{W_i \sin\beta}} - \underset{\text{Water}}{\boxed{P_i \sin[\alpha-\beta]}} \right)}$$

Soil Forces

Weight of the Soil in the Failure Block

The weight of the soil in the failure block is an instrumental parameter in both the driving and resisting forces. The gravitational force on the mass of the bank "inside" of the failure plane is the primary driver of bank failure. However, the component of this weight normal to the failure plane also increases the frictional resistance to failure.

$W_i \sin\beta$ = The component of the weight down the failure plane, driving the soil into the water.

$W_i \cos\beta \tan\phi_i'$ = The frictional resistance of the soil along the failure plane, where:

$W_i \cos\beta$ = component of the weight normal to the failure plain

ϕ_i' = friction angle (which can be measured in the laboratory with triaxial testing or *in situ* with borehole shear equipment).

Cohesion

Cohesion is the inter-particle attraction in a soil matrix. For very fine soils (generally less than 0.0625 mm), particularly those composed of clay minerals, the electrochemical forces between particles can be stronger than the frictional forces. These electrochemical binding forces resist failure in cohesive soils such that:

$c'_i L_i$ = The effective cohesion per unit length (c'_i) acting along the length of the failure plane in a soil layer L_i. (Note: cohesion is actually a shear strength that acts over an area, but L_i becomes an area when it is projected along the streamwise or longitudinal direction).

Hydraulic Forces

For hydraulic forces there are two terms that consider the weight of the water and two terms that consider the pore water pressure.

Hydrostatic Confining Force

The terms that consider the force of the water in the channel:

$P_i \cos(\alpha-\beta) \tan\phi'_i$ = The normal component of the hydrostatic confining force of the water in the channel. This is a resisting force because it adds to the normal force acting on the failure plane and, therefore, increases the frictional strength.

$-P_i \cos(\alpha-\beta)$ = The component of the hydrostatic confining force acting along the failure plane against the direction of failure. The weight of the soil (the primary driving force) is reduced by this component, where:

α = is the angle between vertical and the vector the hydrostatic force (Figure 3-2) exerted by the channel water (orthogonal to the weighted average of the inundated bank slope) are both resisting forces

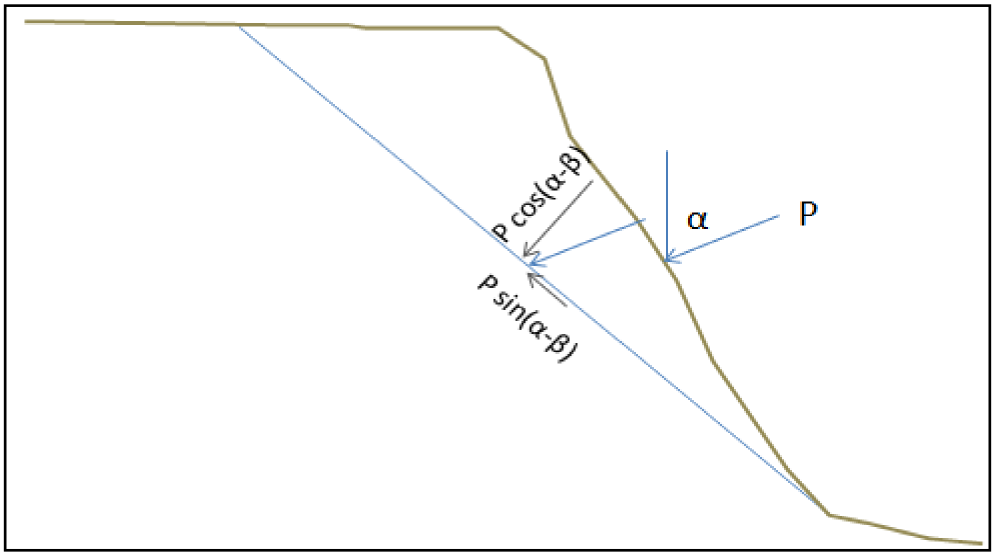


Figure 3-2: Components of the hydrostatic forces acting normal to and along the failure plane.

Pore Water Pressure

The pore water pressure is divided into two components in the numerator:

$-U_i \tan\phi'_i$ = Hydrostatic uplift force (buoyancy is a driving force while suction is a resisting force). Water exerts a vertical force on submerged sand grains, reducing the normal force along the failure plane and, therefore, the frictional resistance to failure. U_i is simply the hydrostatic force, which increases linearly with depth below the groundwater table (Figure 3-3). In the saturated zone $'_b = \varphi'$ so the hydrostatic force is multiplied by tan φ' and can be included in the frictional term of the numerator.

$S_i \tan\phi^b_i$ = The suction forces increase the soil strength due to the development of negative pore water pressure in the unsaturated zone of the soil which pulls the soil grains together. In the unsaturated zone, as water drains, evaporates, transpires, and is not replaced with atmospheric air, negative pressures (suction) develop.

In general, suction S_i is estimated as a continuation of the hydrostatic force into the unsaturated zone. Suction increases with vertical distance above the water table at the same rate that the hydrostatic force increases with vertical distance below the water table. Positive and negative pore water pressures are assumed symmetrical around the water table. This is an idealized assumption, however, that only accounts for gravity draining. Precipitation and infiltration will add water to the unsaturated zone and decrease suction effects and evapo-transpiration will increase negative pore water pressures. If these processes are important, unsaturated pore water pressures will have to be measured (e.g., with a tensiometer).

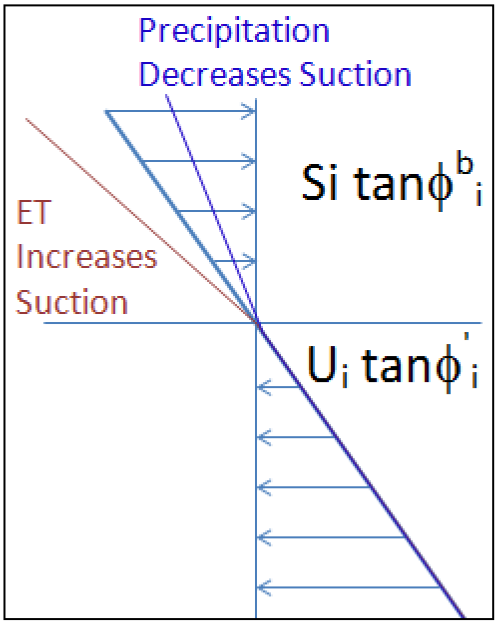


Figure 3-3: Idealized hydrostatic assumption of positive and negative pore water pressure with respect to the ground water surface and potential empirical divergence from the assumption.

Translating negative pore water pressures or suction effects into a force in the free body diagram is the most empirical step of computing the factor of safety. Every other parameter can be measured directly or computed. However suction effects are accounted for with an empirical assumption analogous to the friction slope parameter. The suction is translated into "apparent cohesion", (the equivalent amount of cohesion required to produce the same resisting force as the soil suction). Apparent cohesion (Figure 3-4) is easily included in the force balance, but is not a physical parameter that can be measured and is very difficult to compute. The angle ϕ^b is simply the linear relationship between the matrix suction measured or computed and the corresponding equivalent cohesion force it represents. This angle can be computed but is heavily labor and data intensive to measure so it is often selected based on user judgment. For most materials ϕ^b is generally between ten to thirty degrees depending on soil type. Most applications use a base ϕ^b between ten and fifteen, but it goes to a maximum of the friction angle when the material is saturated (Fredlund, 1986). Since it is one of the least certain parameters it is often considered a calibration parameter.

If the water surface in the channel is close to the groundwater elevation the confining forces of the water in the channel offset most of the driving force of the interstitial water. However, if the water in the channel is substantially lower than the soil water elevation (e.g., in the case of a rapid channel drawdown in poorly drained soils, leaving a perched groundwater table), the confining forces of the water will be removed while the driving forces (the weight of the water and the buoyant reduction in soil friction) remain. This is why the **critical failure condition** is often a case of substantial differential between ground water and surface water elevations.

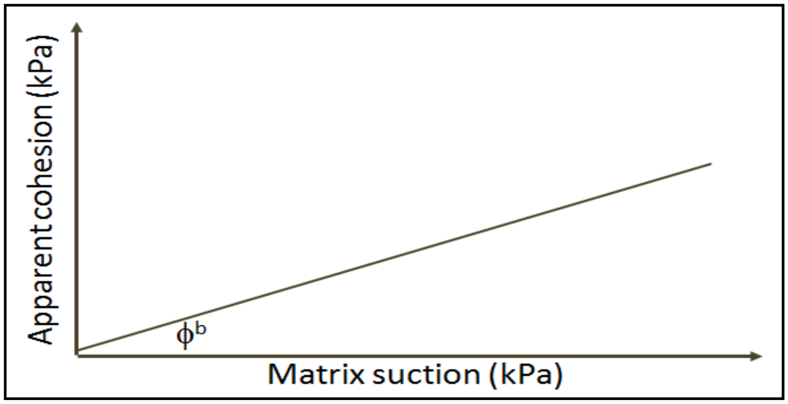


Figure 3-4: Relationship between measured or computed matrix auction and the empirical strength "apparent cohesion" defined by the ϕ^b parameter.

Method of Slices

The Method of Slices methodology included in HEC-RAS follows the more classical geotechnical approach to planar failure. The formulation of the method of slices for bank failure analysis comes from Langendoen (2008). Before the analysis the algorithm divides each user specified material layer into three vertical slices of equivalent width (Figure 3-5). This ensures that the force and momentum balance computed for each segment of the failure plan will not include more than one material type.

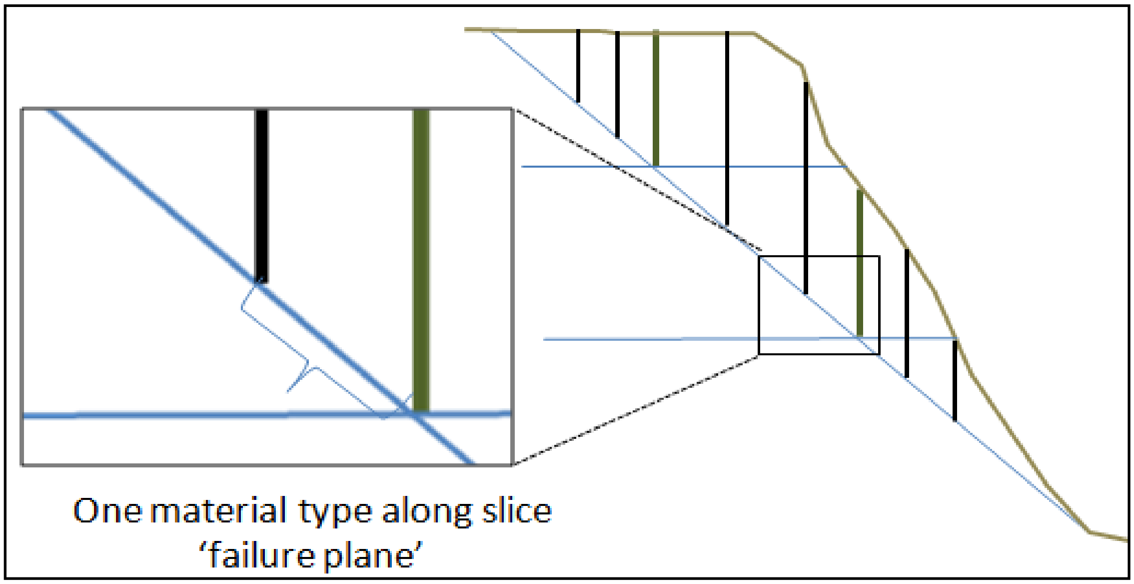


Figure 3-5: Subdivision of layers into slices. The failure block through each layer is divided into three slices of equivalent width.

The initial formulation of the method of slices (Bishop, 1955) considered forces acting at the base of each slice (along the failure plane) and included force (Figure 3-6) and momentum balances that were both vertical and normal to the slip surface. The Morgenstern and Price method (1965) added inter-slice forces in their analysis of earthen dams. The algorithms in USDA-ARS BSTEM for HEC-RAS include both inter-slice forces. The forces that act on each slice include: the weight of the slice W_j, the normal force acting on the base of the slice N_j, the shear force induced at the base of the slice S_j, inter slice normal forces E_j, and the vertical shear forces between slices X_j.

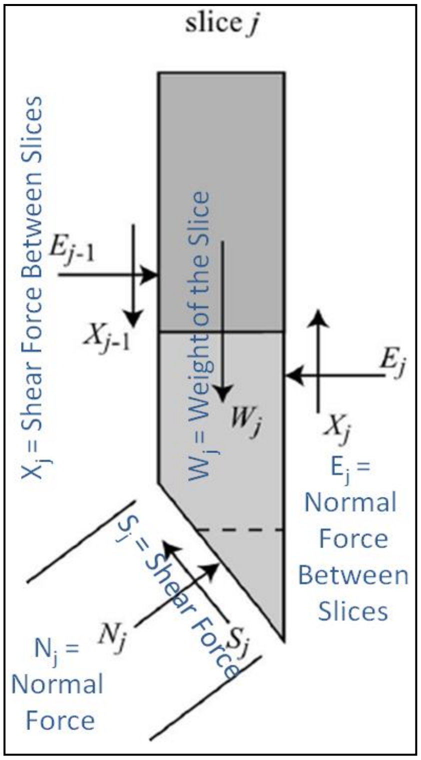


Figure 3-6: Forces acting on a slice

E_j and X_j = The inter-slice normal (E_j) and shear (X_j) forces are unique to the method of slices and deserve attention before the algorithm is described. Calculating inter-slice normal forces (E_j) from a horizontal force balance on the slice is relatively straight forward (Equation 4, Inter-slice Shear Forces). However, there is not an elegant theoretical approach to computing inter-slice shear forces. Stress-strain soil data demonstrate that there is a reasonably reliable empirical relationship of the ratio of inter-slice normal (E_j) and shear (X_j) such that:

$$X_j = \lambda E_j f(x) = 0.4 E_j \sin\left(\pi x / L_x\right) \tag{4}$$

where:

λ = the maximum ratio (forty percent),
f(x) = a non-linear function between zero (0) and one (1) that apportions the ratio spatially,
x = the lateral distance into the bank
L = lateral width of the failure plane

In other words, at its maximum (in the center of the failure block) the shear force is forty percent of the normal force (Figure 3-7), and the shear-to-normal ratio decreases for slices farther from the center and closer to the margins.

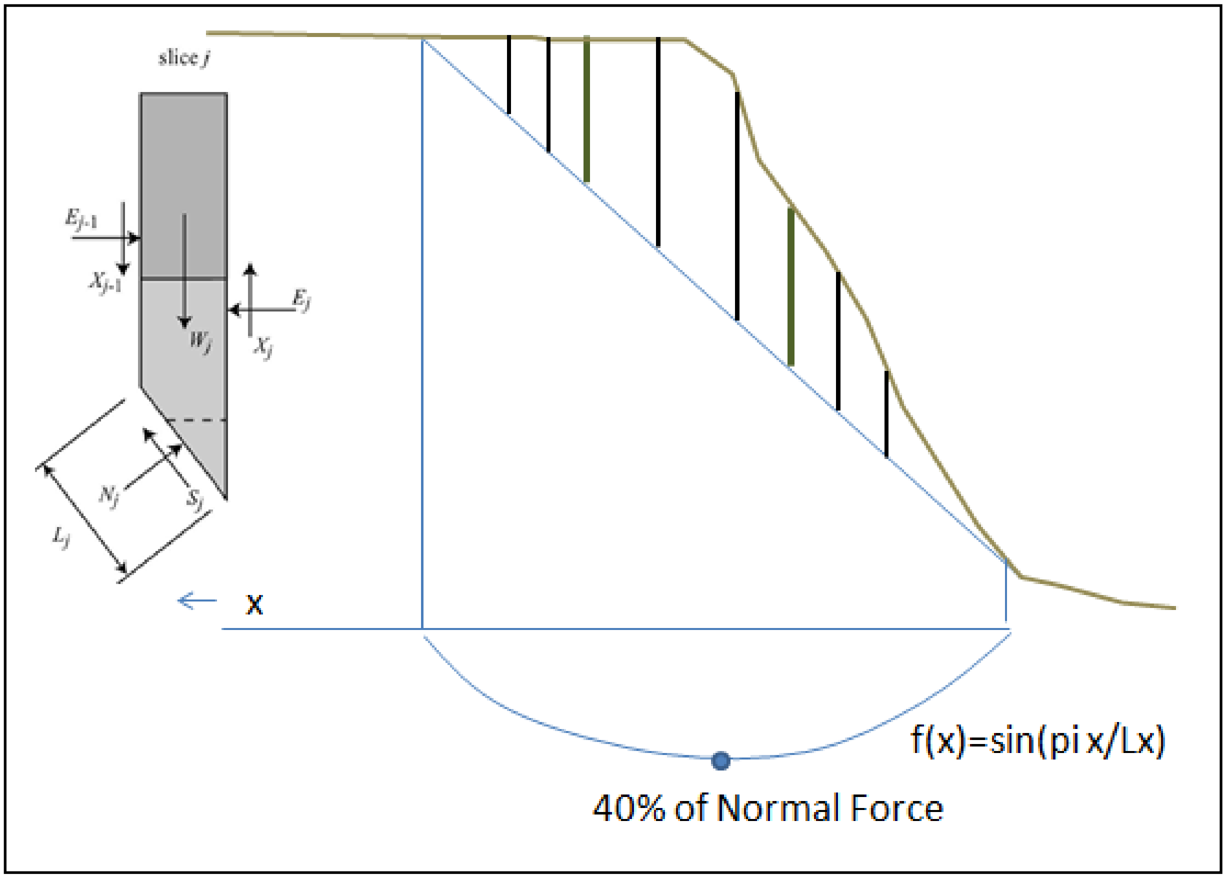


Figure 3-7: Schematic of how the ratio of inter-slice shear stress to inter-slice normal stress (□=0.4) is reduced by f(x) depending on the proximity of the slice to the center of the failure block.

FS can be computed by summing (for all slices, j) the forces acting along the failure plane. The equation for computing FS along the failure slope is a familiar mix (from the Layer Method) of driving (red labels) and resisting (green labels), soil (brown circles) and hydraulic (blue circles) forces in the following equation (Force Balance).

$$FS = \frac{\sec\beta \sum_{j=1}^{J} \left(\overset{\text{Cohesion}}{\boxed{L_j c'_j}} + \overset{\text{Frictional resistance}}{\boxed{N_j \tan\phi'_j}} - \overset{\text{Hydrostatic } \downarrow \text{ frictional resistance}}{\boxed{U_j \tan\phi^b_j}}\right)}{\tan\beta \sum_{j=1}^{J} \underset{\text{Weight of soil}}{\boxed{W_j}} - \underset{\text{Hydrostatic confining force}}{\boxed{F_w}}}$$

force

where:

FS = factor of safety
U = hydrostatic uplift
P = hydrostatic confining force of the water in the channel
ϕ' = friction angle
ϕ^b = relationship between matrix suction and apparent cohesion
c' = effective cohesion
W = weight of the soil
F_w = hydrostatic confining force

This is the Bishop (1955) approach that accounts only for the forces native to the individual slice. However, the normal force at the base of the slice is not a function of the forces intrinsic to the slice itself. It is modified by the inter-slice normal forces on either side (E_j and E_{j-1}) and the inter-slice shear (X_j and X_{j-1}) on either side of the slice. An iterative solution including two additional equations is required to compute these effects.

The inter-slice forces are calculated from the horizontal force balance (Equation 6, Horizontal Force Balance) for the slice:

$$E_j - E_{j-1} = \left[W_j - \left(X_j - X_{j-1}\right)\right]\tan\beta - \left(c'_j L_j + N_j \tan\phi'_j - U_j \tan\phi^b_j\right)\frac{\sec\beta}{FS} \tag{6}$$

Equation 6 has FS imbedded and uses the FS computed in Equation 5. With FS being computed in Equation 5, and the shear forces between neighboring slices (X_j and X_{j-1}) coming from Equation 6, a Normal force at the base of the slice that is modified for inter-slice effects, can be computed from the vertical force balance (Equation 7) of the slice:

$$N_j = \frac{W_j + X_{j-1} - X_j - \left(L_j c_j^{'} - U_j \tan\phi_j^b\right)\dfrac{\sin\beta}{FS}}{\cos\beta + \dfrac{\tan\phi_j^{'}\sin\beta}{FS}} \tag{7}$$

The new normal force at the base of the slice is then substituted back into Equation 5 to compute a new FS, which is used to update the inter-slice forces in Equation 6 and to update the Normal force in Equation 7. The Method of Slices iterates on these three equations (Figure 3-8) until the change in FS between iterations drops below 0.5 percent.

There are some considerations in the code to decrease the computational expense of iteration. The code checks the denominators of the equations for FS and N_j to determine if iteration is necessary.

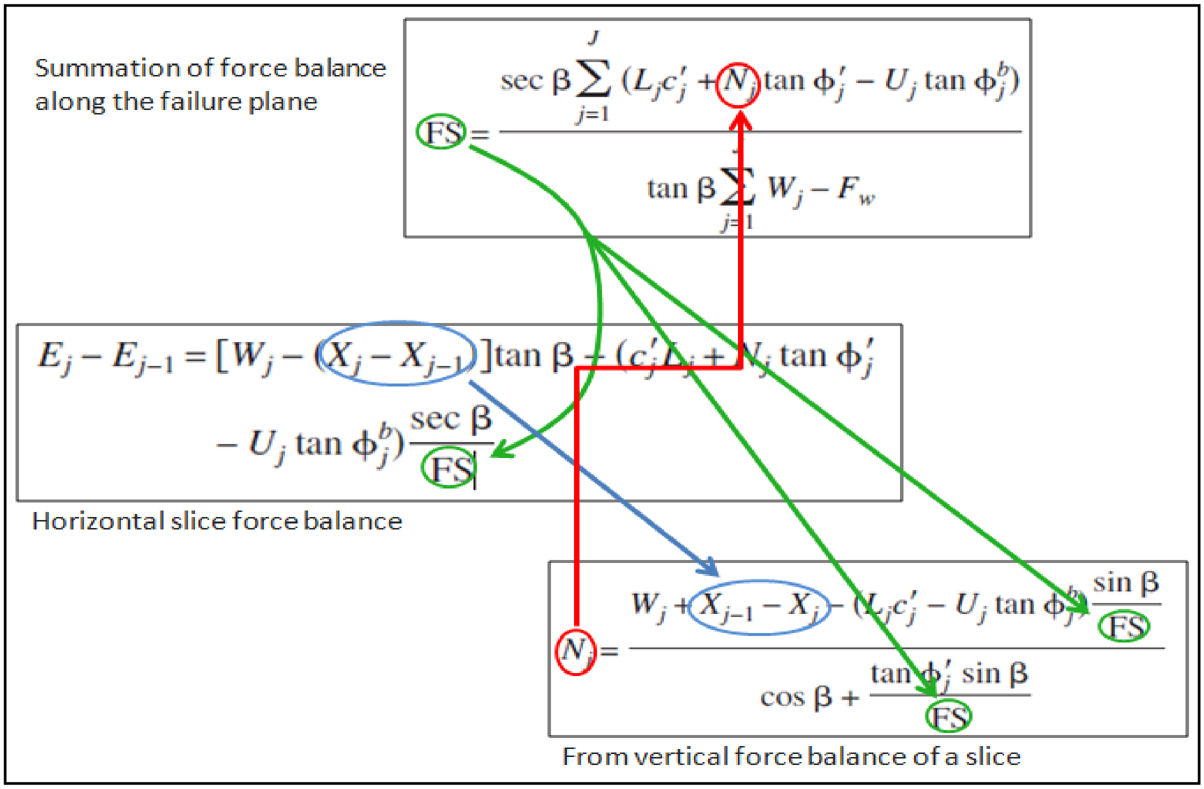


Figure 3-8: Iterative scheme to compute FS for the method of slices including the dependency of the normal force at the base of the slice on the inter-slice forces.

Tension Cracks

Tension cracks are a special case of the Method of Slices computation. Because of the vertical nature of tension cracks, they can only be computed by the Method of Slices. The USDA-ARS standalone version of BSTEM uses the Layer Method by default but switches to the Method of Slices if the tension crack parameter is defined and a tension crack is identified.

If the inter-slice normal forces are negative E less than zero the slice is in "tension". Soil generally performs very poorly under tension. Tension slices tend to be on the "upslope" portion of the failure block because there is more material "sliding away" pulling on the slice. Therefore, the code starts at the (channel side) and works inland, checking each slice interface for E less than zero.

When a slice in tension is found, the software compares the height of the slice interface to the user specified (or internally calculated) "maximum tension crack ″depth". If the slice interface is greater than maximum tension crack, then no tension crack is computed at that location and the next inland interface is analyzed. Therefore the tension crack happens at the slice interface closest to the channel that fulfills the two following criteria:

1) E less than 0 (i.e. the slice interface is "in tension")
2) The height of the interface between the slices is less than the maximum tension crack (Figure 3-9)

The vertical thickness of tension cracks is soil specific and can be determined by visual field inspection of the vertical cut at the upper portion of existing bank failures. It can also be computed with the equation for the depth at which active pressure goes to zero (Equation8) (Lambe and Whitman, 1969):

$$z_c = \frac{2c^{'}}{\gamma}\tan\left(45^{\circ} + \phi^{'}/2\right) \tag{8}$$

HEC-RAS currently uses this equation by default for the method of slices. The standalone version of BSTEM can override this value with a user specified maximum tension crack, but this is not available in HEC-RAS at this time.

If a tension crack is identified, the slices inland from the tension crack are excluded from the stability analysis. Because the failure plane along these inland slices is higher, the inland slices will tend to have higher suction forces and lower buoyant forces. Therefore, a tension crack that excludes these inland slices will reduce the FS and make the bank more likely to fail.

If FS is less than zero and a tension crack is computed, the failure block on the river side of the tension crack is removed from the bank and added as sediment load to the sediment model, while the inland slices remain fixed to the bank, resulting in a vertical wall.

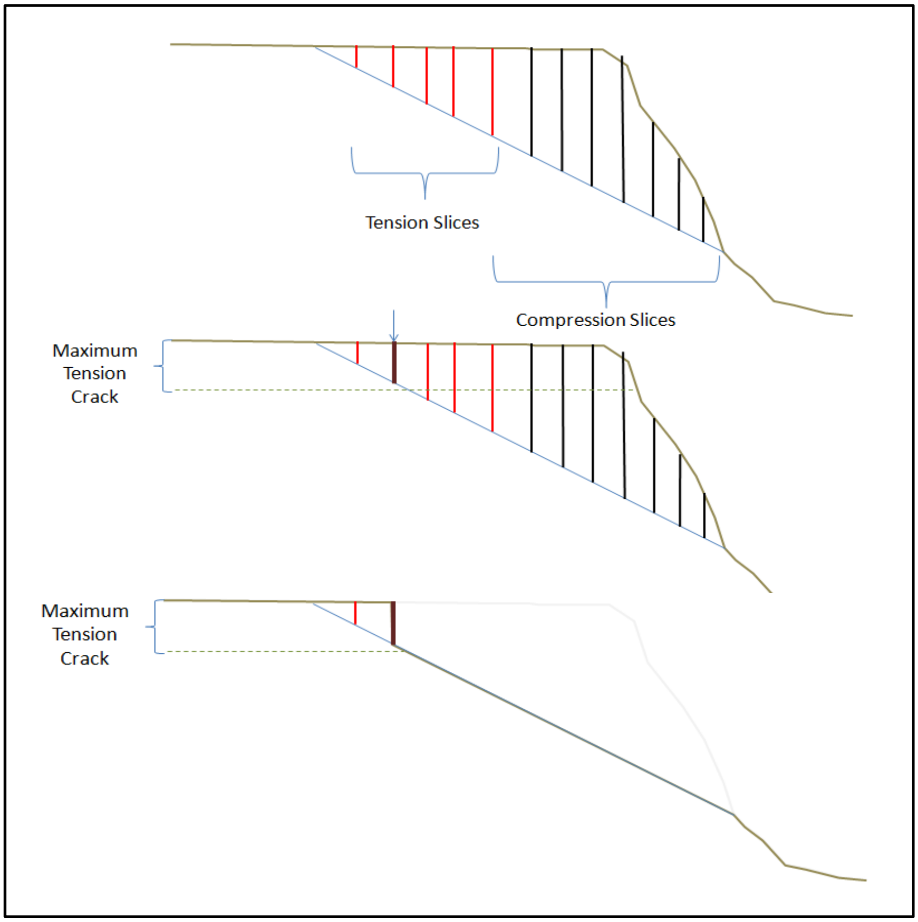


Figure 3-9: Tension crack computation criteria

Cantilever Failures

Cantilever failures, mass wasting of overhanging soil blocks, are also a special case of the Method of Slices. Thorn and Tovey (1981) established three types of cantilever failures (Figure 3-10) that include three distinct processes:

1. The soil block shears off along the vertical or obtuse failure plane.
2. The soil block rotates off the bank due to the tension (e.g., inter-slice normal forces go to zero and cohesion is not sufficient to keep the overhanging block in place.
3. The lower layer of the block falls off.

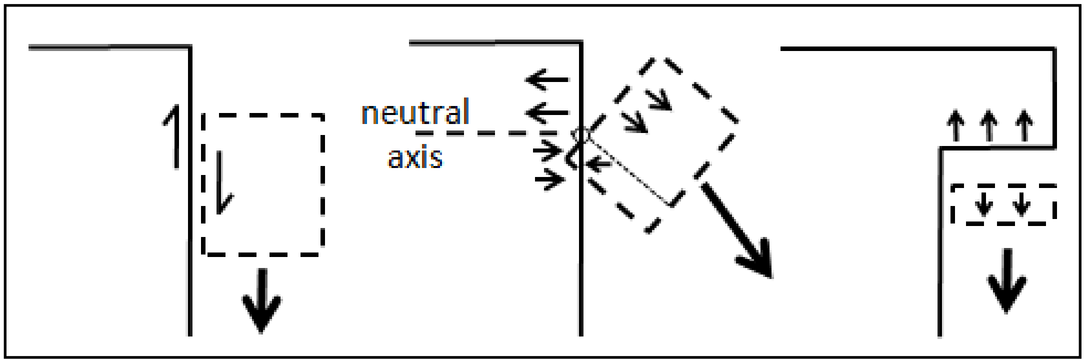


Figure 3-10: A taxonomy of cantilever failure mechanisms (after Thorn and Tovoy, 1981).

There is no special cantilever case algorithm in HEC-RAS. The methods available in HEC-RAS can only apply the Method of Slices to overhanging bank configurations, and therefore can only simulate the first (sliding) mechanism of cantilever failure. Ninety degrees is the maximum failure angle that HEC-RAS will consider.

To identify cantilever failure HEC-RAS checks to see if the maximum β (the maximum failure plane angle that is entirely included in the bank soil) at any evaluation point is greater than or equal to ninety degrees (Figure 3-11). This indicates an overhanging bank and that Method of Slices was used for the evaluation at that point even if the Layer Method is selected.

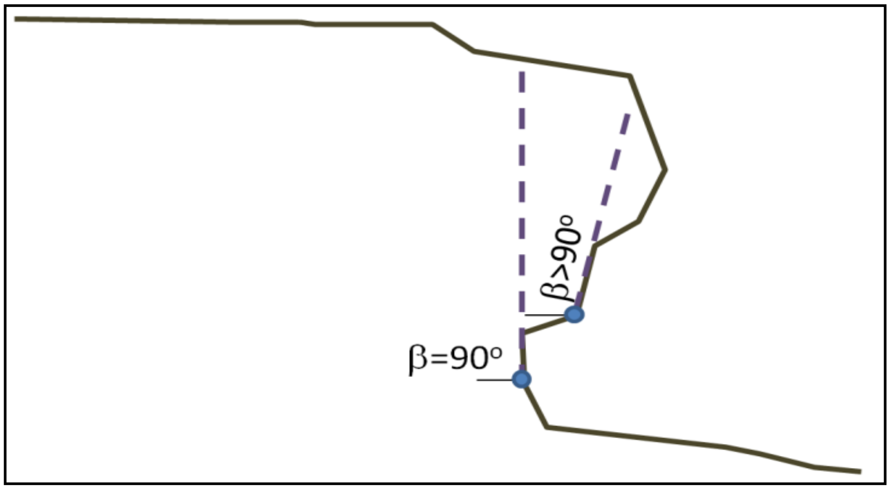


Figure 3-11: Example of maximum failure plane angles for overhanging bank situations where β_{max} is greater than or equal to ninety degrees. These classify as cantilever failures and the software will force a Method of Slices analysis

Selecting a Method

The Layer Method and the Method of Slices generally produce very similar results. Differences between the two methods are summarized in Table 3-1. The standalone version of the USDA-ARS BSTEM model uses the Layer Method unless it has to compute tension cracks or cantilever failure, which cause it to switch to the Method of Slices. The choice mainly involves a trade-off between a theoretical consideration (the normal force distribution) and a practical consideration (run time).

Method of Slices computes a somewhat more realistic distribution of normal stresses along the failure plane (Figure 3-12). The Layer Method computes larger normal stress for larger layers, which tend to be along the top of the failure plane while the Method of Slices computes larger normal stresses for larger slices which tend to exert their forces at the base of the failure plane (which is a more realistic assumption). Therefore, without tension cracks, the Method of Slices will generally compute a slightly higher FS for the same data set. However, because the Method of Slices allows tension cracks, which tend to remove more resisting forces than driving forces, the Method of Slices often returns a lower FS, and more failures.

Table 3-1: Method selection criteria

Layer Method	**Method of Slices**
Customized for bank failure applications.	Closer to the comparable geotechnical analyses.
Higher normal stresses along the failure plane generally computed for the higher layers.	Higher normal stresses along the failure plane generally computed for the deeper layers.
Non-Iterative. More computationally efficient.	Apportions normal stresses according to more physically based assumptions.
Switches to method of slices if tension cracks or overhanging banks form.	Computes tension crack and cantilever failures.

However, because the Method of Slices is iterative and the Layer Method is not, the Layer Method is more computationally efficient and can decrease run times. Since there are already two iterative computations in BSTEM outside of the FS computation (e.g., analysis for several nodes up the bank face and the selection of the critical failure plane for each node) bank failure analysis can be computationally expensive for big projects or long runs. The Layer Method may reduce those run times.

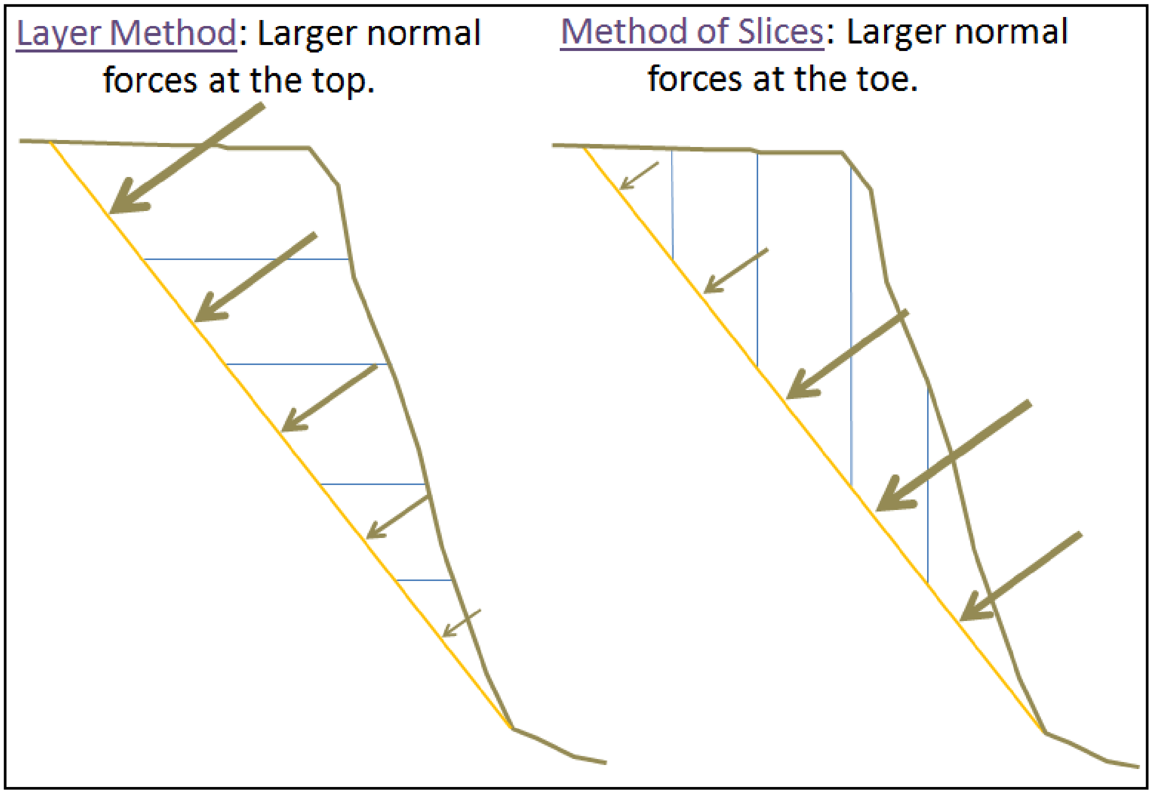


Figure 3-12: Theoretical difference in normal stress computed by Layer Method and Method of Slices.

Steps in a Bank Failure Analysis

The physics described the sections above, computes the FS for a single failure plane. However to determine if the bank will fail and where it will fail several failure planes 1) with different starting elevations on the face of the bank and 2) with different angles have to be evaluated (Figure 3-13).

Therefore, regardless of what method was used to compute the physical FS, the following is a six step iterative evaluation for each bank and time step analyzed:

1. Evaluate nodes at several vertical locations up the bank. Then for each node:
2. Select the bounding failure planes (minimum and maximum angles) and an initial guess for FS_{cr}
3. Compute the FS_i
4. Use that information to select a more likely critical failure plane (using the "bracket and Brent" optimization algorithm from Teukolsky et al. (2007)) (setting FS_{i+1} to a new estimate of FS_{cr})
5. Decide when FS is close enough to FS_{cr} to stop, otherwise repeat Step 3
6. Select the FS_{cr} for all nodes and if FS_{cr} is less than one, fail the bank, update the cross section, and send the bank sediments to the routing model

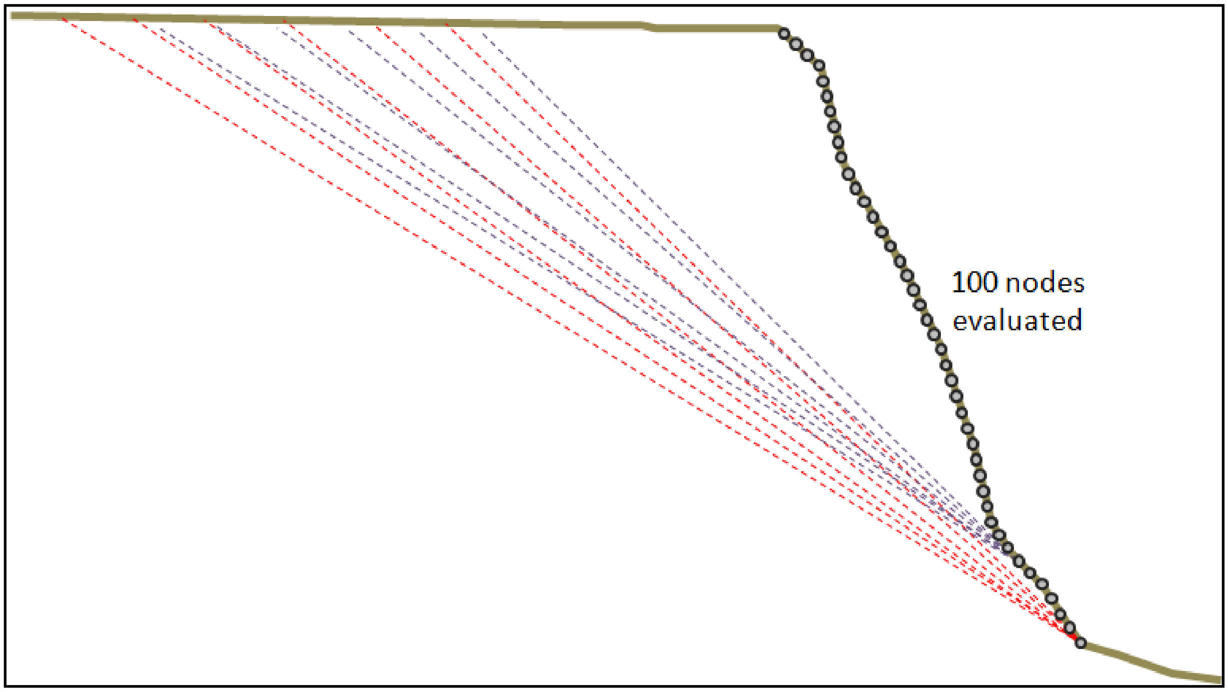


Figure 3-13: Multiple failure planes have to be evaluated at multiple nodes.

The following describes the above steps in more de.

1. Evaluate nodes at several vertical locations up the bank

The software will find a critical failure plane that starts at several vertical locations along the face of the bank. HEC-RAS evaluates 100 points which are evenly spaced vertically between the user specified toe and top of bank (one percent evaluation intervals) by default. Fewer evaluation points can be specified under BSTEM to improve run time. However, bank points that are evenly spaced will not be evenly spaced along an irregular bank.

For each elevation, the bank failure algorithms will find a critical FS failure plane. Instead of running many angles for each node at very small increments, a minimization algorithm with quadratic convergence (bracket and Brent) is used to find the failure plane with the minimum FS at each node with as few failure planes as possible. This process includes the next Steps.

2. **Select the bounding failure planes (minim and maximum angles) and compute a FS for each**

The first step of finding the critical FS of a given bank node is to bound the possible angles (the "bracket" in bracket and Brent). The minimum angle is set to half of the friction angle, which is a reasonable angle below which most bank configurations would be expected to remain stable. The maximum angle is the largest angle that is entirely in the soil matrix (Figure 3-14).

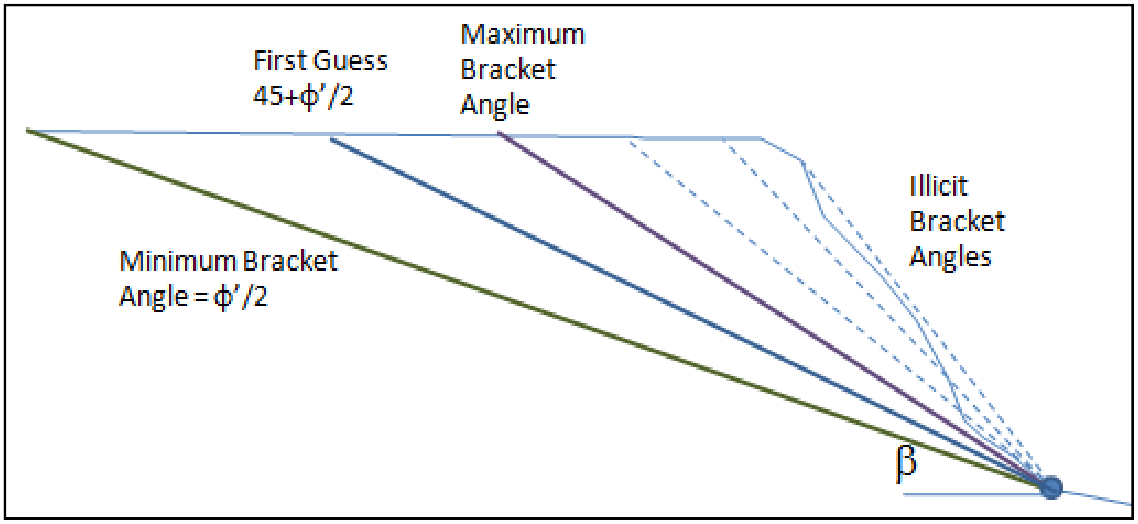


Figure 3-14: Computing the maximum and minimum failure angles and the first guess.

Then the bank failure method makes an initial guess for the critical failure plane to start the parabolic search, which is 45degrees plus half the friction angle.

However, sometimes it is not as simple as the classical configuration in Figure 3-14. A number of unique configurations posed by natural channel banks can cause the default maximum angle to be less than half the friction angle or can generate an initial guess '45°+ϕ'/2) to fall outside of the bracket among other complications. Therefore, there are special cases to deal with unique configurations.

With the maximum and minimum angles set and a first estimate established, the bank failure algorithm is prepared to start the iterative search to determine a critical failure plane angle.

In the initial iteration, an FS is computed for the maximum, minimum, and initial estimate failure plane angles by the methods described above (Figure 3-15). In each successive iteration, an FS is computed for the new failure plane angle selected by the parabolic search.

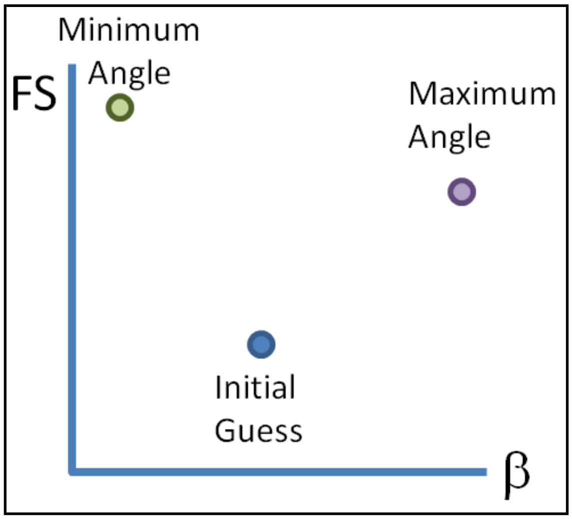


Figure 3-15: FS computed for the maximum and minimum angles and the initial estimate.

FS is computed for the maximum, minimum and best guess angles with the physics described above, and then the three angle-FS pairs are passed to the bracket and Brent (Teukolsky et al. 2007) routine, which fits a parabola to the FSs associated with the three angles and then iterates to find the minimum. With each iteration, the bracket shrinks (the maximum and minimum possible angles converge) and the algorithm completes when the bracket drops below 0.5 deg.

3. Compute FS$_i$

The algorithm computes an FS for the β_i selected by the methods described in detail ab

4. Use that information to select a more likely critical failure plane

Next HEC-RAS uses a parabolic optimization algorithm (bracket and Brent) to find an angle (β) that is likely to have a lower FS. The software fits a second order quadratic equation through the three factors of β - FS points and identifies the angle (β_i in Figure 3-16a) associated with the parabolic minimum.

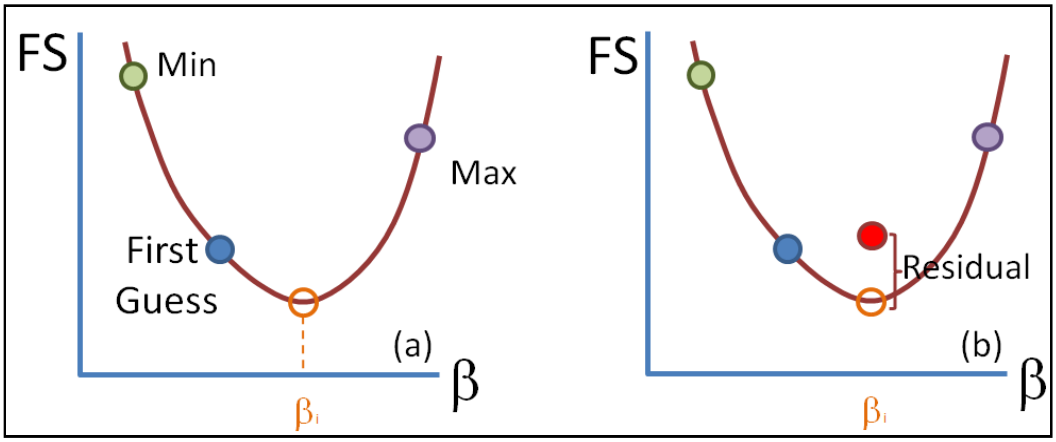


Figure 3-16: A parabolic function is fit to the three points and a) the function minimum is selected as the next failure plane, and b) compute a FS associated with that failure plane and the residual between the FSs predicted by the method.

5. Decide when the FS is close enough to FS_{cr} to stop, otherwise Iterate

The actual relationship between β_i and FS does not necessarily fit a second order quadratic equation. Therefore, the FS computed for the angle selected (β_i) will not precisely match that predicted by the function. Therefore, the bank failure algorithm evaluates the difference between the computed FS and the predicted FS ("residual" in Figure 3-16b). If the difference is less than half a percent (i.e., residual less than 0.5 percent) then the parabolic function is considered a good approximation of the β–FS relationship and the β_i is adopted as the critical failure plane for this bank node.

However, if the residual is greater than 0.5 percent, the algorithm will iterate and return to Step 3, by trying to identify the most likely critical failure plane angle given the new information. The new β_i - FS_i point becomes the new maximum or minimum (depending on which side the last β_i is on) and a new, narrower, second order quadratic is fit to the new three points (Figure 3-17). A new β_{i+1} is selected at the minimum of the function. The FS is calculated (Step 4) and the residual evaluated (Step 5). As this algorithm iterates the range between the maximum and the minimum shrinks as the function converges (usually within a few iterations) to a solution.

However, sometimes β - FS functions that depart substantially from the parabolic model can return false, local minimums. For example, the theoretical function in Figure 18a passes through the same points as Figure 3-17b but would not be predicted by the "narrowing parabolic" method. Therefore, the iteration optimization includes occasional searches to find other β regions with low FSs.

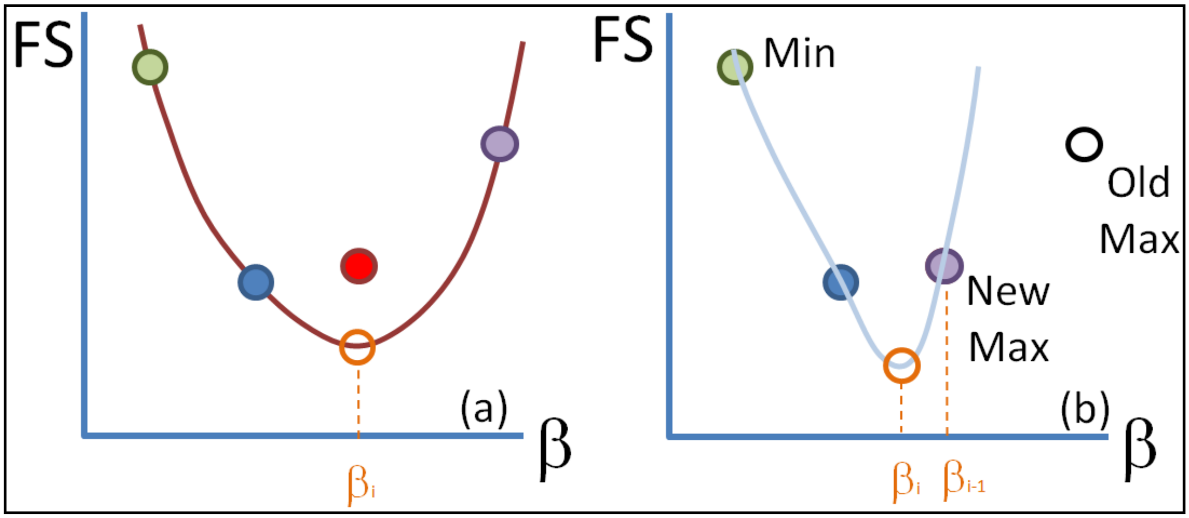


Figure 3-17: The new FS computed for βi becomes the new maximum or minimum and a tighter polynomial is fit to the new three points to identify a new function minimum.

Additionally, sometimes the relationship between β and FS is monotonic (Figure 3-18b). This occurs in the case of cantilever failures where the highest factor of safety is often associated with the maximum angle. If the maximum angle is has the lowest factor of safety in Step 2, this is automatically accepted as the critical failure plane and the model does not iterate.

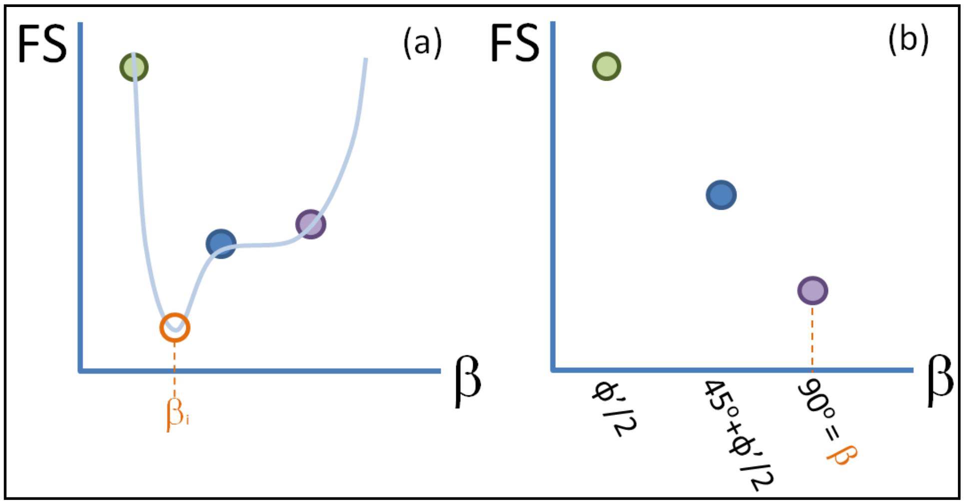


Figure 3-18: Monotonic β- FS function associated with a cantilever curve.

6. Select the FS_{cr} for all nodes and if FS_{cr} is less than one, fail the bank, update the cross section, and send the bank sediments to the routing model

Finally, after the critical failure plane is iteratively computed for each of the vertical evaluation points on the bank, the failure plane with the lowest overall failure plane is selected. If the FS is greater than one, the bank is stable. However, if the FS is less than one, then the bank fails and the bank material inside of the failure plane is removed from the bank and added to the control volume of the sediment routing model associated with the cross section. The material inside of the failure plane is removed, the cross section is updated, and the material is introduced into the sediment routing model as a lateral load.

Toe Erosion (Fluvial or Hydraulic Erosion)

The combination of vertical bed change in the classical HEC-RAS mobile bed computations and the bank failure algorithms can model the interaction of model incision and bank failure. As a channel incises the potential failure plane through the new exposed toe, the bank steepens and the FS drops. Therefore, incision can induce bank failure (or conversely deposition can stabilize banks). However, there is a third that neither the HEC-RAS sediment model nor the bank failure model covered above capture, which is important in modeling bank erosion and loads - toe scour.

Toe scour is a fluvial, hydraulic process driven by the flow (versus bank failure which is primarily a gravity driven geotechnical process). The classical mobile bed algorithms in HEC-RAS only compute vertical movement of the bed, but hydraulic forces can undermine the toe of a bank, which can reduce the length of the failure plane (and the frictional resistance) and decrease the factor of safety of the critical failure plane faster than incision.

Determining the Zone of Scour

The movable bed limits in the HEC-RAS sediment transport module define the transition between incision and scour. Inside of the movable bed limits, the channel is modified by the movable bed model (incision and deposition translated into vertical node movement).

Outside of the movable bed limits, scour equations are used[5]. The model is very sensitive to the selection of these limits.

The scour equations in the USDA-ARS BSTEM that are implemented in HEC-RAS compute lateral bed change of the wetted nodes outside the movable bed limits for cohesive or cohesionless soils based on a radial shear distribution.

Determining τ_{node}

Unlike channel deposition or erosion, toe scour does not affect all nodes equally. This is important for its interaction with the bank failure model because the failure plane will likely pass through the vertical location of maximum scour. However, to compute differential lateral scour, the software must compute a local shear stress for each node.

There are several ways to post process one-dimensional hydraulics to compute local shear stress. The most common is to subdivide the cross section into vertical "prisms" (blue lines in Figure 3-19) and compute a local shear stress based on the hydraulic radius of each one. However, the assumption of zero inter-prism friction only holds along the planes normal to the isovels (contours of constant velocity). Vertical divisions violate this assumption because they are not perpendicular to the isovels.

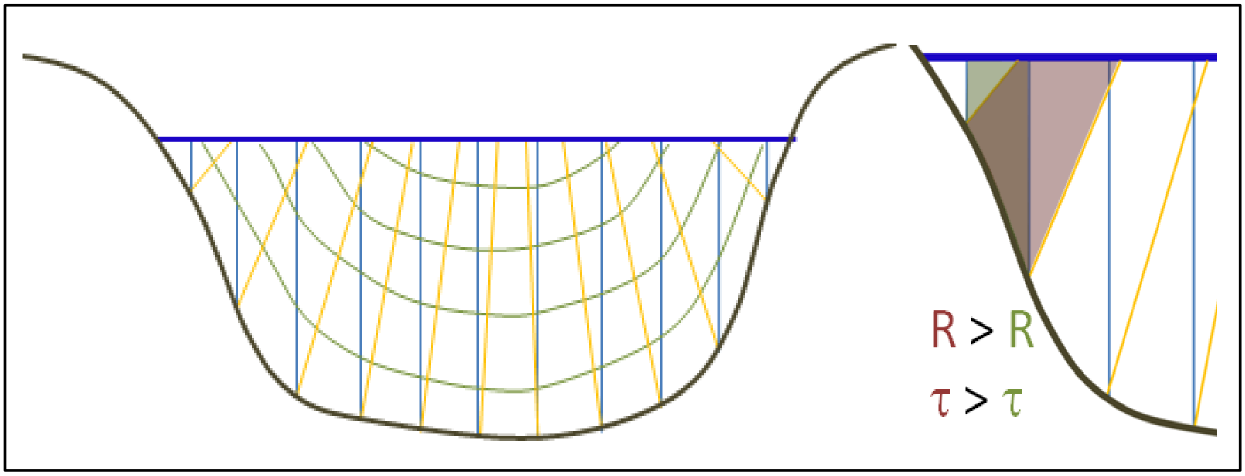


Figure 3-19: Subdividing the cross section into vertical conveyance prisms (blue) versus zones (yellow) perpendicular to the isovels (green).

Alternately, the one-dimensional cross section can be divided into "radial prisms", non-vertical zones by partitions perpendicular to the isovels (yellow lines in Figure 19). These approaches will compute different hydraulic radii (a sensitive variable for computing the shear stress) especially in the zone closest to the bank where the toe scour computations are applied. The radial prisms tend to have higher hydraulic radii, and therefore, higher shear stress that the vertical prism associated with the same bank segment and represent a more realistic shear stress distribution (Figure 3-19). Therefore, the bank erosion algorithms use a radial distribution, dividing the flow field, hydraulic radius, and shear stress with radial prisms.

If bed and bank roughness are approximately the same, then we can assume that the line that bisects the toe is normal to the isovels (Kean and Smith, 2001). Therefore, the first step in developing the radial shear distribution is finding the angle bisecting the toe (Figure 3-20a). Bank and channel segments are computed by connecting the scour toe (the movable bed limit) to the edge of bank and the next interior channel point respectively (Figure 3-20). This segment determines the zone of the one-dimensional cross section dedicated to toe scour.

Modeling Note: This computation makes the scour computations sensitive not only to the selection of the mobile bed limits but also to the elevation of the interior node. Random bed fluctuations can cause this node to diverge from the basic lateral channel slope (Figure 20b) which could result in an artificially truncated or enlarged.

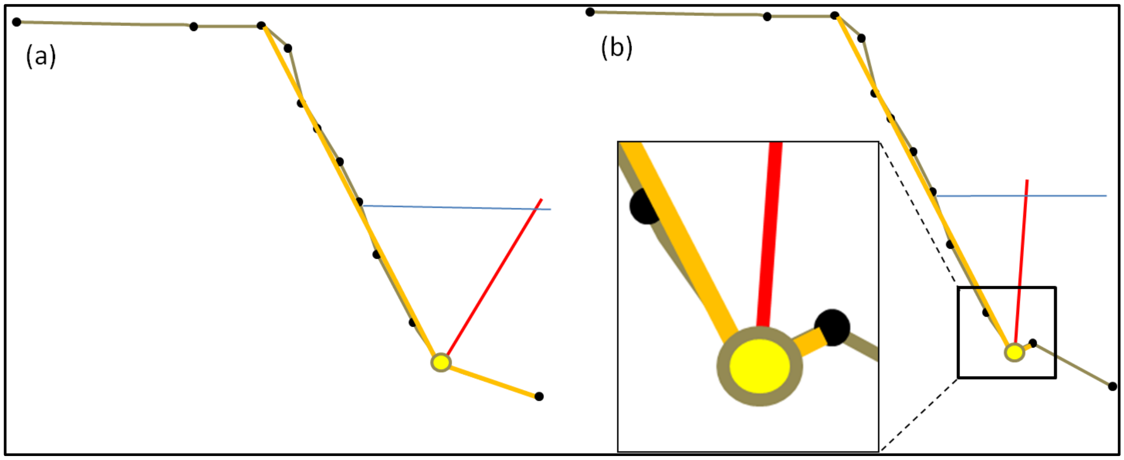


Figure 3-20: Finding the bisecting angle at the toe which will determine the portion of the water column that is contributing to toe scour.

Next a "radial prism" is associated with each node (cross section station-elevation points in the toe scour zone). The water surface intersection point connects the midpoint between wetted bank nodes. The water surface intersection point is a relative proportion of the water depth of the midpoint between nodes and the total depth to the midpoint of the movable bed limit and the next interior node (Figure 3-21).

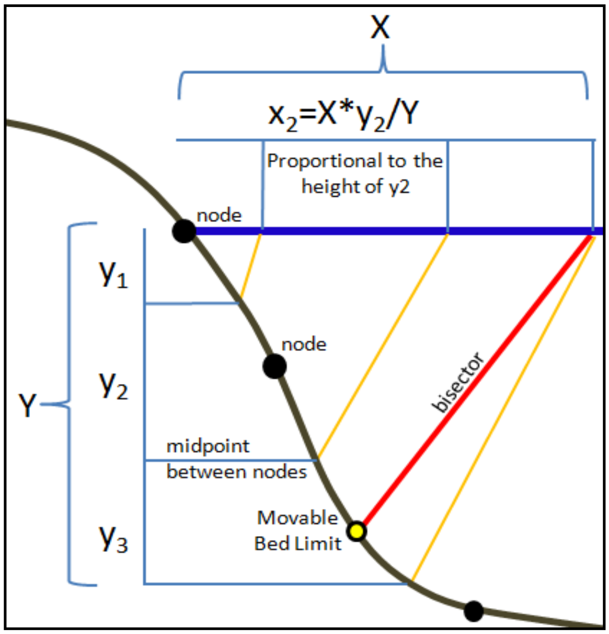


Figure 3-21: The orientation of the radial prisms used to compute a shear at each node is computed by proportioning the intersection of the water surface with the depth within the scour zone.

Once the radial flow prism is computed for each wetted bank node (Figure 3-22), the hydraulic radius of the prism is computed from the area and wetted perimeter (water-water boundaries are ignored). Then the shear stress for each radial prism is computed from the average one-dimensional shear stress as a ratio of:

$$\tau_{\text{i}} = \tau_{\text{avg}} \left(\text{R}_{\text{i}} / \text{R}_{\text{max}} \right)$$

where R_{max} which is typically R_{toe} is the largest hydraulic radius among the radial flow prism.

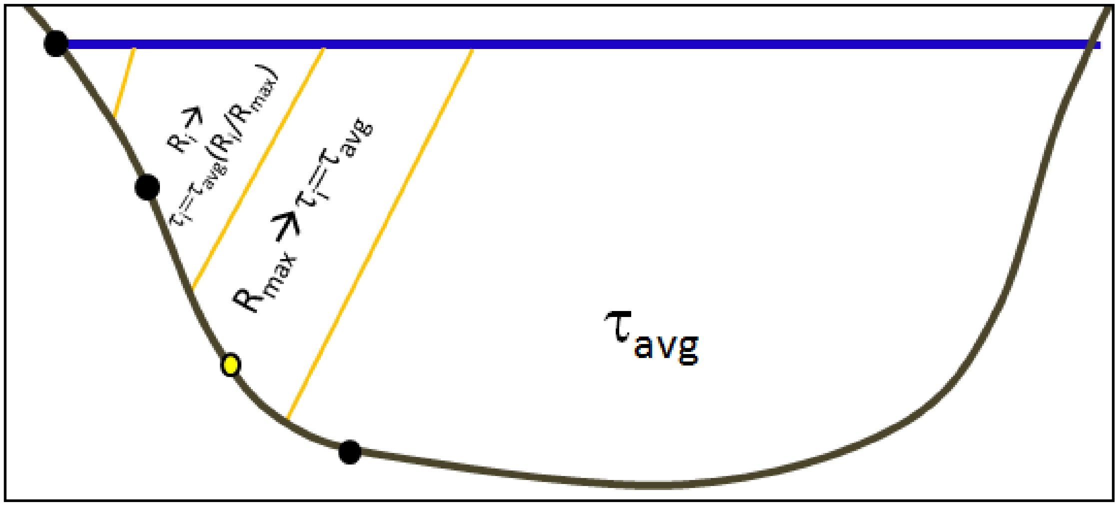


Figure 3-22: Apportioning the local shear by a ratio of the hydraulic radius of the radial prisms.

Scour

If the clay content of the layer is greater than twenty percent, the software uses an excess shear cohesive equation, scoring material based on the erodibility and shear. For clay content less than twenty percent, scour is computed using a transport function. Different nodes (Figure 3-23) can invoke different transport equations depending on the associated layer material. Then the nodes in the toe scour region of the model are adjusted laterally.

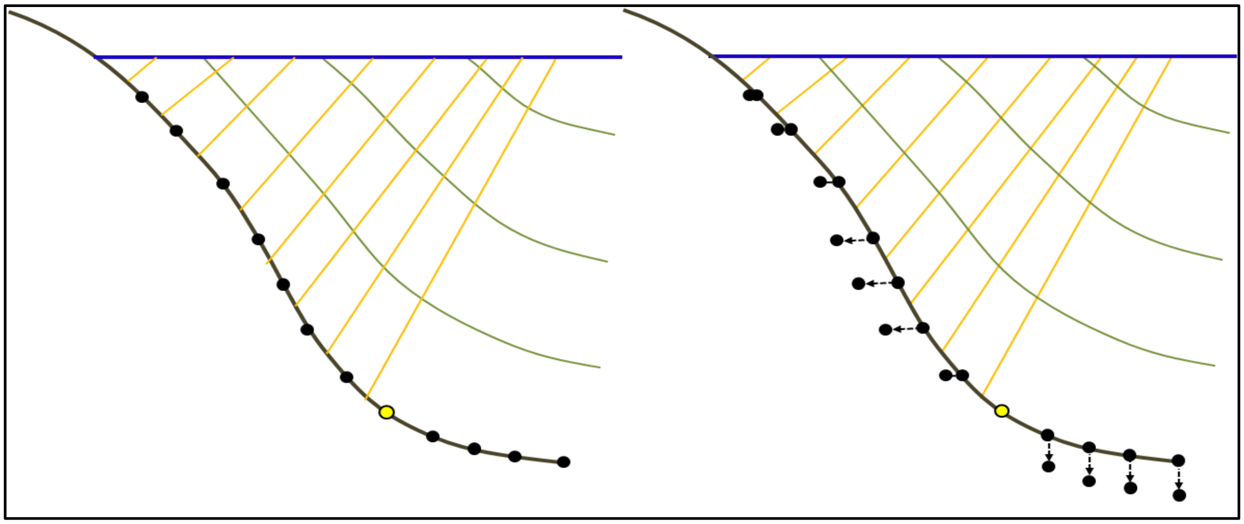


Figure 3-23: Nodes between the movable bed limits are adjusted vertically (and uniformly) and the wetted nodes outside the movable bed limits are adjusted laterally (and independently).

This radial shear distribution commonly computes maximum shear stress at the toe. Therefore, the toe will often scour more than the other nodes, yielding an overhanging bank like the one in Figure 3-24a. HEC-RAS requires increasing station values, so it cannot retain or represent overhanging banks in the current version. Therefore, HEC-RAS assumes that overhanging banks fail vertically, as depicted in Figure 3-24. Because overhanging banks eventually fail, this should not introduce substantial error in long term models.

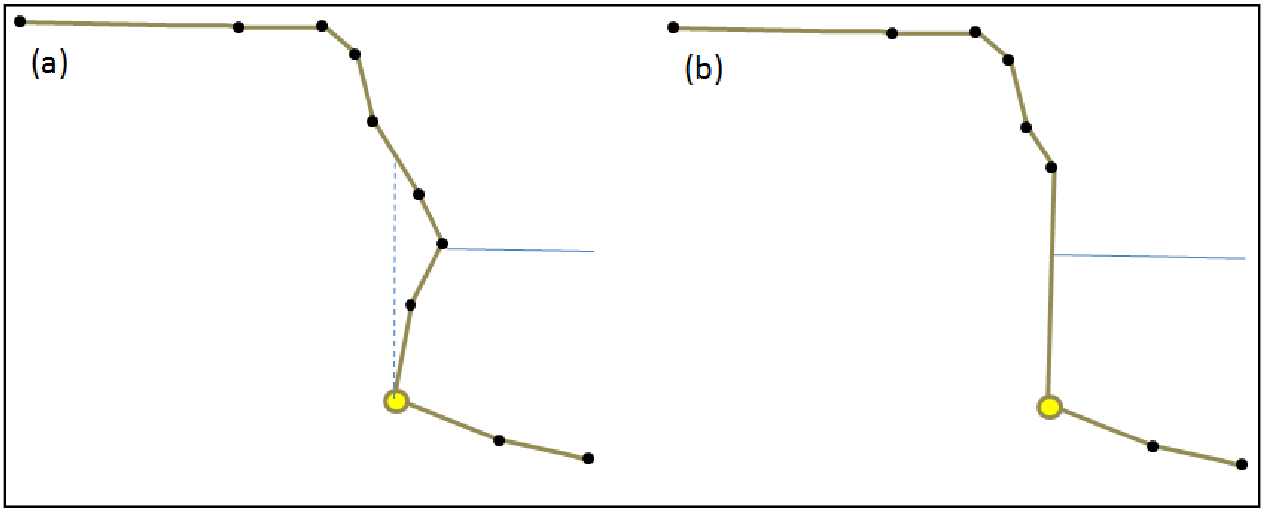


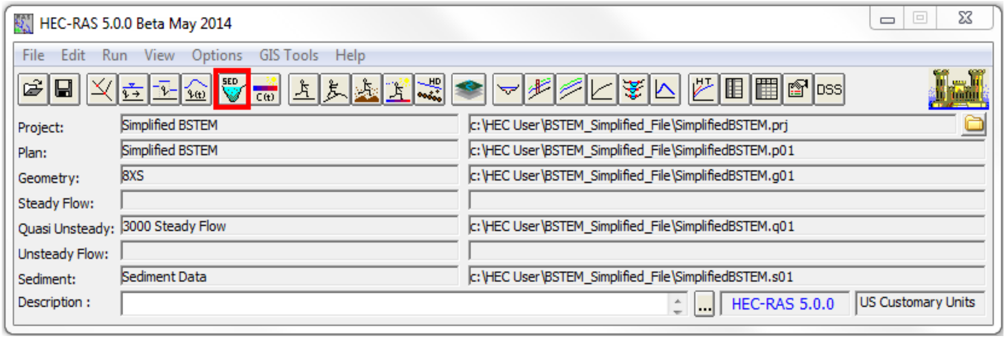
Figure 3-24: Overhanging bank simplification method.

CHAPTER 4 CHAPTER 6 BSTEM: USDA-ARS BANK STABILITY AND TOE EROSION MODEL IN HEC-RAS: USER'S MANUAL

Getting Started

BSTEM toe erosion and bank failure analysis will be performed as part of a sediment transport analysis on any cross section bank that has all the necessary parameters. Computing bank failure at every bank will increase run times. Therefore, it may be advantageous to only specify BSTEM parameters for banks that have a probability of failure.

To enter BSTEM data in HEC-RAS, from the HEC-RAS main Window, from the Toolbar, click Sediment Boundary Conditions (Figure 4-1). Bank failure analysis is currently only computed as part of a sediment transport analysis. The Sediment Data Editor will open (Figure 4-2). From the Sediment Data Editor the user will enter standard sediment transport data on the first two tabs (Figure 4-2). To enter BSTEM information, click the USDA-ARS Bank Stability & Toe Erosions MODEL (BSTEM) tab (Figure 4-2).

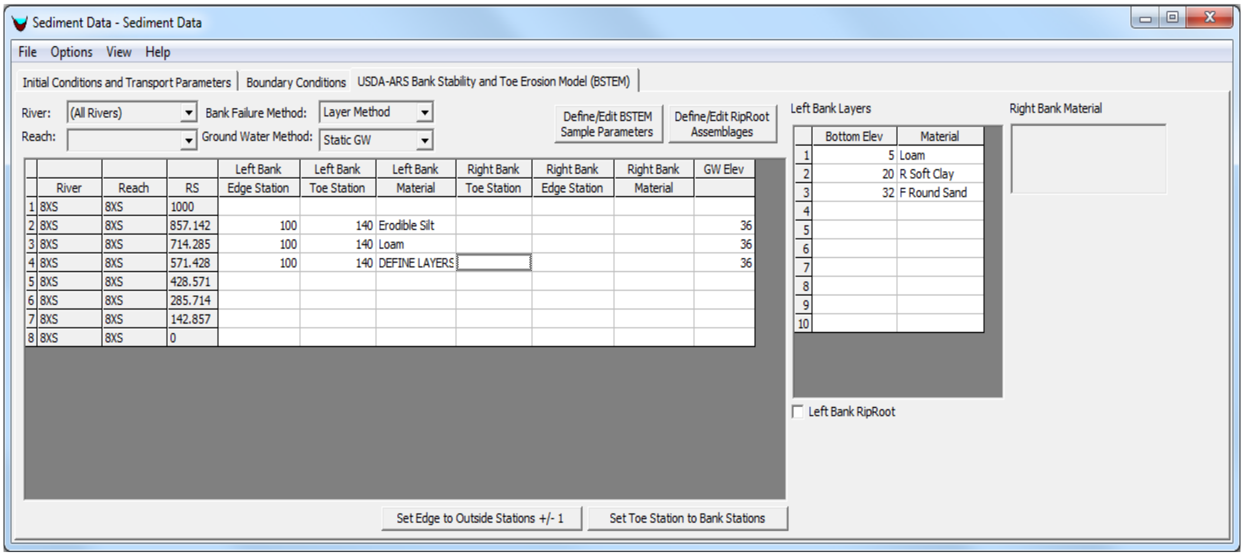


Project:	Simplified BSTEM	c:\HEC User\BSTEM_Simplified_File\SimplifiedBSTEM.prj
Plan:	Simplified BSTEM	c:\HEC User\BSTEM_Simplified_File\SimplifiedBSTEM.p01
Geometry:	8XS	c:\HEC User\BSTEM_Simplified_File\SimplifiedBSTEM.g01
Steady Flow:		
Quasi Unsteady:	3000 Steady Flow	c:\HEC User\BSTEM_Simplified_File\SimplifiedBSTEM.q01
Unsteady Flow:		
Sediment:	Sediment Data	c:\HEC User\BSTEM_Simplified_File\SimplifiedBSTEM.s01
Description :		

HEC-RAS 5.0.0

US Customary Units

Figure 4-1: HEC-RAS Window.



River: (All Rivers)

Reach:

Bank Failure Method: Layer Method

Ground Water Method: Static GW

	River	Reach	RS	Left Bank Edge Station	Left Bank Toe Station	Left Bank Material	Right Bank Toe Station	Right Bank Edge Station	Right Bank Material	GW Elev
1	8XS	8XS	1000							
2	8XS	8XS	857.142	100	140	Erodible Silt				36
3	8XS	8XS	714.285	100	140	Loam				36
4	8XS	8XS	571.428	100	140	DEFINE LAYERS				36
5	8XS	8XS	428.571							
6	8XS	8XS	285.714							
7	8XS	8XS	142.857							
8	8XS	8XS	0							

Left Bank Layers

	Bottom Elev	Material
1	5	Loam
2	20	R Soft Clay
3	32	F Round Sand
4		
5		
6		
7		
8		
9		
10		

Right Bank Material

☐ Left Bank RipRoot

Figure 4-2: HEC-RAS Sediment Data Editor - USDA-ARS BSTEM Tab.

Defining Cross Section Configuration

Setting up HEC-RAS cross sections (for the left or right bank) in such a way that it is also compatible with BSTEM is an extremely important step in getting physically appropriate failures from the BSTEM computations. The conceptual BSTEM half cross section (Figure 4-3) is composed of four segments (green labels in Figure 4-3) with unique slopes:

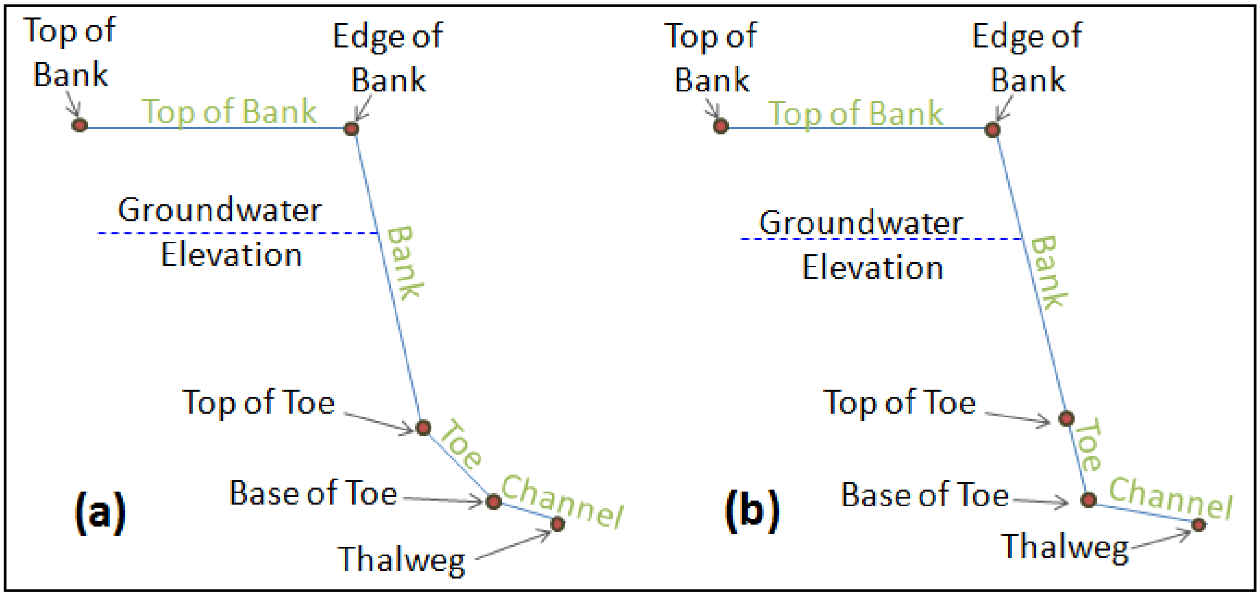


Figure 4-3: Definition of station points for BSTEM half cross sections

1. The **Top of Bank** which is the relatively flat portion of the cross section above the bank.
2. The **Bank** which is the steepest part of the cross section.
3. The **Toe** which is a mild slope between the bank and the channel, presumably composed of blocks of material that have fallen and accumulated at the base of the bank and are protecting the toe or some sort of rip rap or toe protection.
4. The **Channel** which is the region between the toe and the thalweg.

HEC-RAS divides a cross section at the thalweg and uses the station-elevation points to the left of the thalweg for the left BSTEM half-cross section and those to the right of the thalweg for the right BSTEM geometry. There are at least four important current considerations for setting up an HEC-RAS cross section to get good performance from the BSTEM routines.

1. The **Top of Bank** point should be far enough to the left or right (depending on which bank is being modeled) of the **Edge of Bank** to accommodate the full range of possible failure slopes (Figure 5-4).

2. HEC-RAS 5.0 with BSTEM works best if the **Top of Bank** is not the farthest node to the left or right and if there are no station-elevation points between the **Top of Bank** and the **Edge of Bank.**

3. There should be a number of relatively evenly spaced points between the **Edge of Bank** and the **Top of Toe**. BSTEM starts its failure plane search method at each station,

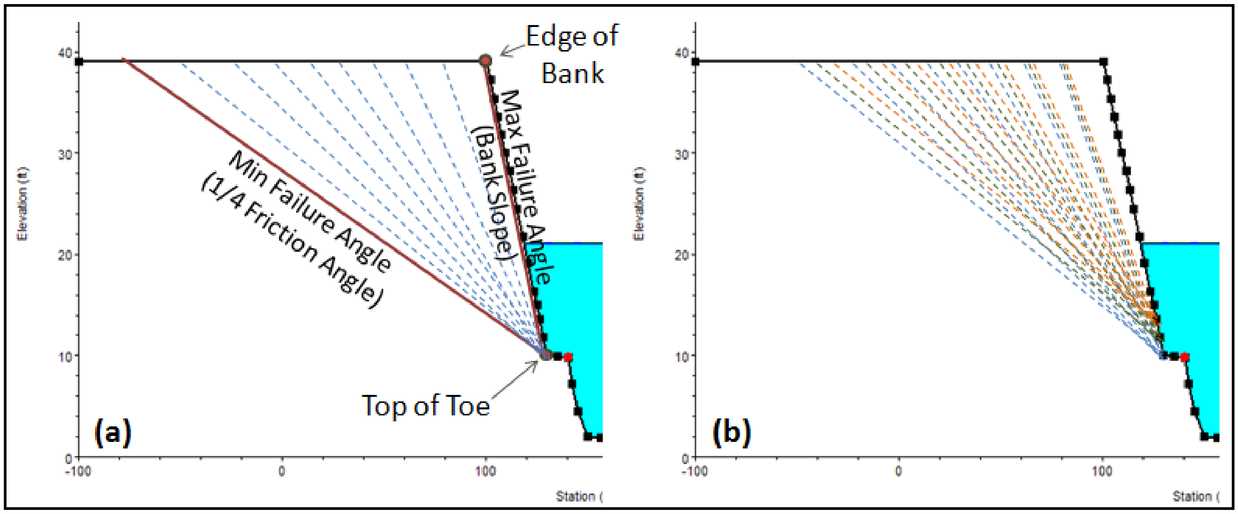


Figure 4-4: (a) The maximum, minimum and incremental angles evaluated (b) at each node between the Top of Toe and Edge of Bank.

4. Elevation point between the **Edge of Bank** and the **Top of Toe** (Figure 5-5). The spacing of nodes between these points will affect the precision of the failure plane computations.

5. HEC-RAS will automatically select the lowest station-elevation point in the cross section to be the **Thalweg**.

Each bank of each cross section being analyzed requires two user defined points, an **Edge of Bank Station** and a **Top of Toe Station**. Note that these points are defined by their station across the cross section, not their elevation. These points are depicted in Figure 5-5 and are entered on the HEC-RAS Sediment Data Editor (Figure 5-2) and are defined in the following.

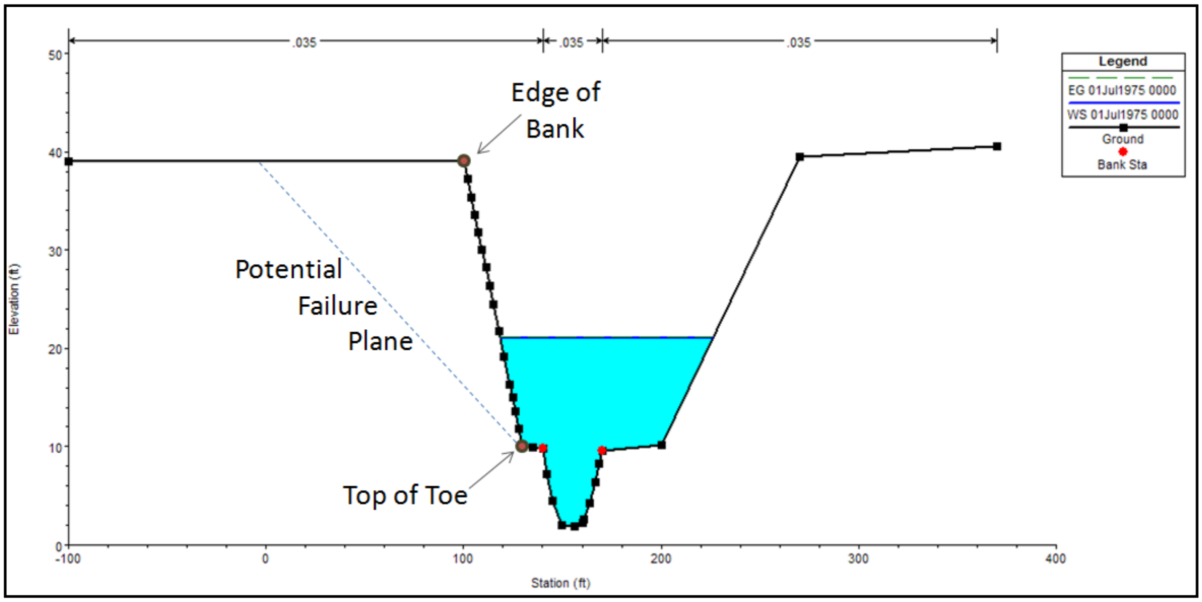


Figure 4-5: Reasonable location for Edge of Bank and Top of Toe definitions on an HEC-RAS cross section.

Left Bank Edge Station:

This should be the inflection point between the bank and the top of the bank. All failure planes considered will intersect the top of bank between the edge of bank and the first cross section station-elevation point.

Right Bank Edge Station:

Analogous to the Left Bank Edge station, this should be the inflection point between the bank and the top of the bank on the left side of the cross section. All failure planes considered will intersect the top of bank between the edge of bank and the last cross section station-elevation point

Left Bank Toe Station:

BSTEM divides the bank into two sections, the Bank and the Toe (Figure 5-5) sections. Conceptually, the toe is material composed of blocks of failed material or engineered toe protection. Therefore, failure planes are only computed through the bank surface *above* the **Top of Toe**. The **Top of Toe** often corresponds to a break in slope or material type but it does not have to (Figure 5-5). In future versions of BSTEM, users will be able to select a separate material type for the toe but in the first alpha version of BSTEM, the software adopts the material type of the bank or layer associated with the toe. This parameter can be automatically set to the HEC-RAS left bank station for every cross section that has **Left Bank Material** defined. From the HEC-RAS Sediment Data Editor (Figure 5-2), click **Set Toe Station to Bank Stations** and click the **Set Toe Stations to Movable Bed Stations** (movable bed limits). Setting movable bed limits and toe stations at the same node is recommended.

Right Bank Toe Station:

The **Right Bank Toe** is analogous to the **Left Bank Toe** section (see above) and can be set to the right bank station for every bank that has **Right Bank Material** defined**.** From the HEC-RAS Sediment Data Editor (Figure 5-2), click **Set Toe Station to Bank Stations** and click the **Set Toe Stations to Movable Bed Stations** (movable bed limits). Setting movable bed limits and toe stations at the same node is recommended.

GW Elev:

In order to compute bank failure on either side of any cross section a **Groundwater Elevation** must be specified. Results will be very sensitive to this parameter. BSTEM does not yet have a physical limit to negative pore water pressure so a very low groundwater table could generate nearly infinite bank stability.

If the static groundwater option is selected, BSTEM will use this groundwater elevation for the entire cross section simulation. If the dynamic groundwater option is selected, the user specified groundwater elevation will become the initial elevation, and groundwater will rise and fall in response to the hydraulic conductivity. The overbank is modeled as a ”reservoir" with a volume determined by the distance between cross sections and the user specified "Reservoir Width" parameter in the BSTEM material parameters, which the model moves between the groundwater reservoir and the channel at the rate of the user specified saturated hydraulic conductivity.

Defining Cross Section Materials

To define cross section materials for BSTEM, the user will enter information from the HEC-RAS Sediment Data Editor (Figure 5-2) from the BSTEM tab:

Left or Right Bank Material:

HEC-RAS requires at least one set of material properties to be specified for each bank it performs bank failure analysis on. Three levels of detail are available for specifying this parameter including:

a. Selecting Pre-Defined Default Parameters
b. Select a Single Set of User Defined Material Parameters for a Bank
c. Define Layers of Unique Material at a Bank

The material specification approach is bank-specific, so different approaches can be used for different banks within the same model.

1. Selecting Pre-Defined Default Parameters

The standalone version of BSTEM includes sixteen default material types that are also included in HEC-RAS. These default material types are each populated with characteristic soil properties distilled from a database of field data collected by the USDA-ARS. The unit weight, friction angle (ϕ'), cohesion, ϕ^b, critical shear stress (τ_c), and erodibility are listed in Table 2 (SI parameters are included at the end of the document). See the description of these parameters in the next section (Soil Strength Parameters).

Table 2. Default materials and material parameters

Default Material Type	**Saturated Unit Weight** (lbf/ft^3)	**Friction Angle** (ϕ')	**Cohesion** (lb/ft^2)	ϕ^b	**Critical Shear** (lb/ft^2)	**Erodibility** (ft^3/lbf-s)
Boulders	127.3	42.0	0	15	10.4	2.85E-05
Cobbles	127.3	42.0	0	15	2.59	5.73E-05
Gravel	127.3	36.0	0	15	0.23	1.92E-04
Coarse Angular Sand	117.8	32.3	8.354	15	0.0106	8.95E-04
Course Round Sand	117.8	28.3	8.354	15	0.0106	8.95E-04
Fine Angular Sand	117.8	32.3	8.354	15	0.00267	8.95E-04
Fine Round Sand	117.8	28.3	8.354	15	0.00267	8.95E-04
Erodible Silt	114.6	26.6	89.81	15	0.00209	2.01E-03
Moderate Silt	114.6	26.6	89.81	15	0.1044	2.86E-04
Resistant Silt	114.6	26.6	89.81	15	1.0443	8.91E-05
Erodible Soft Clay	112.7	26.4	171.26	15	0.00209	2.01E-03
Moderate Soft Clay	112.7	26.4	171.26	15	0.1044	2.86E-04
Resistant Soft Clay	112.7	26.4	171.26	15	1.0443	2.01E-03
Erodible Stiff Clay	112.7	21.1	263.16	15	14.6	2.01E-03
Moderate Stiff Clay	112.7	21.1	263.16	15	0.1044	2.86E-04
Resistant Stiff Clay	112.7	21.1	263.16	15	1.0443	2.01E-03

It is worth noting, however, that these parameters are extremely site specific, and the default parameters are central tendencies of very noisy data sets, particularly for cohesive material types. Therefore, default parameters will often generate substantial errors.

Coupling these bank failure algorithms with the mass balance computations in the mobile bed capabilities in HEC-RAS introduced one additional parameter requirement. Any mass that "fails" into the channel requires a gradation so HEC-RAS can partition it into grain classes for transport. Therefore, idealized gradations were selected for each material type based on their description. These gradations are depicted in Figure 30.

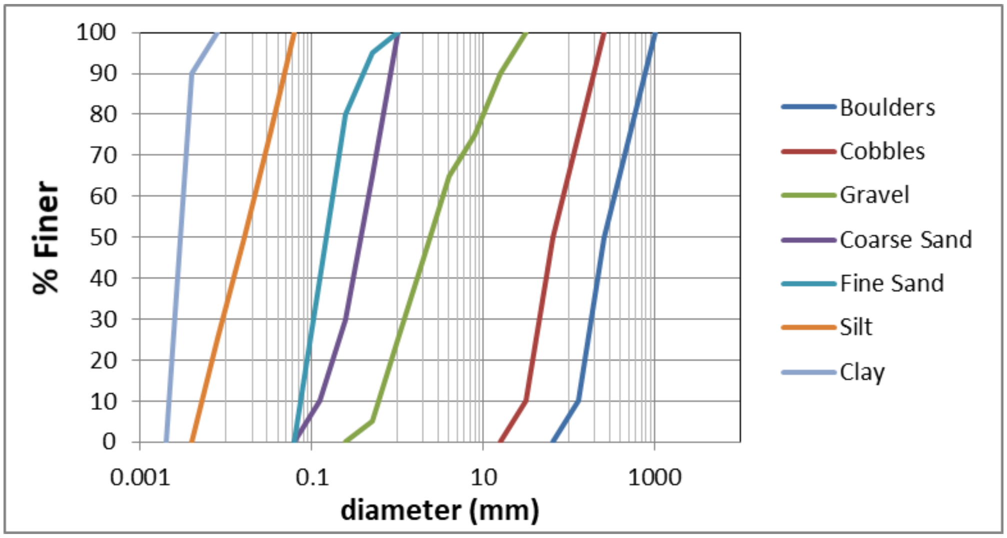
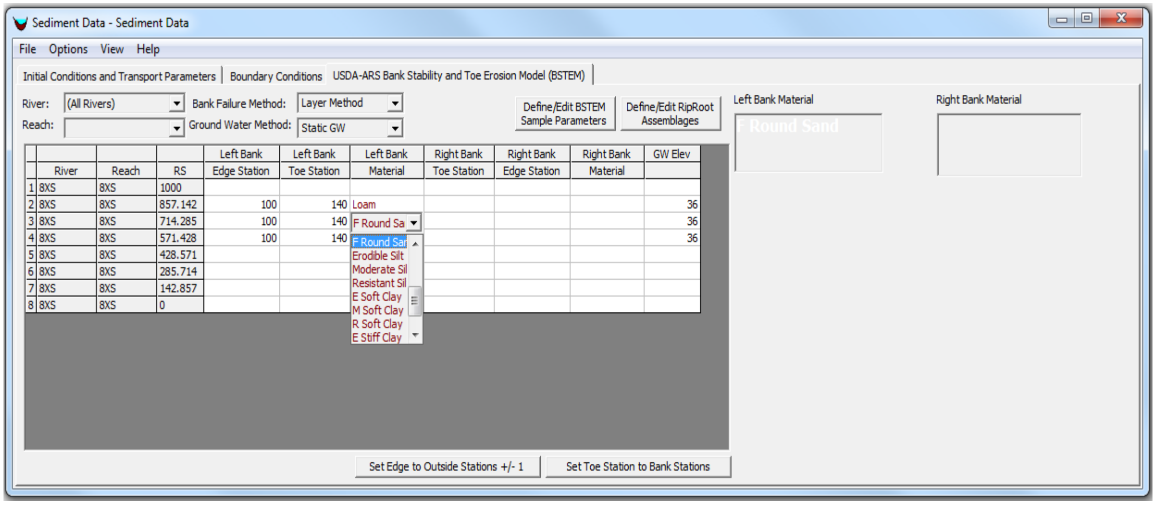


Figure 4-6: Idealized gradations selected for the default material types.

Modeling Note/Warning**:** Models constructed without direct erodibility measurements or calibration data are speculative. Additionally, using default sand materials or coarser will invoke the cohesionless scour methods, which are based on transport functions and tend to over-predict scour. Interpret default material results carefully.

In order to select one of the default material types, from the table on the **Sediment Data Editor**, **BSTEM Tab** (Figure 26), from the columns labeled **Left Bank Material** or **Right Bank Material** click at the cross section of interest. A list of default material types that are available will appear (Figure 31). Ignore the option "**DEFINE LAYERS**", from the list and select the desired material type and it will associate it with that bank (Figure 31).



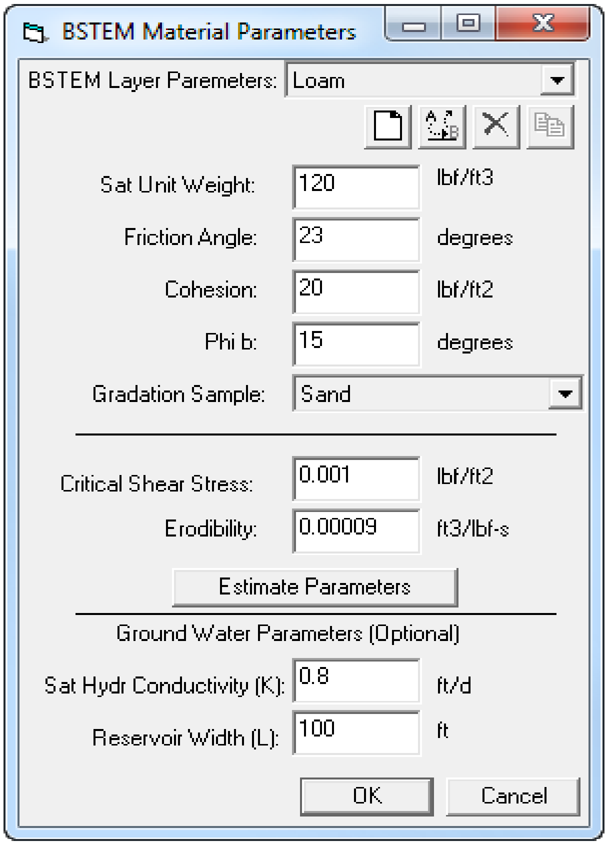
River: (All Rivers)
Reach:
Bank Failure Method: Layer Method
Ground Water Method: Static GW
Left Bank Material: F Round Sand
Right Bank Material:

	River	Reach	RS	Left Bank Edge Station	Left Bank Toe Station	Left Bank Material	Right Bank Toe Station	Right Bank Edge Station	Right Bank Material	GW Elev
1	8XS	8XS	1000							
2	8XS	8XS	857.142	100	140	Loam				36
3	8XS	8XS	714.285	100	140	F Round Sa				36
4	8XS	8XS	571.428	100	140					36
5	8XS	8XS	428.571							
6	8XS	8XS	285.714							
7	8XS	8XS	142.857							
8	8XS	8XS	0							

Figure 4-7– HEC-RAS - Sediment Data Editor - BSTEM Tab - Selecting Cross Section Materials.

2. Select a Single Set of User Defined Material Parameters for a Bank

Because of the inherent variability of these parameters, site specific measurements are recommended. If data is available, customized material types can be associated with a bank. This is analogous to the process for defining sediment gradations in the **Initial Conditions and Transport Parameters Tab** of the **Sediment Data Editor**, where gradation records are defined and then associated with the appropriate cross section.



BSTEM Layer Paremeters: Loam

Sat Unit Weight: 120 lbf/ft3

Friction Angle: 23 degrees

Cohesion: 20 lbf/ft2

Phi b: 15 degrees

Gradation Sample: Sand

Critical Shear Stress: 0.001 lbf/ft2

Erodibility: 0.00009 ft3/lbf-s

Ground Water Parameters (Optional)

Sat Hydr Conductivity (K): 0.8 ft/d

Reservoir Width (L): 100 ft

Figure 4-8: BSTEM Material Parameters Editor.

Before selecting customized materials a user must define the materials by clicking **Define/Edit BSTEM Sample Parameters**. The **BSTEM Material Parameters Editor** will open (Figure 32). To create a new BSTEM material, click **New Record** and specify the name. HEC-RAS will reject any names that are identical to existing or default material names. Five mandatory intrinsic soil strength parameters (used to compute the failure plane and factor of safety), two mandatory erodibility parameters (used to compute toe scour) and one optional parameter can then be entered.

Soil Strength Parameters

The first five parameters are intrinsic soil strength parameters and are associated with the computation of a critical failure plane and the FS associated with that failure plane. These five parameters emerge from classical geotechnical measurements that most soils labs would be able to handle. HEC-RAS uses four user defined parameters with hydrodynamic and geometric data to compute a factor of safety for a range of possible failure planes by computing the ratio of the resisting forces to the driving forces: cohesion (c'), saturated unit weight (W), the angle of internal friction (ϕ'), and the angle representing the relationship between shear matrix suction and apparent cohesion (ϕ^b). These four user defined parameters are entered in the **BSTEM Material Parameters Editor** (Figure 32) and are described below.

Unit Weight:

This is the *saturated* unit weight[7] (combined weight of the solids and water of the soil when saturated). Note that this is different than the unit weight used elsewhere in HEC-RAS sediment transport computations. The unit weight used elsewhere in HEC-RAS sediment transport computations is the mass of the solids per unit volume.

Friction Angle (ϕ'):

The friction angle is a classic geotechnical parameter that is a measurement of the soil strength that quantifies the friction shear resistance of soil. The "angle" of the "friction angle" is derived from the Mohr-Coulomb failure criterion and is the angle of inclination in the classical Mohr diagram. The angle of inclination is a theoretical angle[8] used to compute soil strength and should not be confused with physically intuitive angles like the angle of repose. This also is not the minimum angle of the failure plane. In cases where groundwater elevation is higher than the water surface elevation the bank can lose frictional strength and be left only with cohesion, allowing for a shallower failure plane angle. The fiction angle can be determined by collecting "undisturbed" cores for tri-axial testing in a soils laboratory or it can be measured *in situ* with a borehole shear test. The Iowa Borehole Shear device (Thorne, 1981) is a hand held instrument that is commonly used to collect this parameter from hand augured eight centimeter boreholes for BSTEM studies.

Cohesion:

Cohesion is the attractive force of particles in a soil mixture, usually as a result of electrochemical or biological bonding forces. These forces increase the strength of a soil matrix. Cohesion is generally a minor consideration in granular soils but can account for a substantial amount of soil strength in cohesive materials. Cohesion is computed from the same data as the friction angle and, therefore, must be measured either by tri-axial laboratory tests or *in situ* borehole shear measurements.

Phi b (ϕ^b): As soil drains, capillary tension induce negative pore water pressure or matrix suction. Suction resists bank failure and increases the shear strength of the soil matrix. In the bank failure algorithms, suction is quantified as an "apparent" cohesion" or the equivalent increase in cohesion required to generate the same increase in shear strength (Figure 33).

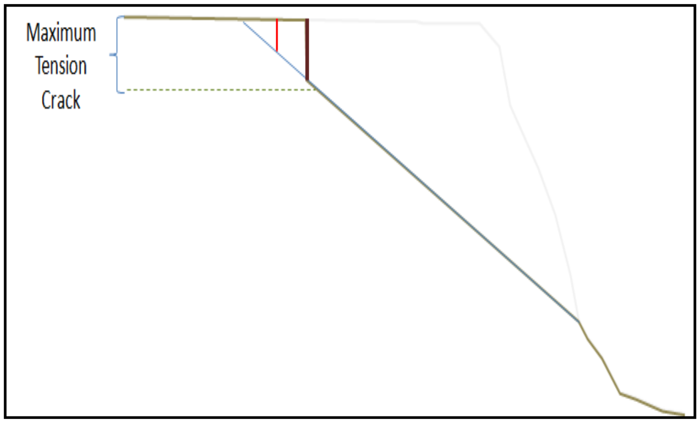
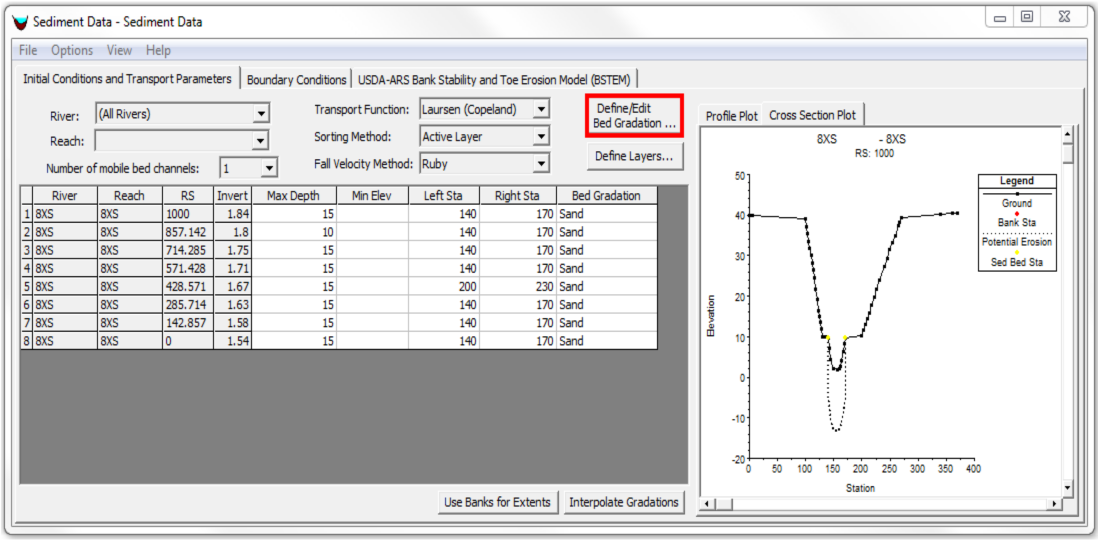


Figure 4-9: ϕ^b is the slope of the relationship between matrix

ϕ^b is a function of soil moisture and maximizes at the friction angel (ϕ') at saturation. For most materials ϕ^b is generally between ten to thirty degrees depending on soil type. ϕ^b is very difficult to go out and fundamentally measure ϕ^b. ϕ^b has been measured a handful of times in research settings. Most applications start between ten and fifteen degrees but ϕ^b goes to a maximum of the friction angle when the material is saturated (Fredlund, 1986). Because of the estimated nature of this parameter it can be used as a calibration factor.

Gradation Sample:

HEC-RAS requires a fifth bank material parameter that is required but not used until after the failure calculation. In order to partition any failed material into grain classes for transport by the sediment transport model, the bank material has to have a bed gradation associated with it. Bed gradations are defined by clicking **Define/Edit Bed Gradation** from the **Initial Conditions and Transport Parameters** Tab of the **HEC-RAS Sediment Data Editor** (Figure 34).



River: (All Rivers)
Reach:
Number of mobile bed channels: 1
Transport Function: Laursen (Copeland)
Sorting Method: Active Layer
Fall Velocity Method: Ruby

	River	Reach	RS	Invert	Max Depth	Min Elev	Left Sta	Right Sta	Bed Gradation
1	8XS	8XS	1000	1.84	15		140	170	Sand
2	8XS	8XS	857.142	1.8	10		140	170	Sand
3	8XS	8XS	714.285	1.75	15		140	170	Sand
4	8XS	8XS	571.428	1.71	15		140	170	Sand
5	8XS	8XS	428.571	1.67	15		200	230	Sand
6	8XS	8XS	285.714	1.63	15		140	170	Sand
7	8XS	8XS	142.857	1.58	15		140	170	Sand
8	8XS	8XS	0	1.54	15		140	170	Sand

Figure 4-10: Defining bed gradations.

Any gradations defined here become automatically available in the **Gradation Sample** list on the **BSTEM Material Parameter Editor** (Figure 32).

Erodibility Parameters

The second set of parameters on the **BSTEM Material Parameters Editor** (Figure 32) are the erodibility parameters. These parameters are specialized for bank failure analysis. Erodibility parameters are measurements of the erodibility of the soils in response to hydrodynamic forcing. Standard soil testing laboratories are not likely to have the capabilities to collect these parameters. However, the USACE Coastal and Hydraulic Lab (ERDC-CHL), other federal agencies, and several universities can quantify these parameters. Bank jet tests (Hanson, 1990) and SEDFLUME laboratory tests (Briaud et al., 2001, Smith et al., 2010) are the best ways to estimate these parameters.

Critical Shear Stress: Critical shear stress is when the bank begins to scour.

Erodibility: The rate of sediment removal in response to a unit shear stress.

In the absence of these parameters Simon et al., 2000 summarized their database of *cohesionless* measurements to find a relationship between critical shear stress and erodibility:

$$\mathrm{E} = 1.42\tau_c^{-0.824}$$

This relationship is based on the regression depicted in Figure 35 which includes a great deal of scatter in log space. This underscores the variable and site specific nature of these parameters, therefore local measurement of these parameters is highly recommended. Also note that this relationship does not account for cohesion and, therefore, should not be used for cohesive soils.

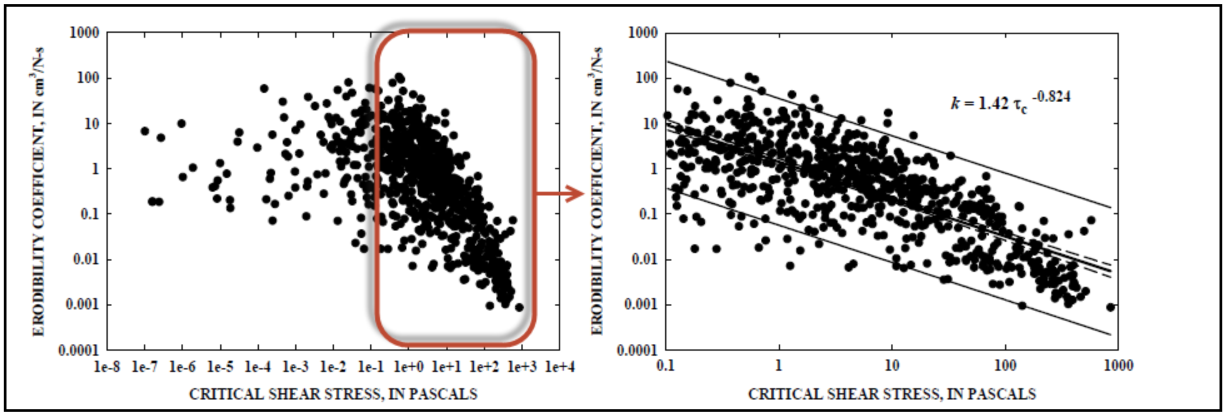


Figure 4-11: Relationship between erodibility and critical shear stress from Simon et al. (2000).

Groundwater Parameters (Optional)

Groundwater parameters are optional and are only used if the dynamic groundwater option is selected in the BSTEM section of HEC-RAS. There are two parameters that determine the rate that water can drain from or infiltrate into a bank. In turn, this determines the lag between the rising or falling of groundwater elevation with respect to the water surface elevation.

Hydraulic Conductivity:

Is the standard Darcy "K" parameter used in groundwater modeling. The hydraulic conductivity is a linear parameter that determines velocity of groundwater proportional to a gradient. Hydraulic conductivity can be measured with field or laboratory tests but is also often documented in regional literature or estimated by expert intuition (analogous ’o Manning's n).

Reservoir Length:

Groundwater dynamics follows a simple reservoir routing model that assumes the banks store water. Water can be added to or drained from the rate of the saturated hydraulic conductivity. The "length" of this reservoir is the bank thickness (perpendicular to the river) that contributes water to the river on pertinent time scales.

If the soils are very permeable or the reservoir is small (high K or low L) the groundwater elevation will track the channel water surface elevation (Figure 36a). If the soils are impermeable or the reservoir is very large, the groundwater will not respond much to flow depth in the channel (Figure 36b). However, intermediate hydraulic conductivities will introduce a lag between channel water surfaces and groundwater elevation (Figure 36c). Because groundwater elevations higher than the confining water surface elevation are the critical condition, groundwater lag can induce failures on the falling limb of the hydrograph, both in the field and in the model.

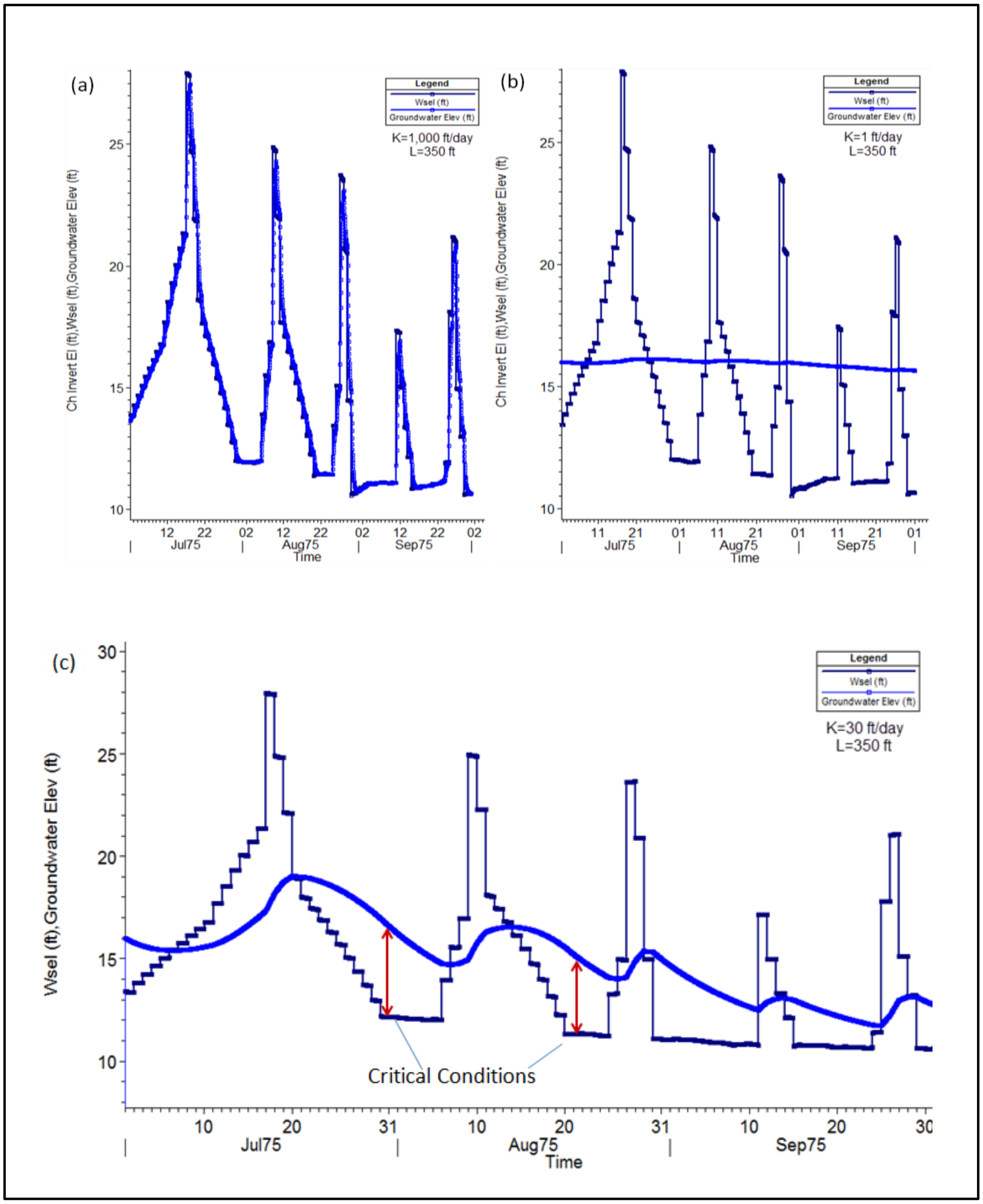
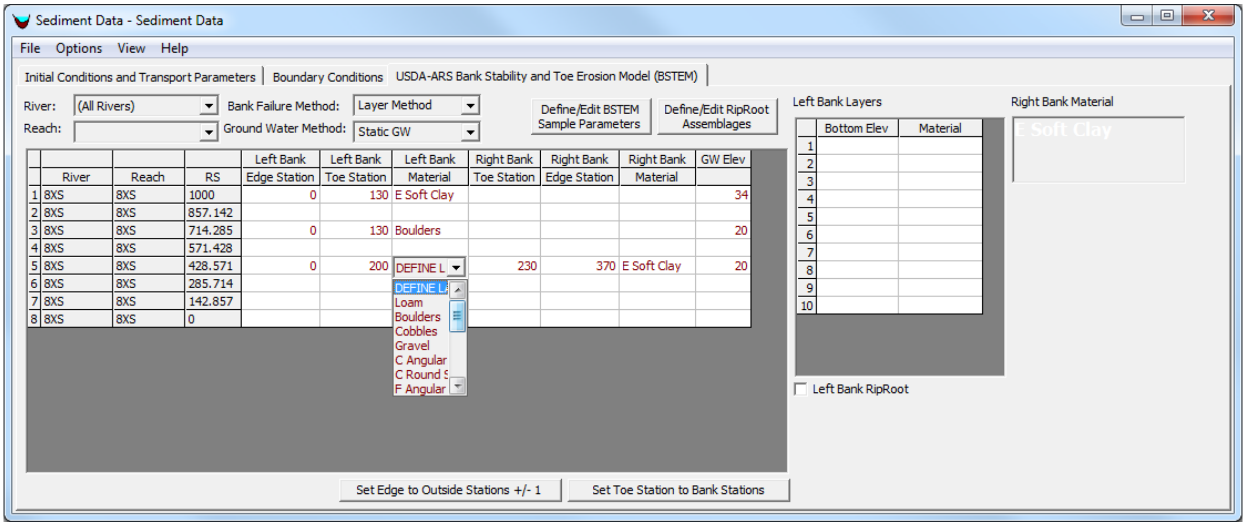


Figure 4-12: Groundwater response to (a) high (b) low and (c) moderate hydraulic conductivities.

3. Define Separate Parameters for Multiple Layers for Each Cross Sections

Finally, it is often advantageous to define several bank material layers. Some banks have distinct stratigraphy, stacking soil layers. Sometimes vegetation is modeled by introducing a surface layer with the same friction angle as the parent material but with a higher cohesion. To specify layers, select **Define Layers**, from the **Left/Right Bank Material** lists available in the **HEC-RAS Sediment Data Editor** (Figure 37). If the **Define Layers** option is selected, a new table will appear on the right side of the editor (Figure 37).



River: (All Rivers)
Reach:
Bank Failure Method: Layer Method
Ground Water Method: Static GW

	River	Reach	RS	Left Bank Edge Station	Left Bank Toe Station	Left Bank Material	Right Bank Toe Station	Right Bank Edge Station	Right Bank Material	GW Elev
1	8XS	8XS	1000	0	130	E Soft Clay				34
2	8XS	8XS	857.142							
3	8XS	8XS	714.285	0	130	Boulders				20
4	8XS	8XS	571.428							
5	8XS	8XS	428.571	0	200	DEFINE L	230	370	E Soft Clay	20
6	8XS	8XS	285.714							
7	8XS	8XS	142.857							
8	8XS	8XS	0							

Left Bank Layers

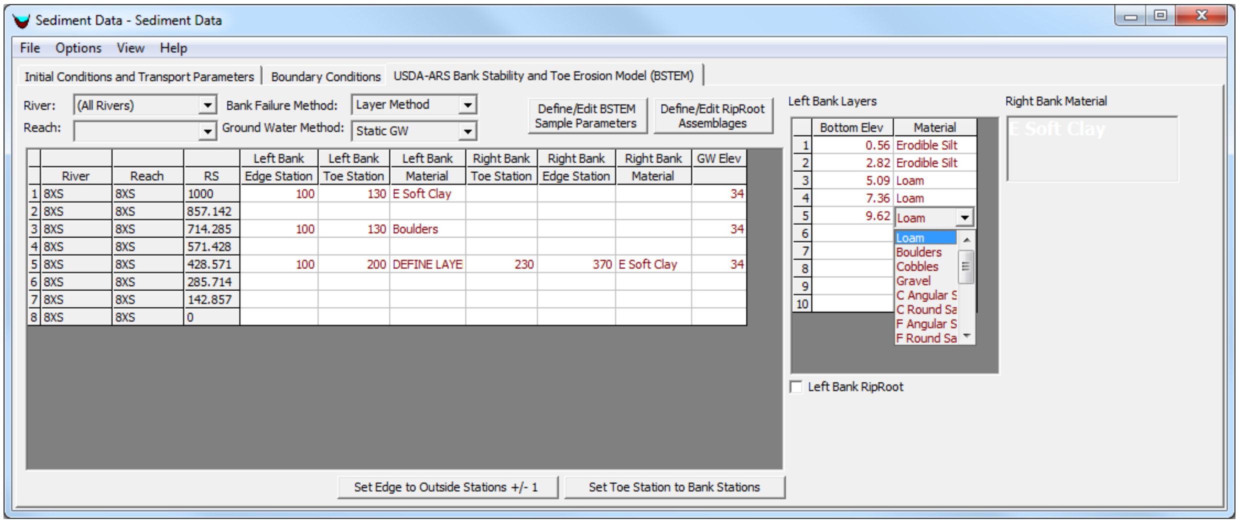
	Bottom Elev	Material
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		

☐ Left Bank RipRoot

Right Bank Material: E Soft Clay

Figure 4-13: Selecting the layer mode for a bank failure.

The bank material layer table requires two parameters: a bottom elevation and a material. Each layer exists between its own bottom elevation and the bottom elevation of the higher layer.   The top layer will extend from the highest point on the half-cross section to the highest specified **Bottom Elevation**. (Note - in the current version bottom elevations MUST be entered from low to high).



River: (All Rivers)
Reach:
Bank Failure Method: Layer Method
Ground Water Method: Static GW

	River	Reach	RS	Left Bank Edge Station	Left Bank Toe Station	Left Bank Material	Right Bank Toe Station	Right Bank Edge Station	Right Bank Material	GW Elev
1	8XS	8XS	1000	100	130	E Soft Clay				34
2	8XS	8XS	857.142							
3	8XS	8XS	714.285	100	130	Boulders				34
4	8XS	8XS	571.428							
5	8XS	8XS	428.571	100	200	DEFINE LAYE	230	370	E Soft Clay	34
6	8XS	8XS	285.714							
7	8XS	8XS	142.857							
8	8XS	8XS	0							

Left Bank Layers

	Bottom Elev	Material
1	0.56	Erodible Silt
2	2.82	Erodible Silt
3	5.09	Loam
4	7.36	Loam
5	9.62	Loam
6		
7		
8		
9		
10		

☐ Left Bank RipRoot

Right Bank Material: E Soft Clay

Figure 4-14: Defining layers and layer material types.

Then, just like the **Bank Material Type** option in the main BSTEM editor, a list of bank materials can be accessed by clicking on the **Material** column (Figure 38). Each layer has to have its own material specified, but the materials do not have to be unique and can be any combination of default or user specified material types. Add layers until the last **Bottom Elevation** extends below the conceivable bottom of the model (i.e., the elevation the model is likely to scour to). The bottom of the deepest layer has to at least extend to the thalweg elevation for the model to run.

Guidelines for Selecting Layer Elevations: Setting layer elevations according to a couple conventions can make an HEC-RAS/BSTEM model more stable. First, set the bottom of the top layer below the lowest point of the overbank, so the layer only intersects the cross section at one point, between the toe and the top of bank (Figure 39). Second, set the bottom of the bottom layer below the deepest possible thalweg elevation (e.g., thalweg-max erodible depth) so the model never scours below the defined layers (Figure 39).

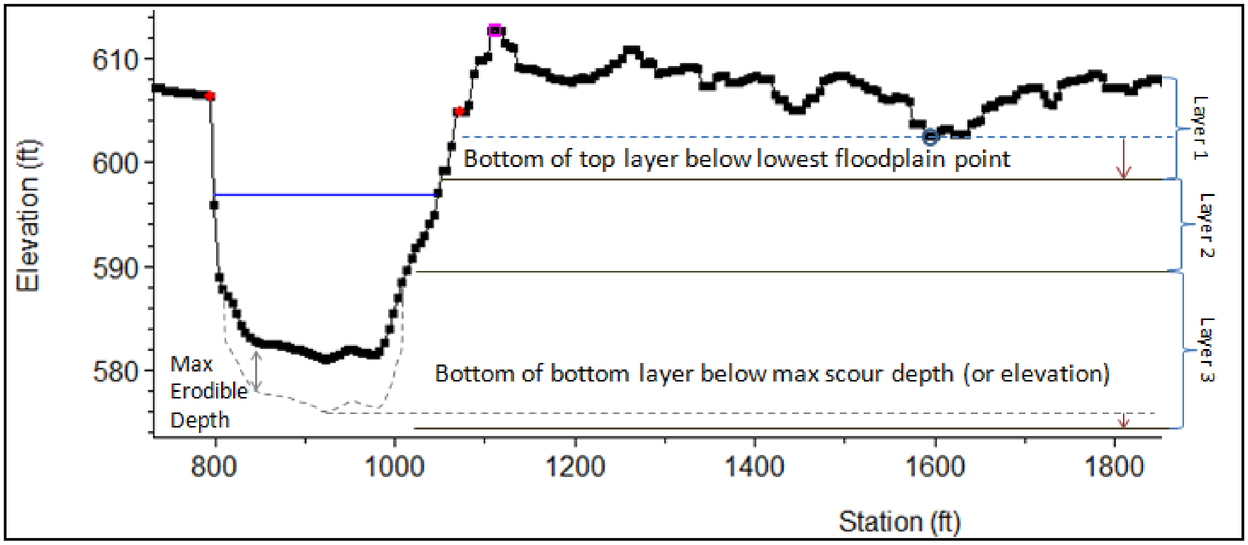
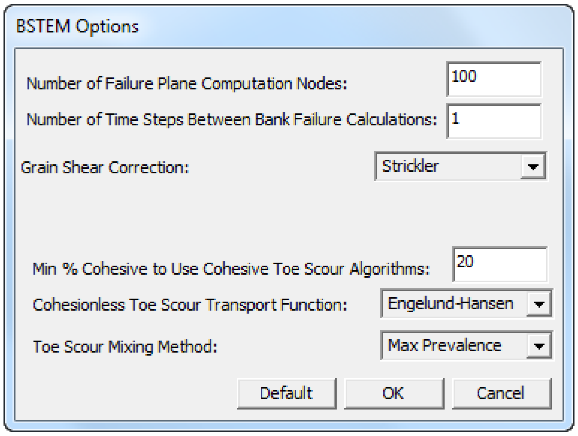


Figure 4-15: Guidelines for setting layer elevations.

USDA-ARS BSTEM Options

The HEC-RAS/BSTEM model integration included several arbitrary parameter thresholds and two processes with multiple methods. These parameters and methods influence results and run times. The **BSTEM Options Editor** (Figure 40) exposes them so users can adjust or select them.



Number of Failure Plane Computation Nodes: 100

Number of Time Steps Between Bank Failure Calculations: 1

Grain Shear Correction: Strickler

Min % Cohesive to Use Cohesive Toe Scour Algorithms: 20

Cohesionless Toe Scour Transport Function: Engelund-Hansen

Toe Scour Mixing Method: Max Prevalence

Figure 4-16: BSTEM Options Editors.

Number of Failure Plane Computation Nodes

The bank failure algorithm computes a critical failure plane at every one percent of the elevation between the toe and edge stations, computing critical failure planes at 100 evenly spaced vertical bank intersection points (Figure 13). This is computationally expensive and often much more detail than necessary and the parameter is editable in HEC-RAS. Users can specify the number of vertical computation bank failure points. HEC-RAS will evenly distribute the computation points vertically, between the bank toe and edge elevations.

Number of Time Steps Between Failure Computations

Bank failure algorithms are computationally expensive. These algorithms can increase sediment model run times by an order of magnitude. Users can reduce run times by defining BSTEM parameters only at the half-cross sections where bank processes are expected. Bank failure conditions (i.e., FS less than one) are not usually instantaneous. If FS drops below one, the failure condition generally lasts for several time steps. Skipping bank failure computations will introduce error, but given the uncertainties of the model, the error may be acceptable trade off for run time.

Grain Shear Correction

Only part of the shear stress water exerts on soils translates into transport. Shear partitioning theory for bed transport is more mature, parsing shear into form and grain shear (and sometimes into other components). This theory is not as applicable to banks. However, the isolated measurements, either by jet tests in the field or SEDFLUME in the lab, tend to isolate grain shear effects. Therefore, the toe scour mechanisms apply a **Strickler** grain shear correction by default. From the **BSTEM Options Editor** (Figure 40), from the **Grain Shear Correction** list, select **None,** this will turn the correction off. Turning the grain shear correction off will increase the shear stress on the bank and will increase scour.

Minimum Percent Cohesive to Use Toe Scour Algorithms

BSTEM has two approaches to toe scour. The cohesive algorithms use the excess shear equation to compute scour rates based on measured erodibility data. The cohesionless algorithms apply transport functions to compute scour. The cohesionless methods are generally less accurate, but it is difficult to estimate cohesionless erodibility either in the lab or in the field.

HEC-RAS/BSTEM decides between these methods for each soil layer by computing the percentage of the bank soil that is cohesive (i.e., in the first five HEC-RAS grain classes, less than .063 millimeters is the default grain class definition). HEC-RAS computes this percentage from the gradation defined in the **BSTEM Material Parameter Editor** (Figure 30) from the soil type list, or the narrow gradations of the default soil types (Figure 30). By default, if **20 percent** or more of the soil is cohesive, (clay or silt), BSTEM uses the cohesive methods. However, if less than **20 percent** of the soil is finer than the cohesive threshold, BSTEM will apply the cohesionless transport equations.

The twenty percent threshold is not entirely arbitrary. Around twenty percent cohesive content, the fine particles fill the soil voids enough for their cohesive properties to dominate the erodibility of the larger particles. However, in reality, the transition from cohesive matrix support to cohsionless framework support is a gradient not a step function. Therefore, the parameter is exposed as a user option in the BSTEM Options in the Sediment Data Editor.

If the transport functions return unreasonable scour rates, as often happens, users can model cohesionless materials with the cohesive erodibility approach. To force the cohesive, excess shear, erodibility method, set the **Min % Cohesive** to **0** in the BSTEM Options in the Sediment Data Editor**.**

Transport Function

As described in the previous section, if a soil layer has less than 20 percent (or a user specified percentage) cohesive material, BSTEM will apply a transport function to compute toe scour (Figure 41). The USDA-ARS BSTEM model uses an NSED transport function library to compute transport. This library includes six transport functions, including:

- Engelund-Hansen
- Parker (1990)
- Wilcock and Crowe (2000)
- Meyer-Peter Muler
- Wu (2000)

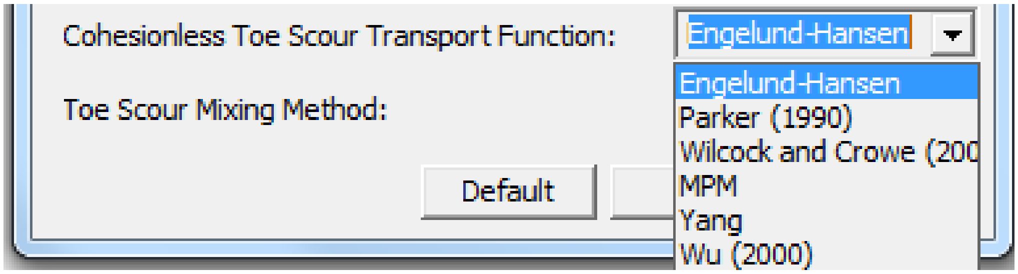


Figure 4-17: BSTEM Options Editor - Transport functions available for cohesionless toe scour in BSTEM.

Select and apply transport functions with ***extreme caution*** recognizing the intent and range of applicability of each. Transport functions are notoriously uncertain, computing transports that commonly differ by at least one order of magnitude. Engelund and Hansen (1967) and Yang (1996) work best for sand. Meyer-Peter and Müller (MPM) (1948) will probably perform best for coarse materials. Parker (1990) and Wilcock and Crowe (2003) are both **surface based** methods, intended for heterogeneous soil mixtures with sand and gravel components. These two methods account for mixing, hiding and armoring implicitly, which tends to moderate transport and sometimes makes the methods more appropriate for toe scour in heterogeneous materials.

Also, it should be noted that most of these transport functions were derived for one-dimensional alluvial transport at the cross section scale. BSTEM applies these transport functions to bank scour at the node scale. This makes transport functions, already uncertain in their intended setting, loose process analogies in toe scour. The transport functions often over predict scour substantially and results should be interpreted carefully.

Toe Scour Mixing Method

The HEC-RAS sediment transport follows Einstein(1950), HEC-6, and most sediment transport models by apportioning transport across available grain classes in proportion to the gradation of the bed.

$$T_c = \sum_{j=1}^{n} \beta_j T_j$$

Where: T_c is Total transport capacity, n is the number of grain size classes, B_j is the percentage of the active layer composed of material in grain size class "j", and T_j is the Transport potential computed for the material in grain class "j". Partitioning capacity based on the gradation of the active layer is a classic assumption based Einstein's (1950), who proposed sediment discharge of a size class is proportional to the fractional abundance of that size class in the bed

This approach generally works when couple with an "active layer" bed model that tracks the gradation of a surface layer separately. Without an active layer, transport functions compute huge masses for small particles, removing these materials from deep within the bed, much deeper than physically possible.

The toe scour method does not have an active layer. Therefore, transport methods have unrestricted access to all the fine materials in the bank. Apart from the standard uncertainty of the transport functions, this is the primary reason that the cohesionless method overpredicts transport, it can numerically wick fine materials deep in the bank, while the coarser materials remain.

The HEC-RAS/BSTEM development team experimented with three mixing methods to mitigate this numerical artifact:

Cumulative: Applies the same assumption as the bed, apportioning capacity by the prevalence in the bank layer. However, since the bank layer has no active layer and does not update, this provides an unlimited supply of finer material and usually over-predicts scour.

Maximum Prevalence (default): This method apportions capacity according to the relative proportion of the bank gradation. However, it only erodes the most prevalent grain class. This assumes that the dominant grain class moderates scour. This method is more appropriate if trace fines and low percentage fine sands cause the other methods to over-predict scour and was designed for framework supported materials.

Maximum Capacity: This method was designed for matrix supported materials. It assumes that the prevalent fine material, the one with the largest product of transport potential and prevalence, controls the scour distance. So the scour distance associated with the largest capacity grain class is applied, assuming that the other particles are larger clasts that will fall into the channel when released from the scoured fine matrix.

Output

HEC-RAS does not compute USDA-ARS BSTEM results by default. To request BSTEM output, from the **Sediment Transport Analysis** dialog box, from the **Options** menu**,** click **Sediment Output Options.** The **Sediment Output Options** dialog box will open, **from the Output Level** list select **6**. Once that setup is done, from the HEC-RAS main window (Figure 4-2), from the **View** menu, click **Sediment Output**. The **Sediment Plot** dialog box will open. In general, the new sediment output (which reads HDF5 output), is more complete and user friendly. However, the legacy sediment output viewers from HEC-RAS Versions 4.0 were retained because they have a few capabilities (e.g. plotting multiple variables and creating new geometry files) that the new viewers lack.

HEC-RAS computes several commonly used BSTEM results. The total mass eroded from a cross section in a computation increment (for both banks and both processes) is reported under **BSTEM All**. The total mass eroded from the banks can also be reported by grain class (e.g. BSTEM (7)) or by bank and process (Figure 4-18). Finally **Factor of Safety** (Figure 4-19) for each bank and **Groundwater Elevation** (Figure 4-20) are available. All of these variables can be viewed as profiles (all the cross sections in a reach at a selected time step) or as time series, (all values over time at a selected cross section). The BSTEM output variables are defined in Table 3.

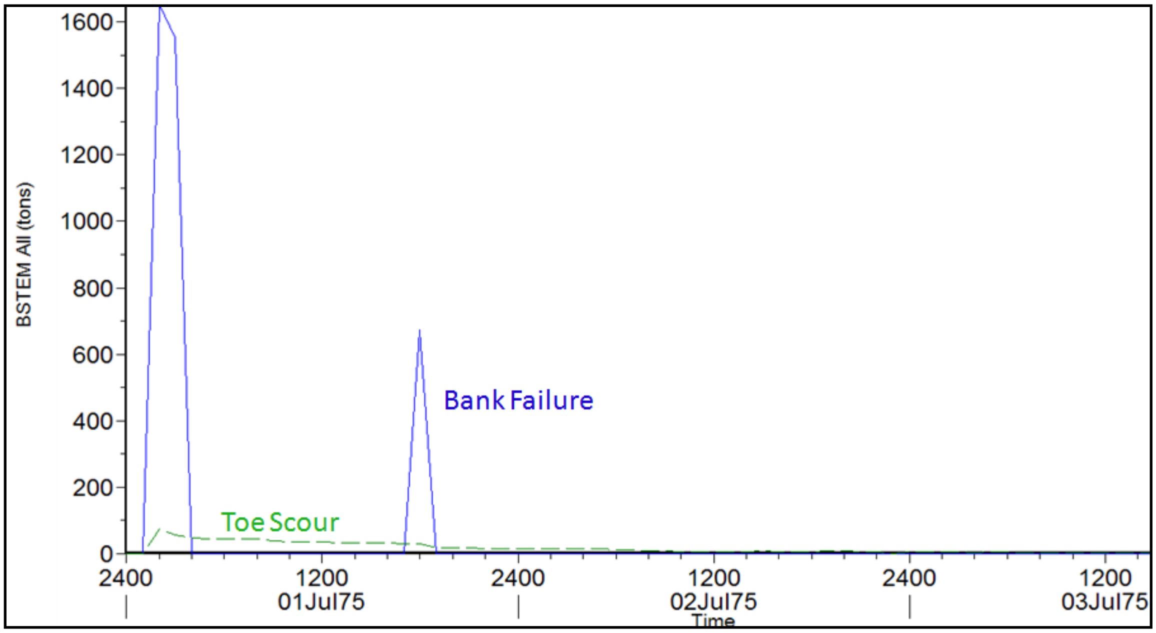


Figure 4-18: Time series of bank mass eroded by process.

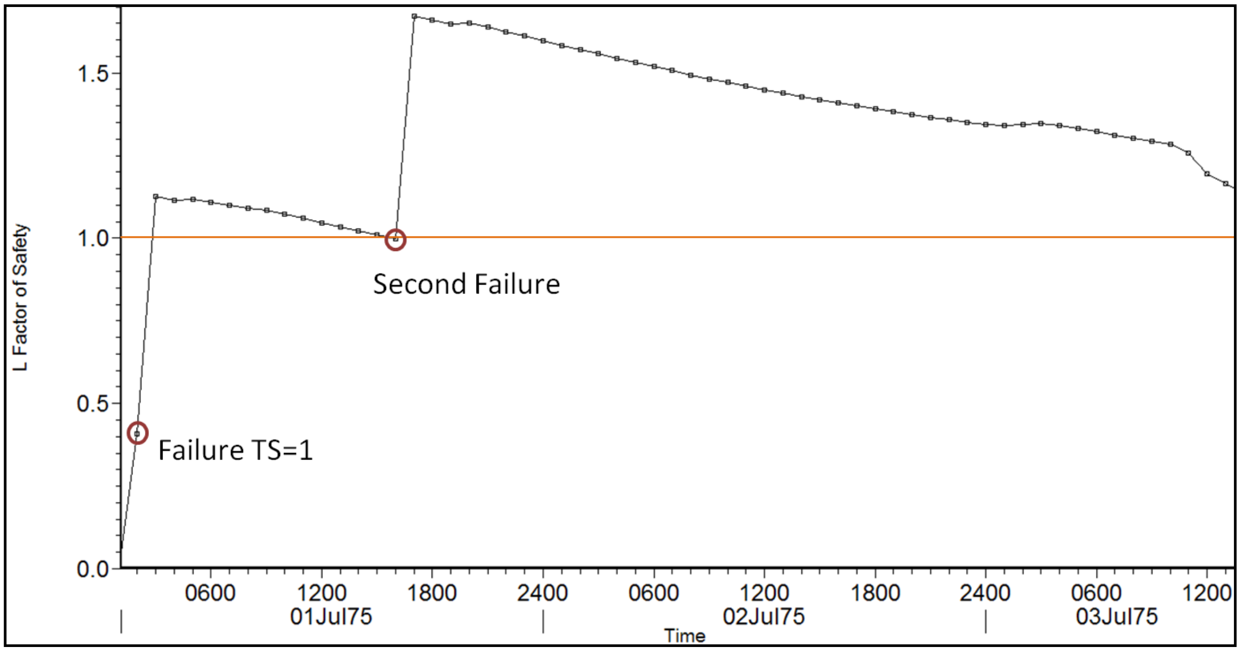


Figure 4-19: Time series of Factor of Safety.

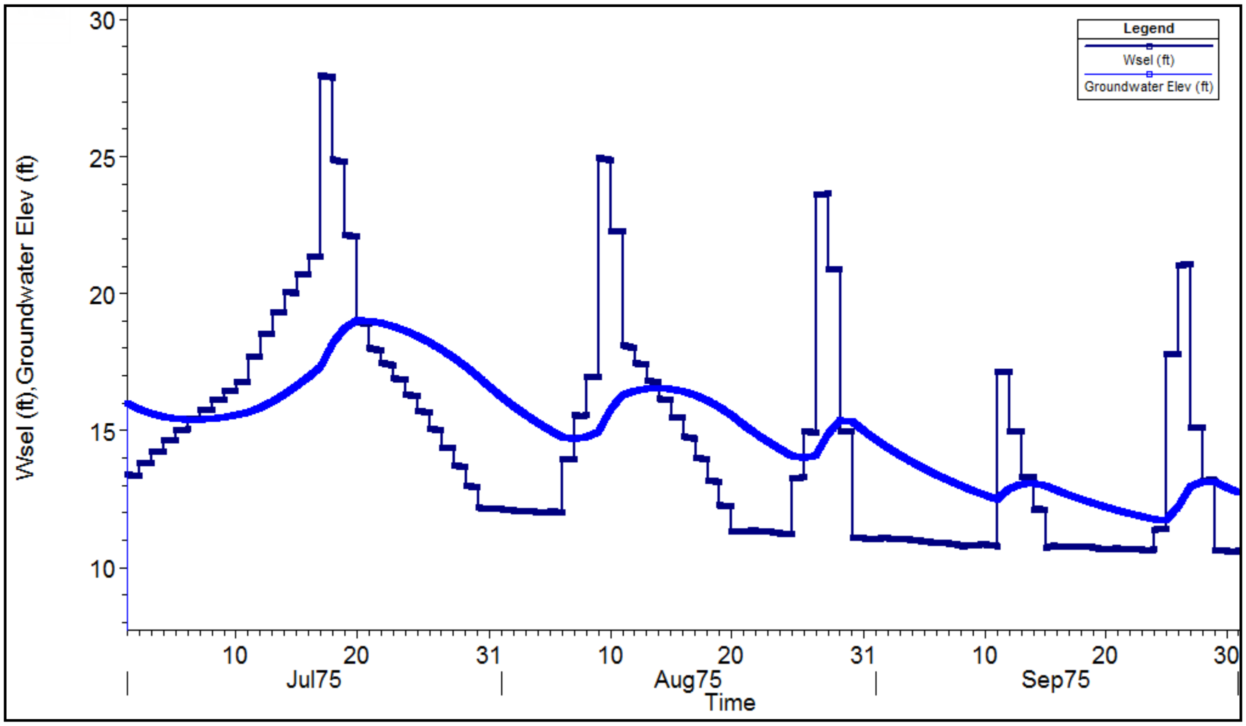


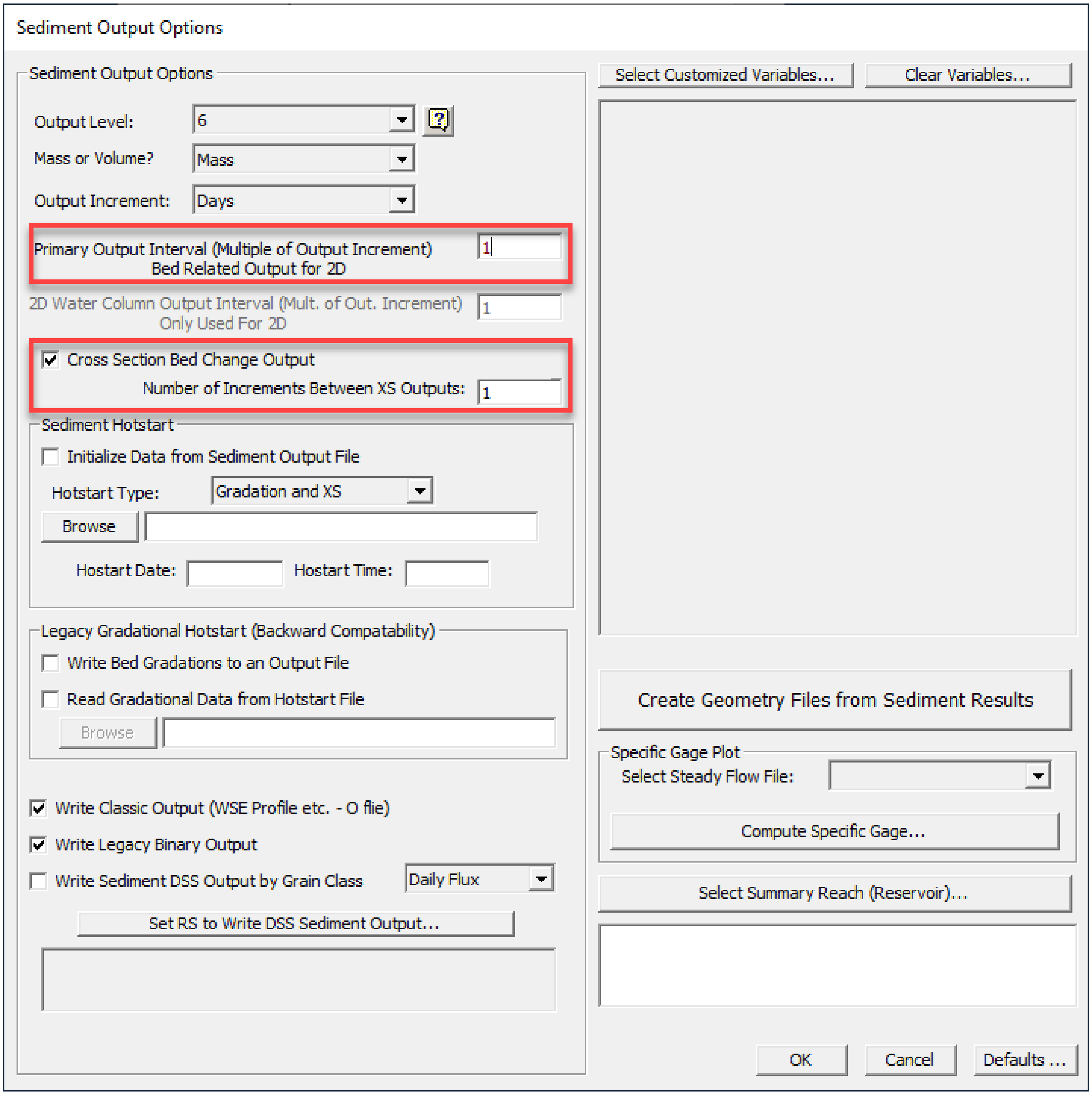
Figure 4-20: Groundwater and water surface time series plot demonstrating the lag between water surface and groundwater elevations.

HEC-RAS modifies cross sections when the sediment model computes bed change or when BSTEM computes bank migration. Viewing cross section changes is often the most valuable output to understand and troubleshoot an HEC-RAS/BSTEM model. Cross section output files can be very large. HEC-RAS only outputs starting and final cross sections by default. The user can request more frequent cross section output from the **Sediment Output Options** dialog box (Figure 4-21). From the **Sediment Transport Analysis** dialog box, from the **Options** menu**,** click **Sediment Output Options.** The **Sediment Output Options** dialog box will open (Figure 4-21). From this dialog box users can request cross section data and specify the increment, Figure 4-22 provides an example. The **Sediment Output Viewer** from version 5.0 also plots the water surface elevation and the BSTEM toe associated with the cross section (Figure 4-23).

Table 4-1: BSTEM Output Variable Names and Descriptions in HEC-RAS

Variable	Descriptions
BSTEM Mass (Vol) (tons or ft^3)	Total sediment mass (or volume) –obilized - from both cross-sect–on banks - by toe scour and bank failure for each cross section for each computation increment. (Total and by Grain Class)
BSTEM CumMass (Vol) (tons or ft^3)	Cumulative mass (or volume) mobilized from the cross section for both banks and both BSTEM processes since the beginning of the simulation. (Total and by Grain Class)
BSTEM Long CumMass (Vol) (tons or ft^3)	The cumulative mass mobilized from the toe and banks since the beginning of the simulation, summed from upstream to downstream. (i.e. The value at the downstream cross section is the total eroded from the banks for the whole reach).
L/R BSTEM Mass Failure (tons or ft^3) L/R BSTEM Mass Failure Cum	Mass removed from the left or right bank by bank failure processes for each computation increment. This variable is available for the selected computation increment and the total since the beginning of the simulation (Cum).
L/R BSTEM Toe Mass (tons or ft^3) L/R BSTEM Toe Mass Cum	Mass removed from the left bank by toe scour for each computation increment. This variable is available for the selected computation increment and the total since the beginning of the simulation (Cum).
L/R Factor of Safety (Decimal Fraction)	Minimum factor of safety computed in the left or right bank for each computation increment.
BSTEM L/R Toe Station (ft or m)	The lateral station (i.e. the station-elevation point) of the toe. This tracks the lateral migration of the toe.
BSTEM L/R Toe Elevation (ft or m)	The elevation of the station-elevation point identified as the toe.
BSTEM L/R Top Station (ft or m)	The lateral station (i.e. the station-elevation point) of the point identified as the "top of bank". This tracks the lateral migration of a second point on the bank (besides the toe).
BSTEM L/R Top Elevation (ft or m)	The elevation of the station-elevation point identified as the "top of bank".
Movable Elv L/R: (ft)	The elevation of the movable bed limit. This is not a BSTEM specific variable, but can be helpful if the MBL is the BSTEM toe.

Movable Sta L/R:	Tracks the lateral position of the movable bed limit. If the BSTEM toe is the same as the MBL, this result will quantify toe scour distance.
Groundwater Elev (feet)	Ground water elevation computed in BSTEM, either static, user specified, or computed with the groundwater lag method.



Sediment Output Options

Sediment Output Options

Output Level: 6

Mass or Volume? Mass

Output Increment: Days

Primary Output Interval (Multiple of Output Increment) Bed Related Output for 2D: 1

2D Water Column Output Interval (Mult. of Out. Increment) Only Used For 2D: 1

☑ Cross Section Bed Change Output

Number of Increments Between XS Outputs: 1

Sediment Hotstart

☐ Initialize Data from Sediment Output File

Hotstart Type: Gradation and XS

Hostart Date:

Hostart Time:

Legacy Gradational Hotstart (Backward Compatability)

☐ Write Bed Gradations to an Output File

☐ Read Gradational Data from Hotstart File

☑ Write Classic Output (WSE Profile etc. - O flie)

☑ Write Legacy Binary Output

☐ Write Sediment DSS Output by Grain Class: Daily Flux

Specific Gage Plot

Select Steady Flow File:

Figure 4-21: Requesting and specifying the frequency of sediment cross section output in the Sediment Output Options dialog box.

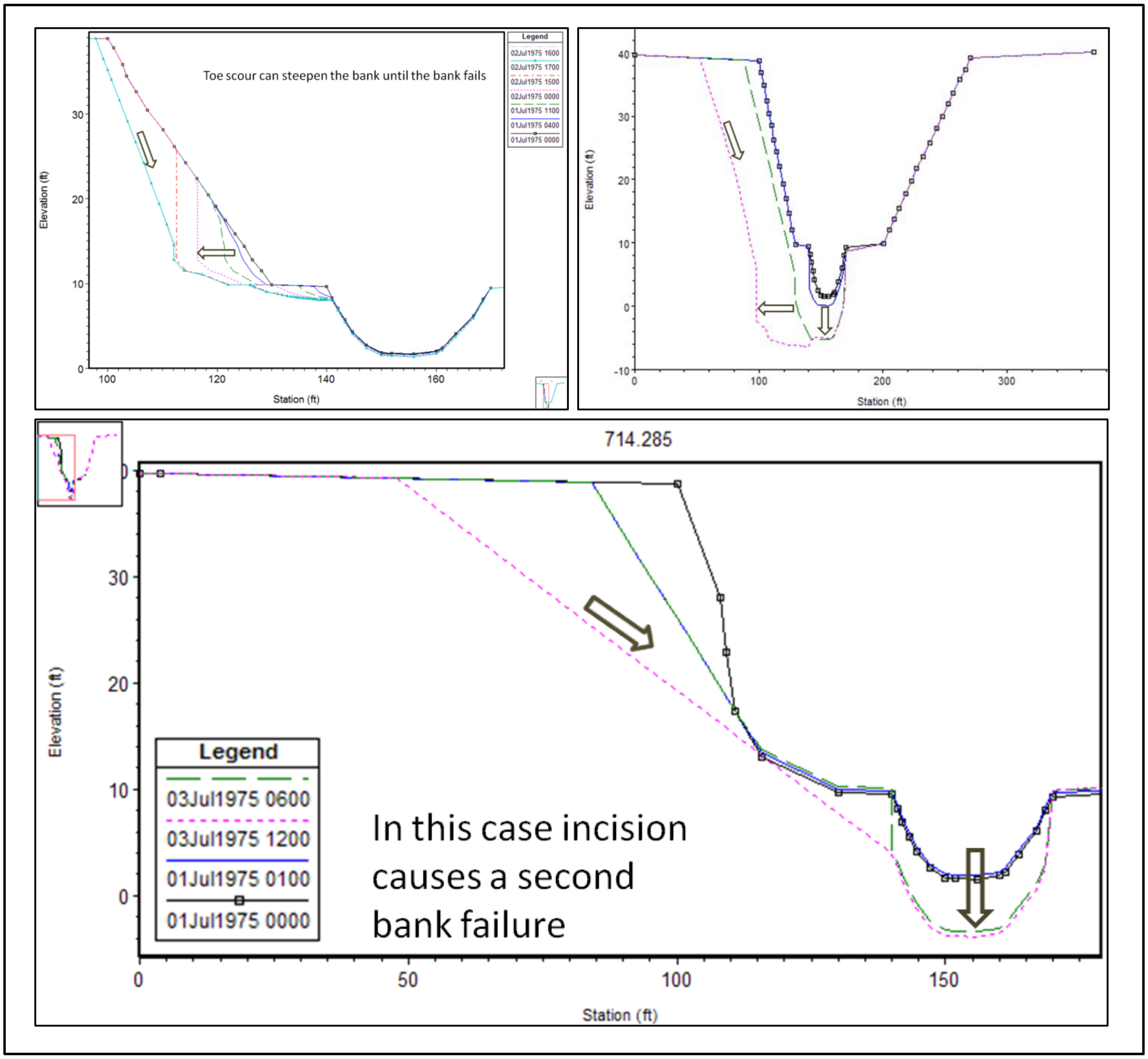


Figure 4-22: Example HEC-RAS cross section outputs including toe scour, incision and bank failure at various stages in the simulations.

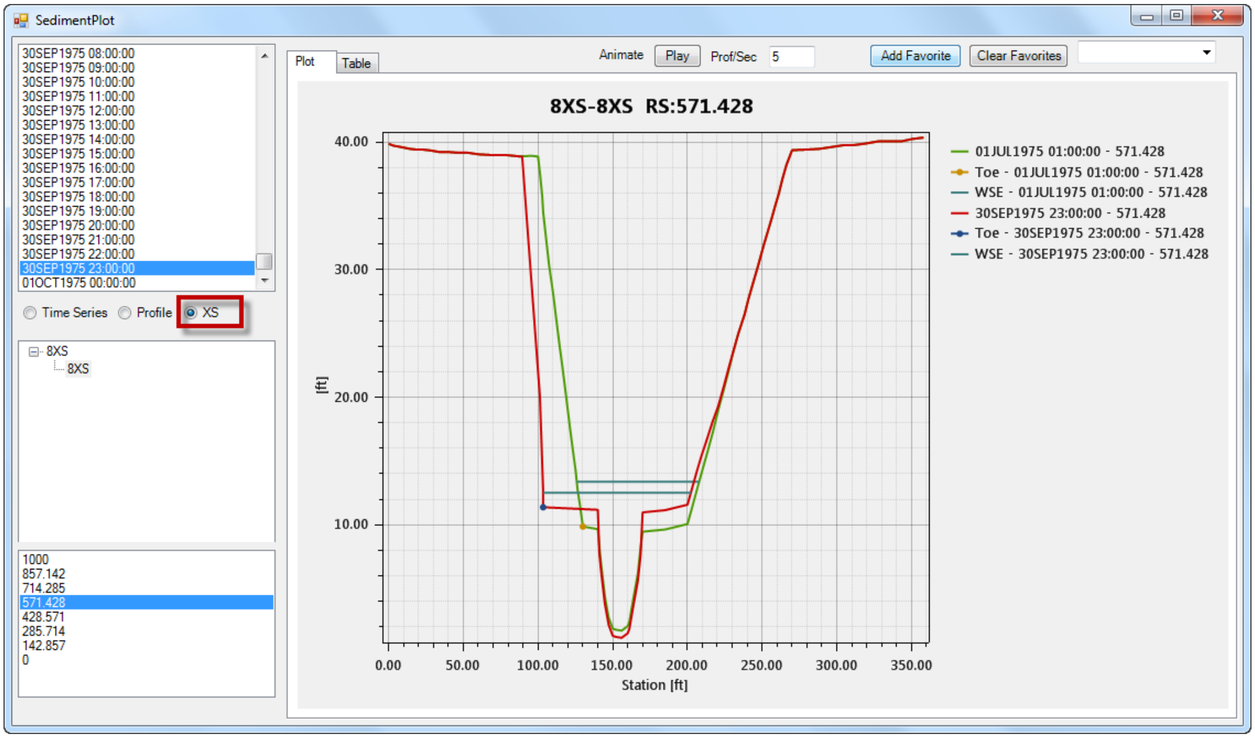


Figure 4-23: Bank migration cross section output with the new Sediment Output viewer.

Model Validation

Finally, model testing was conducted to demonstrate the reliability of the HEC-RAS/BSTEM algorithms. Several test scenarios were constructed and modeled with HEC-RAS, the standalone version of BSTEM 5.4 and the standalone FORTRAN version of BSTEM used in the integration (which was subjected to rigorous independent validation against BSTEM 5.4 (Simon et al., 2010)). The before and after cross sections for a bank failure event are displayed in Figure 4-24. The FORTRAN version of the algorithms in HEC-RAS replicates BSTEM 5.4 very closely. Small divergence can be explained by a couple algorithm differences between the FORTRAN version and BSTEM 5.4.

Gibson et al. (2015) also applied the model to Goodwin Creek, following the work of Langendoen and Simon (2008). Goodwin creek is a highly instrumented reach with substantial bank migration, carefully measured over a decade with dozens of repeated cross sections, making it an ideal site for evaluating a bank process model. Gibson et al. (2015) used the parameters from of Langendoen and Simon (2008), to test the model against a known calibration. The integrated HEC-RAS/USDA-ARS BSTEM model performed well compared to prototype data (Figure 4-25) and the CONCEPTS runs in Langendoen and Simon (2008).

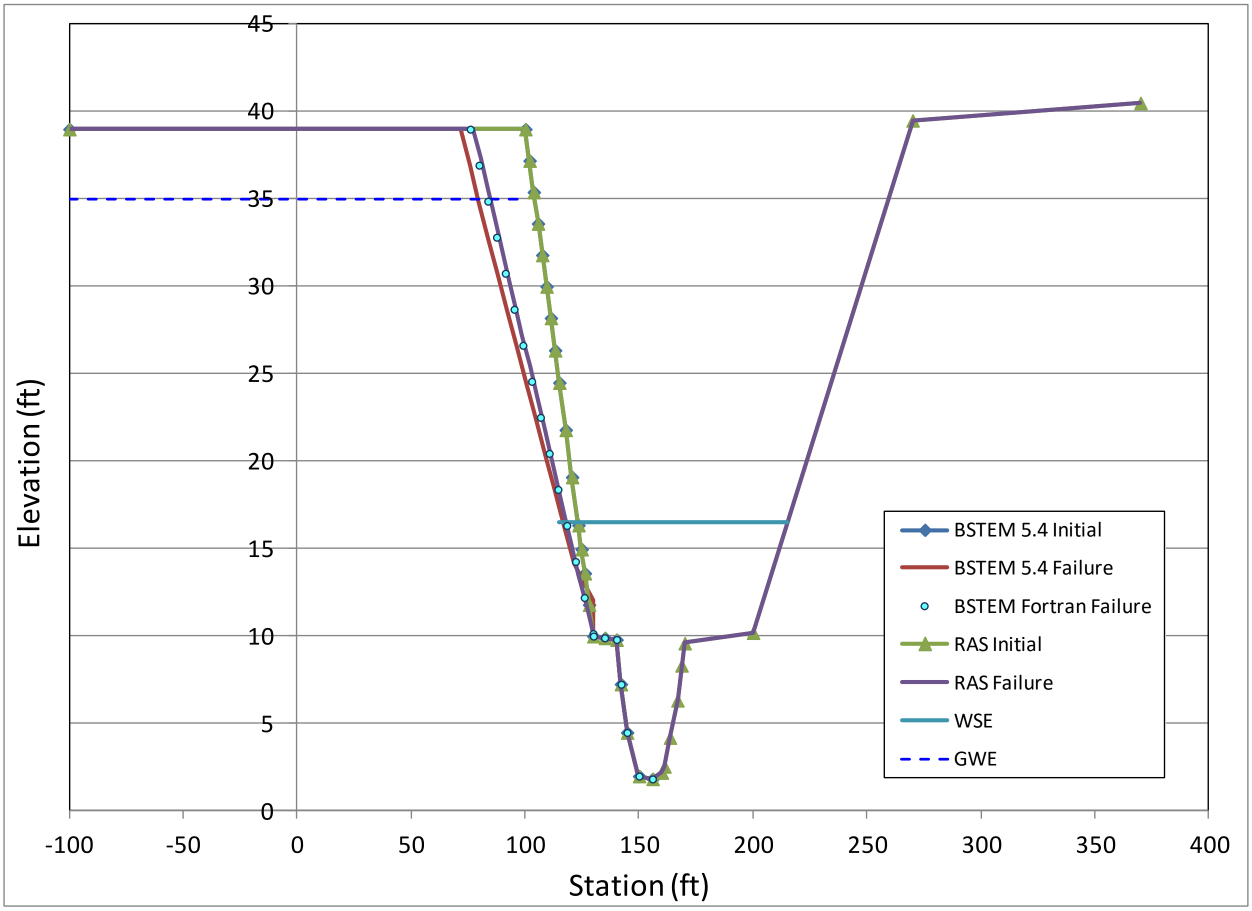


Figure 4-24: Output from a validation test of the HEC-RAS implementation of the bank failure capabilities and the standalone models.

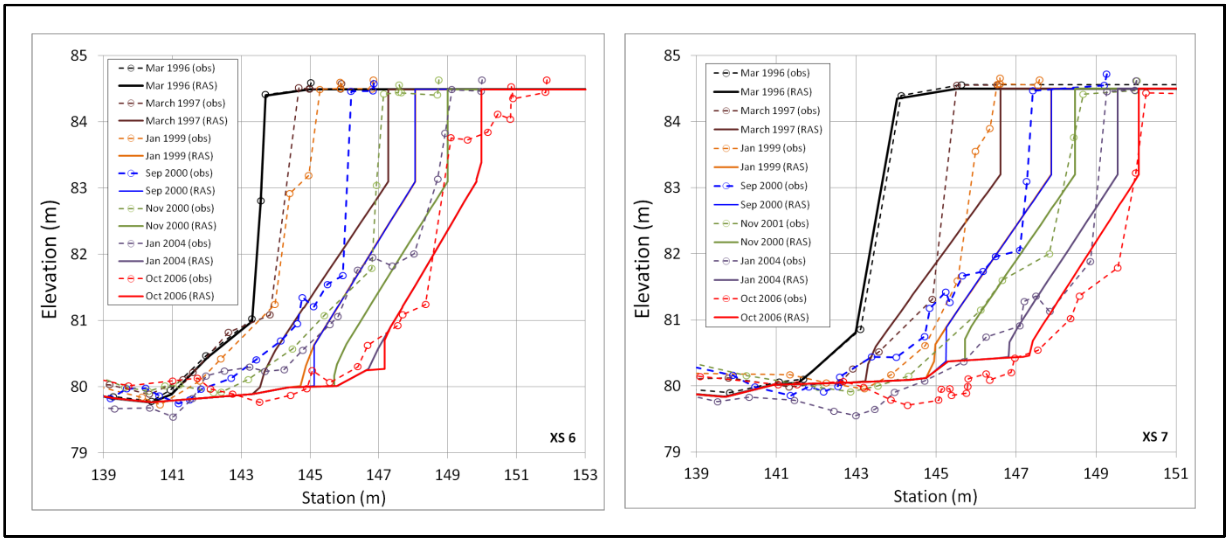


Figure 4-25: Select Goodwin Creek repeated right bank surveys at the two central cross sections with HEC-RAS/BSTEM cross section migration from Gibson et al. (2015).

BSTME Modeling Guidelines, Tips, and Troubleshooting

The HEC-RAS/BSTEM development team has compiled several modeling tips and guidelines that can make coupled bed-bank modeling more stable and less frustrating. Consider the following approaches and tips before setting up a model or to help troubleshoot models that are crashing or behaving poorly.

Stepwise Modeling Process

Sediment transport modeling with HEC-RAS was already complex and highly parameterized before bank failure. Bank failure makes it more complex. Complex models that account for more processes explicitly make careful, strategic, sequential modeling practice more important.

Model processes from simple to complex. Add complexity one step at a time. A stepwise modeling process, that adds complexity incrementally, carefully calibrating and evaluating results of each modeling step, will produce more accurate models and sane modelers.

Create an HEC-RAS/BSTEM model in the following incremental steps, carefully completing, evaluating, and calibrating each step before adding the complexity of the next step.

a. **Calibrate Hydraulics:** Create the geometry and calibrate model hydraulics in the steady flow module over the range of expected flows.

b. **Model/Calibrate Sediment Transport**: Isolate the sediment transport mechanics by carefully modeling bed sediment without bank processes first. Build a robust (Thomas and Chang, 2012) calibrated model, or at least, evaluate results to understand the sensitive parameters.

c. **Model/Calibrate Bank Erosion and Bank Failure**: By setting the cross sections as **Pass Through Nodes** (under the **Options** menu in the **Sediment Data Editor**), users can isolate bank processes and refine bank methods and parameters without the complexity bed process feedbacks.

d. **Integrate Bank Erosion and Failure plus Mobile Bed Sediment Transport Model**: After the hydraulics are calibrated and the bed and bank sediment models have been refined independently, then combine all the components, and calibrate the coupled model to bed and bank change.

Selecting a Toe

The USDA-ARS BSTEM model is very sensitive to the toe node selected. Tips for selecting the toe include:

1. Make the **BSTEM Toe Station** the same as the **Movable Bed Limit** (**Left Station** and **Right Station** in **Initial Conditions and Transport Parameters** in the **Sediment Data Editor**). While there is a tool to set the **Toe Stations** to the **Movable Bed Limits**, it is often better to go the other way, selecting a toe and then setting the **Movable Bed Limit** station equal to the **Toe Station**.

2. HEC-RAS distorts cross sections vertically in the cross section display. This makes them easier to visualize, but can make it difficult to select a toe. When selecting toe stations, change the aspect ratio of the cross section plotter and zoom in along the horizontal axis to get a 1:1 H:V ratio from the plot (Figure 4-26). This adjustment will make it easier to pick an actual toe from an undistorted cross section plot.

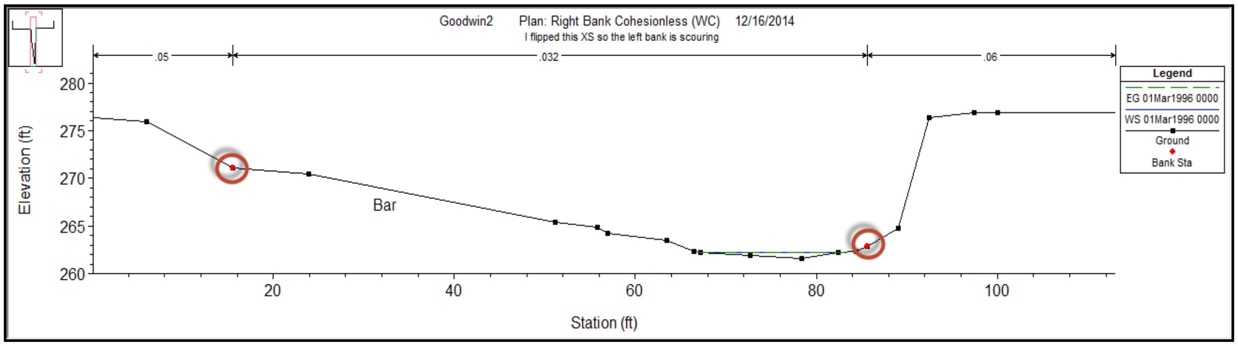


Figure 4-26: Cross section viewer adjusted to approximately a 1:1 aspect ratio to help select the toe station.

Monotonic Bank Geometry

HEC-RAS allows complex cross sections. USDA-ARS BSTEM idealized cross sections in a couple of important ways. HEC added logic to adapt BSTEM to complex cross sections but some cross sections shapes still tend to be unstable. In particular, avoid "bank depressions" (Figure 4-27) if possible. Cross section node elevations should increase from the toe to the edge of the bank.

The model can become unstable when a soil layer boundary crosses the cross section more than once. Therefore, if the cross section includes an important bank depression, make sure that the soil layer does not pass through it.

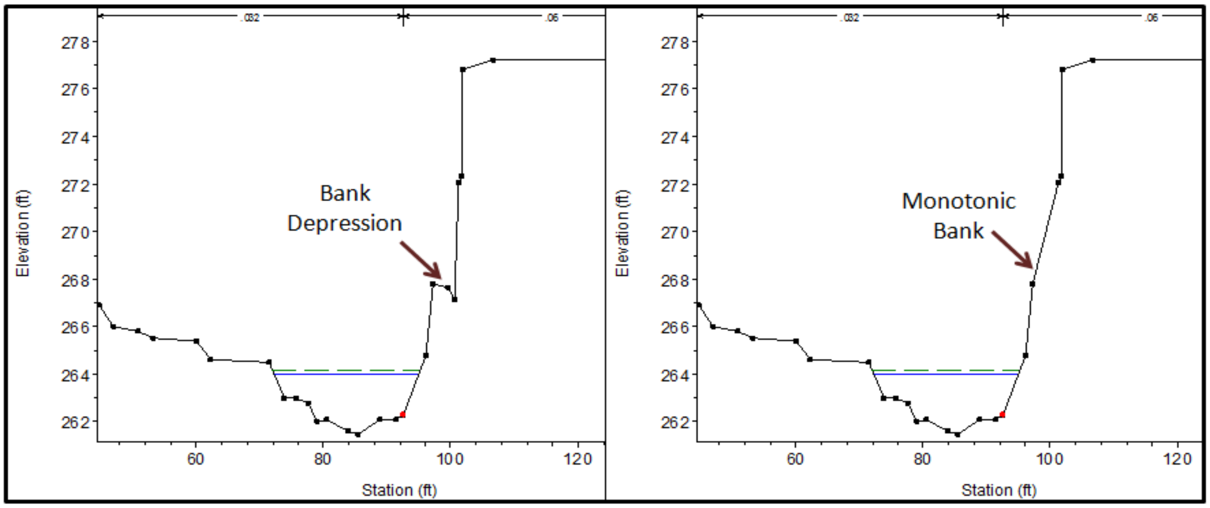


Figure 4-27: Avoid bank depressions (left) where possible, particularly with soil layers. Monotonic

Floodplain Geometry

The portion of the cross section outside the **Edge of Bank Station** must conform to three conventions to provide optimal results:

1. The floodplain must be wide enough to include the maximum failure plane angle. For long term simulations this includes the maximum failure plane from the maximum scour location. As a rule of thumb, include a floodplain wide enough to encompass at least a ten degree angle from the toe station.

2. The floodplain needs intermediate station-elevation points between the edge of the bank and the end of the cross section (Figure 4-28) for BSTEM to compute failure planes effectively.

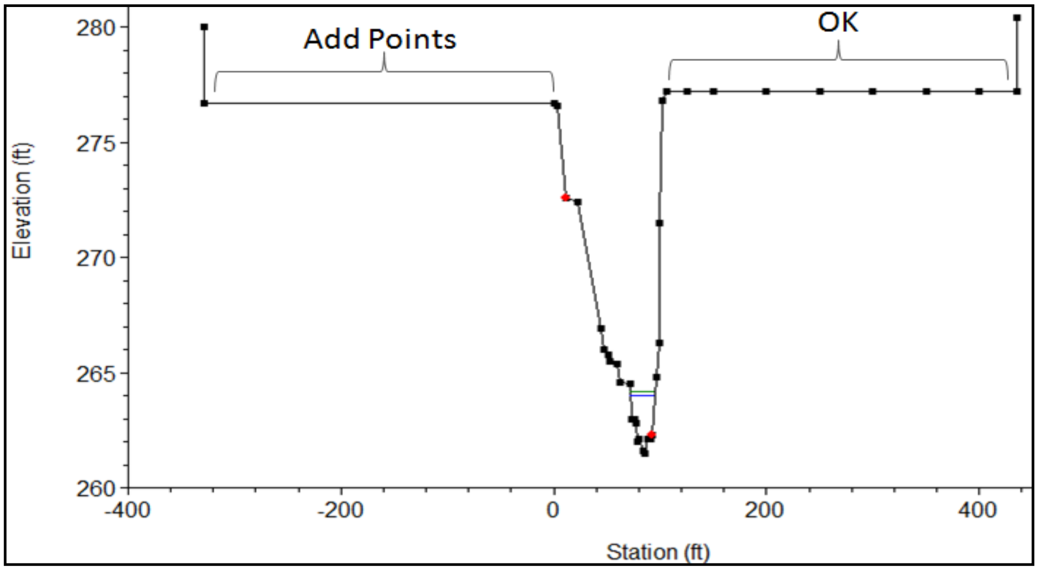


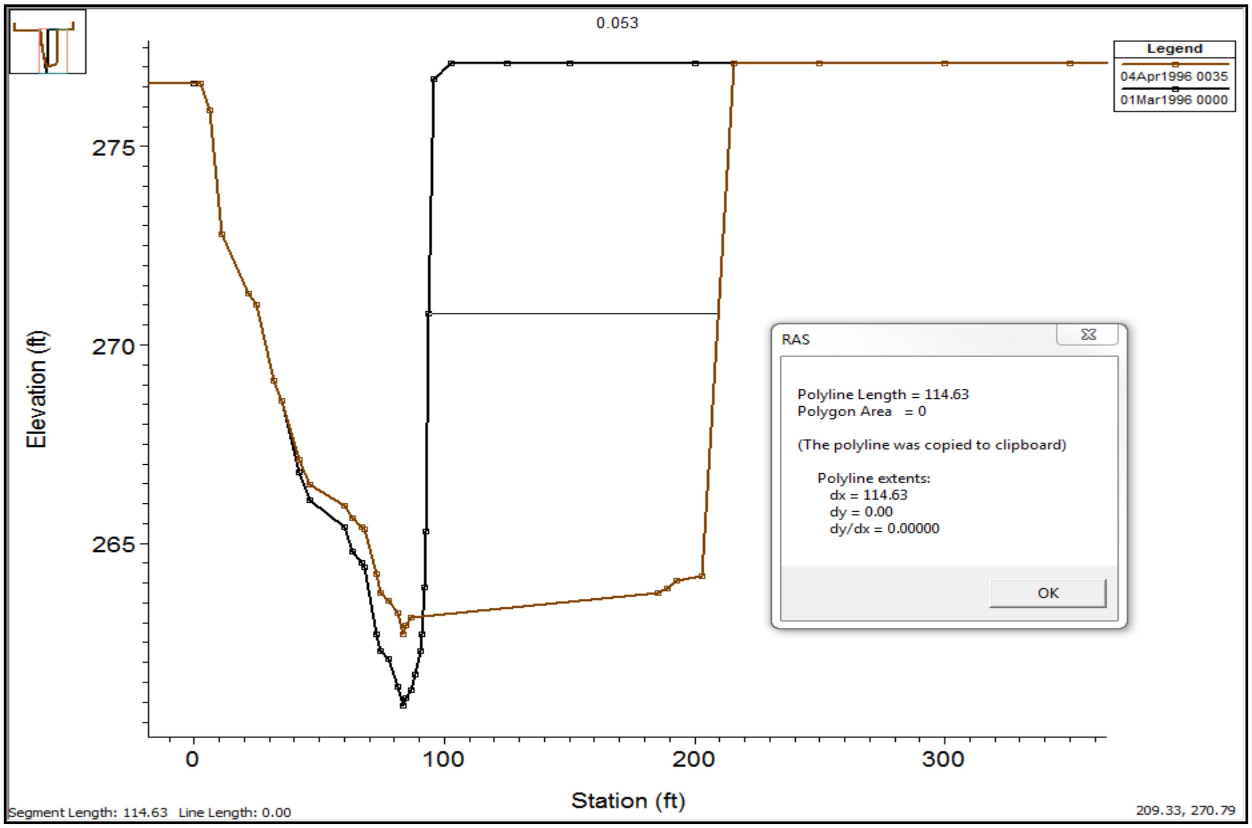
Figure 4-28: BSTEM requires cross section station-elevation points between the Bank Edge Station and the end of the cross section.

3. If the floodplain is irregular (like Figure 39) it should not intersect with a layer. If the cross section includes multiple soil layers, the top layer should include all of the cross section nodes outside of the bank edge station.

4. HEC-RAS should be able to handle wet depressions and ineffective flow areas outside the bank edge, but the more flodplain complexity in a cross section the more likely that the bracket and Brent method (Teukolsky et al., 2007) will converge on a false maximum or that the cross section update will encouter a problem. So avoid incidental cross section complexity, particularly in the overbank.

Too Much Scour

Most HEC-RAS/BSTEM model failures come from having too much toe scour. Since soil erodibility data can vary by orders of magnitude, even in the same site, selecting high cohesive erodibility will compute excessive scour. Cohesionless methods (Figure 4-29), that compute toe scour with transport equations almost always over predict scour, sometimes dramatically.



Polyline Length = 114.63
Polygon Area = 0

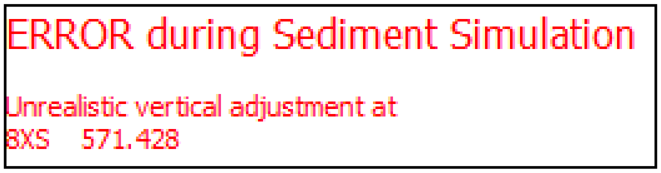
(The polyline was copied to clipboard)

Polyline extents:
dx = 114.63
dy = 0.00
dy/dx = 0.00000

Figure 4-29: In this model, the cohesionless transport methods computed more than 100 feet of bank scour in just over a month, which is order of magnitude faster than the actual bank recession rate.

Common Runtime Error Messages

The **unrealistic vertical adjustment** error (Figure 4-30) is the most common sediment error in general and HEC-RAS/BSTEM in particular. This error indicates that HEC-RAS computed very large bed changes at the indicated cross section in the final time step before the program stopped.



```
ERROR during Sediment Simulation

Unrealistic vertical adjustment at
8XS    571.428
```

Figure 4-30: The Unrealistic Vertical Adjustment Error.

Often this error can be resolved by reducing the computation increment. However, sometimes more systemic model or data problems make the error persist at very small computational increments. The most common causes include:

1. Excessive toe scour: The most common cause of model failure is excessive toe scour (see previous section). Lower the erodibility substantially or turn off the cohesionless transport methods (go to the BSTEM Options editor under the Options menu in the Sediment Data editor) to stabilize the model.

2. Bed material does not match transport function: If the bed material is too fine for the transport function, or if the transport function over predicts transport in the reach, the mis-match can lead to large, rapid bed changes, destabilizeing the model. A common error involves assigning fine bank material gradations to the bed.

3. Equilibrium Load: If the equilibrium load boundary condition is used with bed gradations that include no-trivial silt or clay, this boundary condition can compute enormous fine grained sediment loads at the boundary. Small decreases in transport downsteam can cause large bed changes. User defined rating curves are almost always better sediment boundary condition options, even if they are speculative.

Unusual Cross Section Shape

Sometimes active cross sections can produce strange shapes, like the example shown in Figure 55. First, make sure the toe station and the movable bed limits are set to the same station. Second, the ARS-USDA BSTEM features often work best if HEC-RAS allows deposition outside the movable bed limits. In the **Sediment Data Editor**, go to the **Options** menu and select **Bed Change Options**. Then, under **Deposition** select the **Allow Deposition Outside of the Movable Bed Limits** option. This will constrain erosion to the movable bed limits (which will migrate with the toe if they have the same staring station) but will deposit any wetted node in the cross section. The model in Figure 4-31 was re-run in Figure 4-32 with this option selected and produced more realistic results.

Groundwater Table

Results can be very sensitive to groundwater. Two particular groundwater errors that can create model problems:

1. Never specify a starting or static groundwater table that is higher than the bank edge.

2. Groundwater elevations far below the channel water surface elevation will prevent the bank from failing. The USDA-ARS BSTEM applies a hydrostatic assumption, computing suction according to a hydrostatic gradient from the groundwater elevation. Therefore, in ephemeral streams or situations where the groundwater table is unknown, estimate the groundwater elevation or put it at an average surface water elevation banks should fail.

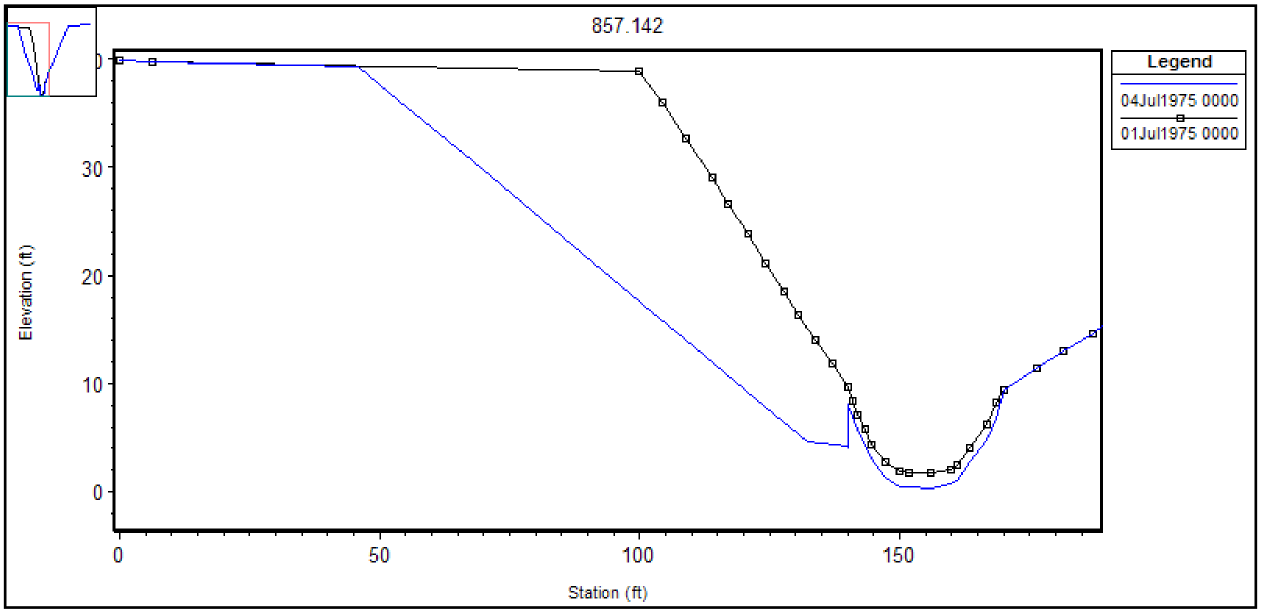


Figure 4-31: Strange cross section shape caused by deposition inside the movable bed limits, but not outside.

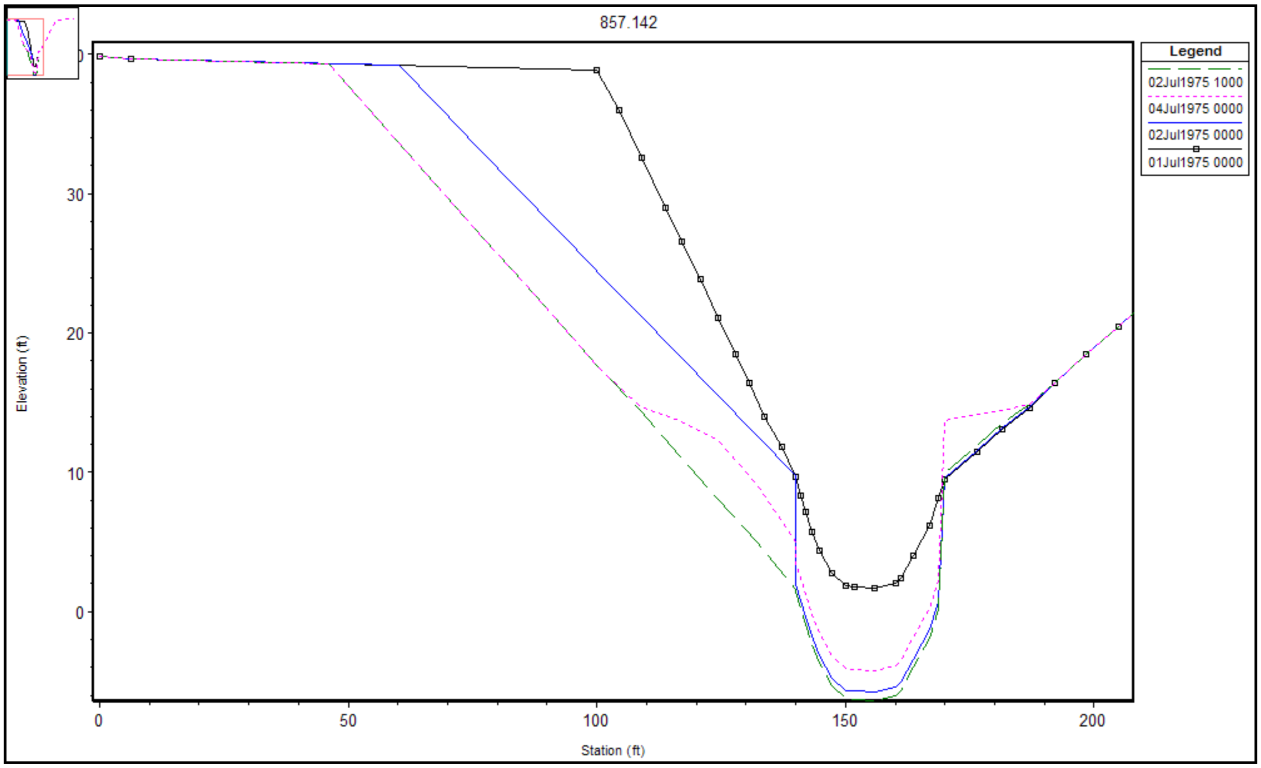


Figure 4-32: The same simulation as Figure 55, but allowing for deposition in the overbanks.

Scour Outside of a Bend

In natural systems, banks are usually most active on the outside of a bend or meander. HEC-RAS is a one-dimensional model and does not simulate the multi-dimensional forces that cause this preferential erosion. Banks migrate more on the outside of bends because multi-dimensional effects produce higher shears there. Because HEC-RAS uses an excess shear equation to compute scour, users can simulate preferential bank scour by decreasing the critical shear at bend cross sections. This will approximate the physical process, increasing the (τ-τ_c) shear difference by decreasing the critical shear instead of increasing the shear.

Acknowledgements

The integration of the USDA-ARS Bank Failure and Toe Erosion Methods (BSTEM) in HEC-RAS has been a significant effort with multiple funding partners including:

-The Regional Sediment Management Program (USACE)

-The Missouri River Recovery Project (USACE)

-The Australian Rivers Institute

-The Flood and Coastal R&D Program (USACE)

HEC has also collaborated with and received code and/or technical guidance from:

-Andrew Simon PhD and Natasha Bankhead PhD (Cardno Entrix)

-Eddy Langendoen PhD and the USDA-ARS

-The US Bureau of Reclamation

The integration of HEC-RAS and BSTEM has been a substantial undertaking including multiple contributors in the USACE, the private sector, other Federal agencies, and even international interests. Andrew Simon (PhD - Cardno ENTRIX, formerly of USDA-ARS) partnered with HEC to initiate, envision and facilitate the integration. Eddy Langendoen (PhD - USDA-ARS) has provided essential technical support and advice throughout the process. The integration utilized code developed by Rob Thomas (PhD - University of Hull, formerly of University of Tennessee) and Yong Lai (PhD - USBR), funded by the Bureau of Reclamation and the Taiwanese Water Resources Agency, with input from Yavuz Ozeren (PhD - University of Mississippi). John Shelly (PhD - NWK) and Paul Boyd (PhD - NWO) provided District guidance and feedback on the development. Stanford Gibson (PhD - HEC) and Steve Piper (RMA) worked on the integrated HEC-RAS code. Funding for the development, troubleshooting, and documentation of the integrated HEC-RAS/BSTEM product has come from multiple sources including two Corps's R&D Programs (Regional Sediment Management and Flood & Coastal Storm Damage Reduction), the Australia Rivers Institute, and the Missouri River Recovery Program.

Scour Units

The cohesive model used in the bed model is different than that used in the bank model. The bed model removes sediment by mass. Mass is removed per area, per time in response to a force (e.g. N/m2-hr/Pa which translates to the slope of the relationship between mass removed pere area per time and the force, which is 1/time). In the bank model a volume is removed in response to a force, so the units are Volume/force-time (e.g. M3/Pa-hr).

This difference is because bulk mass is removed from the bed and applied uniformly over the bed. The bank model shifts each node laterally, independently. Therefore, a "volume" is translated into a lateral shift, per node.

The following table provides conversion factors to move between SI and US customary units.

Table 4-2: Conversion Factors.

From	**Multiply by**	**To**
m^3/N/s	0.42	1/hr
Pa	0.0208	psf
m^3/N-s	6365.9	ft^3/lbf-s
1/hr	2.39	m^3/N/s
psf	47.9	Pa
ft^3/lbf-s	0.000157	m^3/N-s

References

Bishop, A.W. (1955) "The Use of the Slip Circle in the Stability Analysis of Slopes," *Geotechnique*, 5, 7-17.

Briaud J.-L., Ting F., Chen H.C., Cao Y., Han S.-W., Kwak K. (2001) "Erosion Function Apparatus for Scour Rate Predictions", *Journal of Geotechnical and Geoenvironmental Engineering*, 127(2), 105-113

Einstein, H.A. (1950) *The Bed-Load Function for Sediment Transport in Open Channel Flows*, Technical Bulletin No 1026, United States Department of Agriculture, 74p.

Engelund, F., and Hansen, E. (1967). A Monograph on Sediment Transport in Alluvial Streams. Danish Technical (Teknisk Forlag).

Fredlund, D.G., 1986. Slope-stability analysis incorporating the effect of soil suction. In: Anderson, M.G., Richards, K.S.Eds.., Slope Stability. Wiley, Chichester, pp. 113–145.

Gibson, S., Brunner, G., Piper, S., and Jensen, M. (2006) "Sediment Transport Computations in HEC-RAS." Eighth Federal Interagency Sedimentation Conference (8thFISC), Reno, NV, 57-64.

Gibson, S., Simon, A., Langendoen, E., Bankhead, N., Shelley, J. (2015) A Physically-Based Channel-Modeling Framework Integrating HEC-RAS Sediment Transport Capabilities and the USDA-ARS Bank-Stability and Toe-Erosion Model (BSTEM), SEDHYD Federal interagency conference

Hanson, G. J. (1990) Surface erodibility of earthen channels at high stresses: I. Open channels testing. Trans. ASAE 33(1): 127-131.

Kean, J.W. and Smith, J.D. (2005) "Generation and verification of theoretical rating curves in the Whitewater River basin, Kansas," *Journal of Geophysical Review,* 110, F04012, doi:10.1029/2004JF000250.

Lai, Y. G., Thomas, R. E., Ozeren, Y., Simon, A., Greimann, B. P., and Wu. K. (2014). Modeling of multilayer cohesive bank erosion with a coupled bank stability and mobile-bed model. Geomorphology, doi: 10.1016/j.geomorph.2014.07.017.

Lambe, T.W. and Whitman, R.V. (1969) *Soil Mechanics,* John Wiley and Sons, 553p.

Langendoen, E.J. and Simon, A. (2008), Modeling the evolution of incised streams, II: Streambank erosion. Journal of Hydraulic Engineering, 134(7): 905-915.

Morgenstern, N. and Price, V.E., (1965), "The Analysis of the Stability of General Slip Surfaces", Geotechnique, Vol. 15, No. 1, pp 79 - 93.

Parker, G. 1990a. Surface-based bedload transport relation for gravel rivers. *Journal of Hydraulic Research*. 28: 417-436.

Shelley, J., Gibson, S., and Williams, A. (2015) "Unsteady Flow and Sediment Modeling in a Large Reservoir Using HEC-RAS 5.0" Federal Interagency Sediment Conference.

Smith, S.J., Peterson, M.D., and Pratt, T.C. 2010. Numerical modeling studies supporting Port of Anchorage deepening and expansion, part ii: measuring physical processes. Proc. Estuarine and Coastal Modeling Conference 2009. pp. 286-300. ASCE.

Simon A., Thomas, R., and Klimetz, L. (2010) Comparison and Experiences with Field Techniques to Measure Critical Shear Stress and Erodibility of Cohesive Deposits, 2nd Joint Federal Interagency Conference, Las Vegas, NV, June 27 - July 1, 2010.

Simon, A., Ozeren, Y., and Thomas, R. E. (2012) Comparison of the Bank-Stability Sub Model with in the Visual Basic and FORTRAN Versions of (BSTEM), 18p.

Simon, A., Curini, A., Darby, S.E., and Langendoen, E.J. (2000). "Bank and near-bank processes in an incised channel", Geomorphology, 35, pp. 193-217.

Simon, A., Curini, A., Darby, S.E., and Langendoen, E.J., (2000), Bank and near-bank processes in an incised channel. Geomorphology, 35: 193-217.Simon et al., (2008), Application of a deterministic bank-stability model to design a reach-scale restoration project.

Simon, A., Derrick, D., Alonso, C.V., and Bankhead, N.L., 2008. Application of a deterministic bank-stability model to design a reach-scale restoration project. Proc. ASCE-EWRI, World Environmental Water Resources Congress, Honolulu, Hawaii, 10 p. (on CD).

Simon, A., Pollen-Bankhead, N., and Thomas, R.E., (2011). Development and application of a deterministic bank stability and toe-erosion model for stream restoration. In. Stream Restoration in Dynamic Fluvial Systems: Scientific Approaches, Analyses, and Tools. A. Simon, S.J. Bennett, and J.M. Castro (Eds.), Geophysical Monograph Series, 194, 500 p. ISBN 978-0-87590-483-2, Washington, DC.

Teukolsky, S.A., Vetterling, W.T., and Flannery, B.P. (2007) Numerical Recopies: The Art of Scientific Computing, Cambridge University Press; 3 edition, 1256 p.

Thomas, T. and Cheng, H. (2012) "Computational Modeling of Sedimentation Processes" ASCE Manual of Practice 110: Sedimentation Engineering: Processes, Measurements, Modeling, and Practice, 649-681

Thorne, C.R. and Tovey, N.K. (1981) "Stability of Composite River Banks," *Earth Surface and Landforms*, 6, 469-484.

Thorne, C.R. (1981) Field measurements of rates of bank erosion and bank material strength. Erosion and Sediment Transport Measurement. Proceedings of the Florence Symposium, IAHS Publication 133, 503-512.

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

Yang, C.T. (1973) "Incipient motion and Sediment Transport," *Journal of the Hydraulics Division*, (99)10, 1679-1704

SI Table

Table 2. Default materials and material parameters.

Case Material	**Wt (kN/m^3)**	**frAng**	**C (kPa)**	**ΠηιΒ**	**Tc(Pa)**	**E (cm3/Ns)**
Default Material Type	**Saturated Unit Weight** (kN/m^3)	**Friction Angle** (ϕ')	**Cohesion** (kPa)	ϕ^b	**Critical Shear** (Pa)	**Erodibility** (m^3/N-s)
Boulders	20.0	42.0	0	15	498	4.48E-09
Cobbles	20.0	42.0	0	15	124	9.00E-09
Gravel	20.0	36.0	0	15	11	3.02E-08
Coarse Angular Sand	18.5	32.3	0.4	15	0.506	1.41E-07
Course Round Sand	18.5	28.3	0.4	15	0.506	1.41E-07
Fine Angular Sand	18.5	32.3	0.4	15	0.128	1.41E-07
Fine Round Sand	18.5	28.3	0.4	15	0.128	1.41E-07
Erodible Silt	18.0	26.6	4.3	15	0.1	3.16E-07
Moderate Silt	18.0	26.6	4.3	15	5	4.50E-08
Resistant Silt	18.0	26.6	4.3	15	50	1.40E-08
Erodible Soft Clay	17.7	26.4	8.2	15	0.1	3.16E-07
Moderate Soft Clay	17.7	26.4	8.2	15	5	4.50E-08
Resistant Soft Clay	17.7	26.4	8.2	15	50	3.16E-07
Erodible Stiff Clay	17.7	21.1	12.6	15	699.1	3.16E-07
Moderate Stiff Clay	17.7	21.1	12.6	15	5	4.50E-08
Resistant Stiff Clay	17.7	21.1	12.6	15	50	3.16E-07

CHAPTER 5

Sediment Impact Analysis Methods (SIAM)

SIAM is a sediment budget tool that compares annualized sediment reach transport capacities to supplies and indicates reaches of overall sediment surplus or deficit. SIAM is a screening level tool to compute rough, relative responses to a range of alternatives, in order to identify the most promising alternatives (which should then be modeled in more detail). The algorithms in SIAM evaluate sediment impact caused by local changes on the system from a sediment continuity perspective. The results map potential imbalances and instabilities in a channel network and provide the first step in designing or refining remediation.

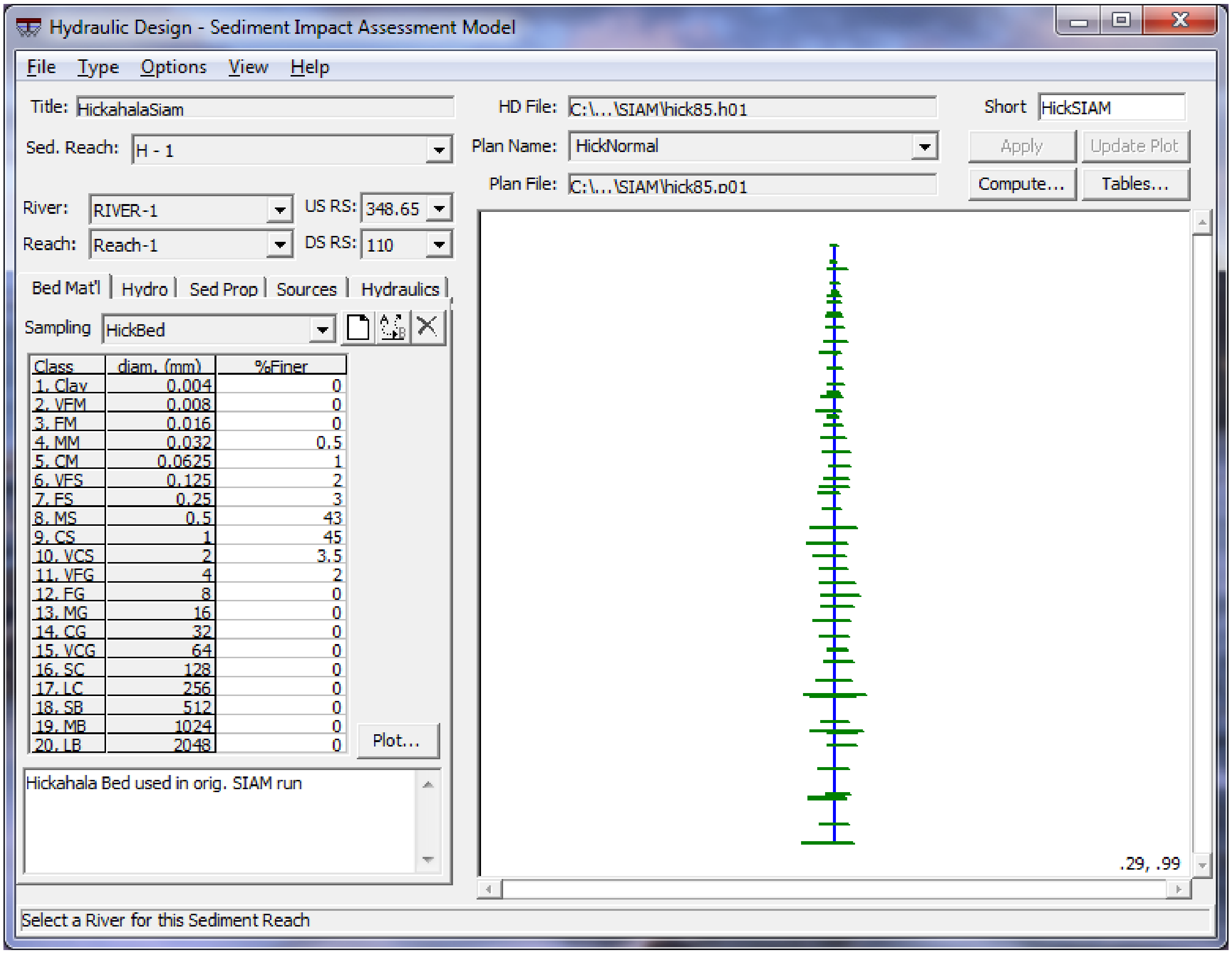
Users can begin with existing geometry and flow data and develop a set of sediment reaches with unique sediment and hydraulic characteristics. The SIAM program will then perform sediment transport capacity computations to determine potential imbalances and instabilities in a channel network. SIAM does not predict intermediate or final morphological patterns and does not update cross sections, but rather indicates trends of locations in the system for potential sediment surpluses or deficits. The results can be used to design or refine remediation efforts in the system.

Getting Started

SIAM is located in the Hydraulic Design Functions module and can be accessed by selecting **Hydraulic Design Functions** under the **Run** menu or by pressing the HD button. SIAM is not the default Hydraulic Design tool, so it must be selected from the **Type** menu from the Hydraulic Design editor. The SIAM window in the HD editor is depicted in Figure 18-1.

Defining a Sediment Reach

The HEC-RAS hydraulic model must initially be subdivided into sediment reaches. A sediment reach is a grouping of cross sections with relatively consistent hydraulic and sediment properties. Hydraulic parameters are averaged over the cross sections comprising a sediment reach and a single set of sediment data is entered for it. When the user first opens SIAM, they will be prompted to provide a name for the first sediment reach. Additional sediment reaches can be created by selecting **New Sediment Reach** under the sediment menu. Sediment reaches must be defined such that all cross sections are included within one and only one sediment reach. The four drop down selectors: **River**, **Reach**, **US RS**, and **DS RS** are designed to designate the upstream and downstream cross sections that form the limits of the sediment reach. (Figure 5-1) Sediment reaches cannot cross junctions and, therefore, must exist entirely within the same hydraulic reach. For example, if an HEC-RAS model contains three hydraulic reaches, it must have three or more sediment reaches. Hydraulic reaches should be subdivided into sediment reaches if they have significantly distinct hydraulic properties, hydrology or sediment data.



Title: HickahalaSiam

Sed. Reach: H - 1

River: RIVER-1

Reach: Reach-1

US RS: 348.65

DS RS: 110

HD File: C:\...\SIAM\hick85.h01

Plan Name: HickNormal

Plan File: C:\...\SIAM\hick85.p01

Short HickSIAM

Sampling HickBed

Class	diam. (mm)	%Finer
1. Clay	0.004	0
2. VFM	0.008	0
3. FM	0.016	0
4. MM	0.032	0.5
5. CM	0.0625	1
6. VFS	0.125	2
7. FS	0.25	3
8. MS	0.5	43
9. CS	1	45
10. VCS	2	3.5
11. VFG	4	2
12. FG	8	0
13. MG	16	0
14. CG	32	0
15. VCG	64	0
16. SC	128	0
17. LC	256	0
18. SB	512	0
19. MB	1024	0
20. LB	2048	0

Hickahala Bed used in orig. SIAM run

Select a River for this Sediment Reach

Figure 5-1: SIAM editor in the hydraulic design window with the bed material tab active.

Once the sediment reaches are defined, they must be populated with data. There are five data tabs:

Bed Mat'l – Bed material gradation data

Hydro – Annualized flow distribution

Sed Prop – A variety of sediment properties required to run the model

Sources – Accounting of local and annual sediment sources to the reach

Hydraulics – Reach weighted averaged hydraulic parameters for the sediment reach (automatically populated by HEC-RAS)

Each of these data tabs must be completed before the model will run.

Entering Data

Bed Material

Each sediment reach requires bed material information. However, any number of bed material sampling records can be defined in the **Bed Mat'l** records tab. A given bed material sample can be used exclusively for one sediment reach or can be shared by more than one sediment reach. The record shown in the sampling drop-down box when data is saved will be the record assigned to the sediment reach active at that time. When a new sediment reach is selected, the contents of the tabs records are automatically saved to the previously active sediment reach. The SIAM window with the bed material tab activated is shown in Figure 5-1. When a new SIAM project is started, after the user enters a name for the new sediment reach, a prompt will be given to name a new bed sampling record. Once this is done, the new bed sampling record will appear in the Sampling drop-down box, as will all other created bed material records.

Once a bed sample template is created the gradation can be specified in the grid. Twenty grain classes are available. The name and geometric mean grain size for each class are displayed. Gradation is entered as the percent of the total sediment gradation, which is finer than the listed particle diameter, by weight (e.g a number between 0 and 100). Any grade classes that are not assigned a percent finer value will be treated as if they do not exist in the bed material.

A text box is located at the bottom of the tab for the user to add notes that identify or otherwise describe the currently active bed material record.

Buttons available on the bed material tab are:

🗋 Create a new Bed Material Sampling record.

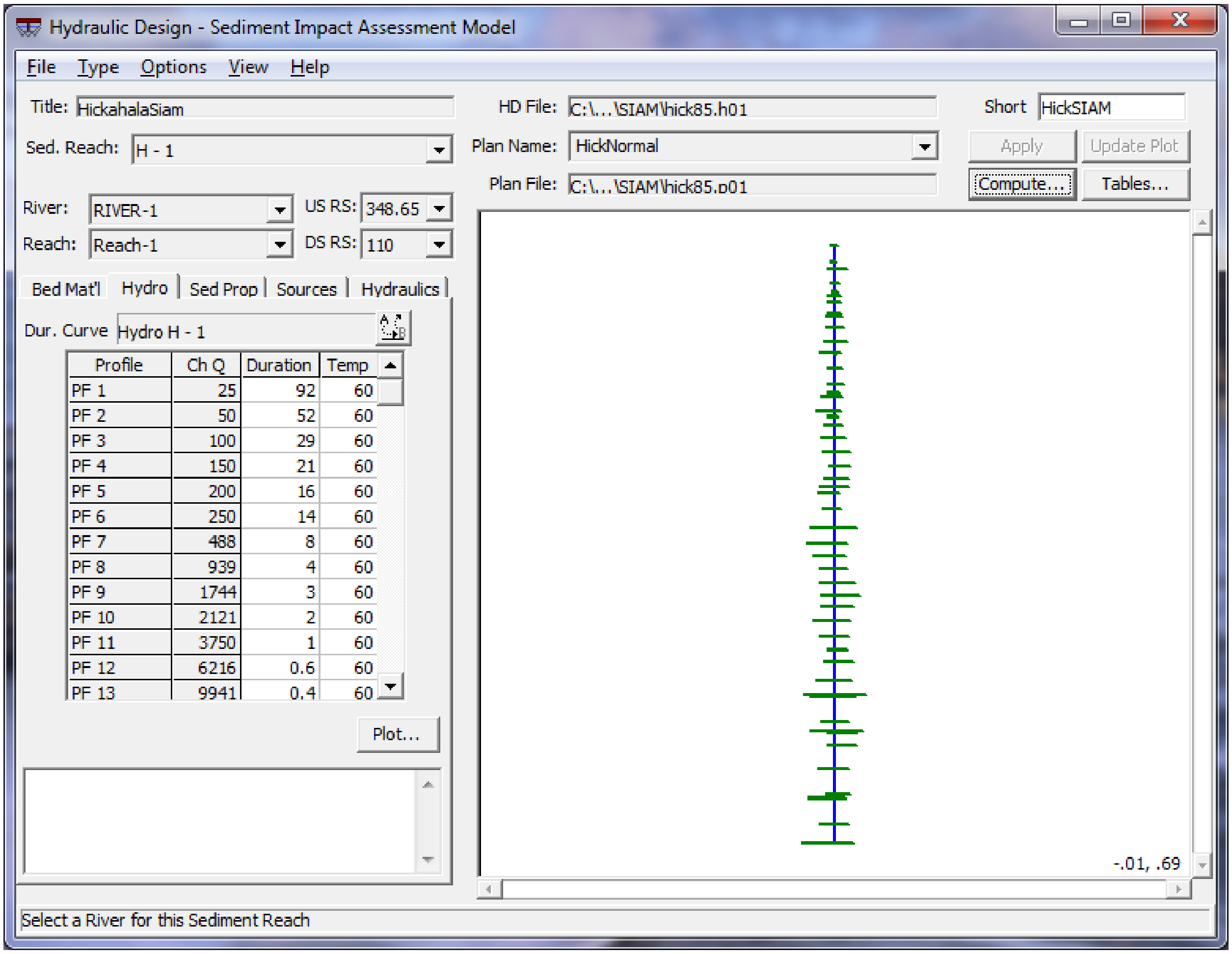
A→B Rename the current Bed Material Sampling record.

✕ Delete the current Bed Material Sampling record.

Plot... Plot the current Bed Material Gradation curve.

Hydrology

Before a SIAM model can be developed a standard, steady flow HEC-RAS model must be created and run. The SIAM **Hydro** tab is automatically populated with Hydrology records when a new sediment reach is defined. By default, the new hydrology record will be named "Hydro – (Sediment Reach Name)". Although this record must remain with the sediment reach it was created with, the user can change its name. The Hydro tab is shown in Figure 5-2.



Title: HickahalaSiam

Sed. Reach: H - 1

River: RIVER-1

Reach: Reach-1

US RS: 348.65

DS RS: 110

HD File: C:\...\SIAM\hick85.h01

Plan Name: HickNormal

Plan File: C:\...\SIAM\hick85.p01

Short HickSIAM

Dur. Curve Hydro H - 1

Profile	Ch Q	Duration	Temp
PF 1	25	92	60
PF 2	50	52	60
PF 3	100	29	60
PF 4	150	21	60
PF 5	200	16	60
PF 6	250	14	60
PF 7	488	8	60
PF 8	939	4	60
PF 9	1744	3	60
PF 10	2121	2	60
PF 11	3750	1	60
PF 12	6216	0.6	60
PF 13	9941	0.4	60

Select a River for this Sediment Reach

Figure 5-2: Hydrology data tab.

The **Profile** column is automatically populated with the profile associated with the current plan file. The **Ch Q** column is also automatically populated with a sediment reach length-weighted channel discharge. These values update if the bounding cross sections of the sediment reach change.

SIAM predicts annual trends and is based on an annualized flow duration curve. Therefore, the populated profiles must be distributed over 365 days. The user enters duration increments in the **Duration** column, for each profile, in units of days per year. These durations should sum to 365. SIAM will utilize all of the days input for its annualized flow and will not normalize to a year.

Water temperature is also required for each profile. This allows the user to vary the temperature seasonally. Buttons available on the Hydro tab are:

Rename the current Hydrology record.

Plot... Plot the current Duration curve.

An example plot of a full hydrologic record is shown in Figure 5-3.

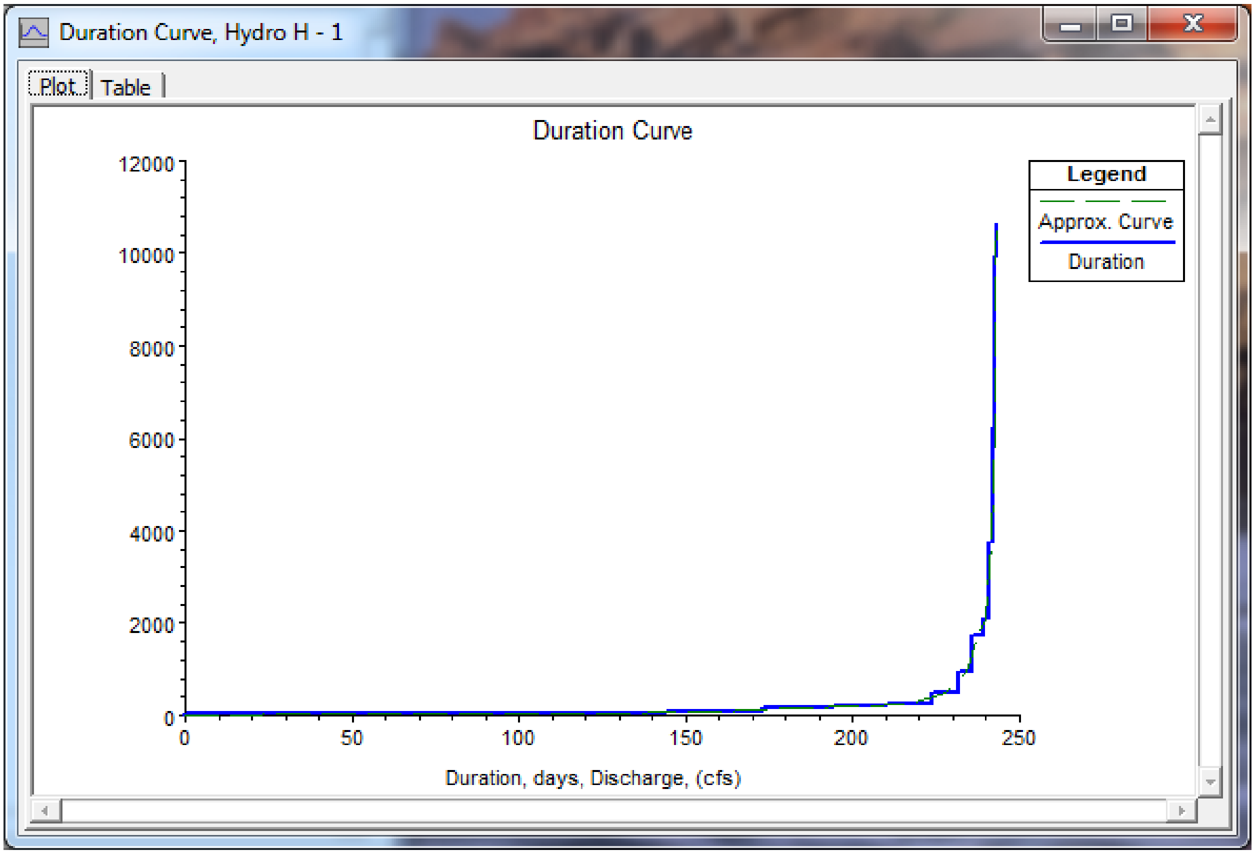


Figure 5-3: Plot of annualized duration curve.

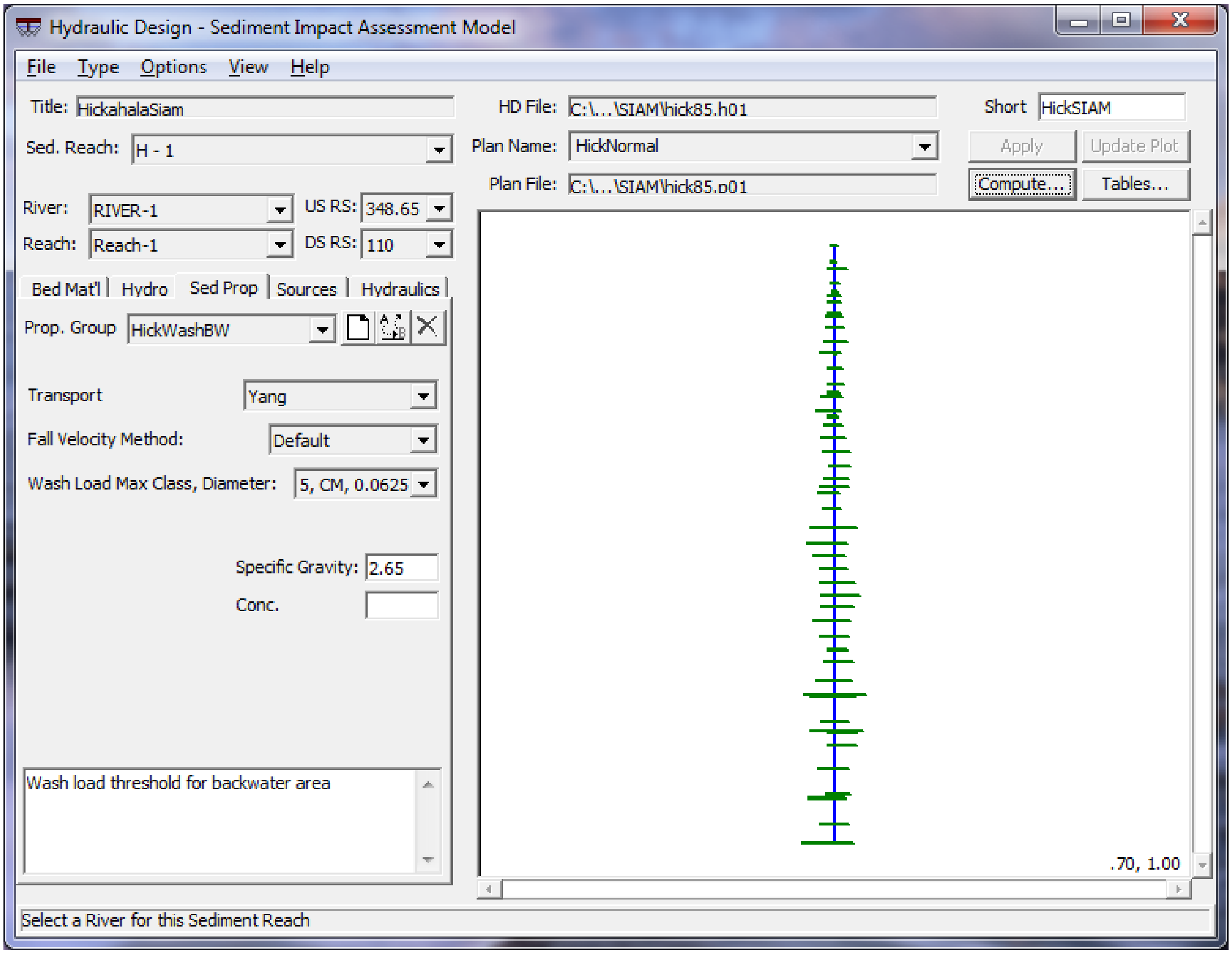
Sediment Properties

Sediment Property records are similar to the Bed Gradation templates in that a given Sediment Property record can be used exclusively for one sediment reach or can be shared by more than one sediment reach. These properties are defined in the **Sed Prop** tab. The record shown in the **Prop. Group** drop-down box at the time data is saved, will be the record assigned to the currently active sediment reach. The SIAM window with the **Sed Prop** tab activated is shown in Figure 5-4.

Transport Function

SIAM uses one of six transport functions to compute the annualized transport capacity. The appropriate equation is selected from the drop down box labeled **Transport Function**. Results are very sensitive to the transport function selection so care should be taken when selecting this option. For more description of these functions see Chapter 17 as well as the technical reference manual.

Separate transport functions can also be applied for different grain classes by selecting **Multiple Transport Functions by Grain Size** from the **Options** menu item. When this is selected, the transport function dropdown box becomes a command button with the caption **Multiple Transport Eqs**. Clicking this button to accessed the multiple transport functions grid, as shown in Figure 5-5.



Title: HickahalaSiam

HD File: C:\...\SIAM\hick85.h01

Short HickSIAM

Sed. Reach: H - 1

Plan Name: HickNormal

Plan File: C:\...\SIAM\hick85.p01

River: RIVER-1

US RS: 348.65

Reach: Reach-1

DS RS: 110

Prop. Group HickWashBW

Transport Yang

Fall Velocity Method: Default

Wash Load Max Class, Diameter: 5, CM, 0.0625

Specific Gravity: 2.65

Conc.

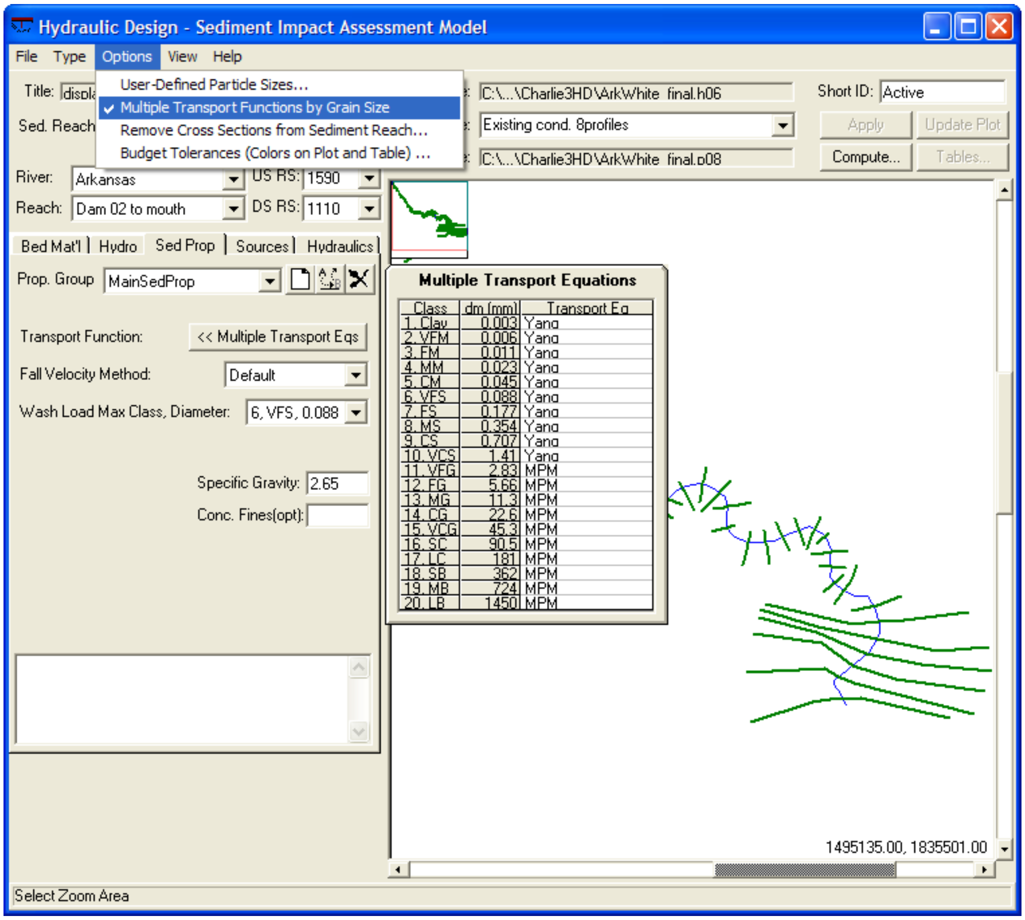
Wash load threshold for backwater area

Select a River for this Sediment Reach

Figure 5-4: Sediment property tab.

This grid lists the 20 grain classes and their respective geometric mean particle diameter size. By clicking on a cell in the **Transport Eq.** Column, the user can access a drop down box which allows selection of a grain class specific transport equation. Once selected, all cells below the currently active cell populate with the same transport equation.

Note: The grain class specific transport equation feature should be used with caution. When two different transport functions are used to compute transport potential for adjacent grain classes a discontinuity is often introduced. This could result in such difficulties as a larger computed potential for the larger grain class or an unreasonable drop in transport potential from one grain class to another. If this option is selected, pay careful attention to the results for material around the size of the transport transition(s). A similar caution should also be observed when attributing different transport equations to different reaches. This will cause spatial rather than gradational discontinuities and should be approached with similar caution.



Title: displa

Sed. Reach

C:\...\Charlie3HD\ArkWhite final.h06

Existing cond. 8profiles

C:\...\Charlie3HD\ArkWhite final.p08

Short ID: Active

River: Arkansas

US RS: 1590

Reach: Dam 02 to mouth

DS RS: 1110

Prop. Group MainSedProp

Transport Function: << Multiple Transport Eqs

Fall Velocity Method: Default

Wash Load Max Class, Diameter: 6, VFS, 0.088

Specific Gravity: 2.65

Conc. Fines(opt):

Multiple Transport Equations

Class	dm (mm)	Transport Eq
1. Clay	0.003	Yang
2. VFM	0.006	Yang
3. FM	0.011	Yang
4. MM	0.023	Yang
5. CM	0.045	Yang
6. VFS	0.088	Yang
7. FS	0.177	Yang
8. MS	0.354	Yang
9. CS	0.707	Yang
10. VCS	1.41	Yang
11. VFG	2.83	MPM
12. FG	5.66	MPM
13. MG	11.3	MPM
14. CG	22.6	MPM
15. VCG	45.3	MPM
16. SC	90.5	MPM
17. LC	181	MPM
18. SB	362	MPM
19. MB	724	MPM
20. LB	1450	MPM

Figure 5-5: Grain class specific grain class function feature.

Fall Velocity Method

The **Fall Velocity Method** drop down box allows the user to select the method of fall velocity computation. If **Default** is selected, the method associated with the respective transport function in the literature is used. Otherwise, the selected fall velocity method will be used. The three fall velocity methods available are: Toffaleti, Van Rijn, and Rubey.

Wash Load Max Class, Diameter

Wash load is the material in the system, but not present in appreciable quantities in the bed. SIAM does not apply the standard transport equations to compute a mass balance for wash load materials. Instead, it automatically passes them through the sediment reach. If the wash load threshold drops from one sediment reach to the next adjacent downstream reach, the material in the grain class(es) that is no longer wash load is added to the bedload and subjected to the standard mass balance approach.

A wash load threshold must be set for each sediment reach. The drop down box labeled **Wash Load Max Class** lists 10 grade classes (clays through sands for the standard grain classes) and their upper bound particle size in mm.

Specific Gravity

The specific gravity of sediment is also required. It can be entered in the field labeled **Specific Gravity**. The default is 2.65.

Conc. of Fines (opt)

The concentration of fine sediments is an optional value used to adjust the transport rate for high concentration scenarios. The adjustment is based on Colby's (Colby, 1964) findings regarding the effects of fine sediment and temperature on kinematic viscosity, and consequently particle fall velocity. Values are given in parts sediment per one million parts water, by weight.

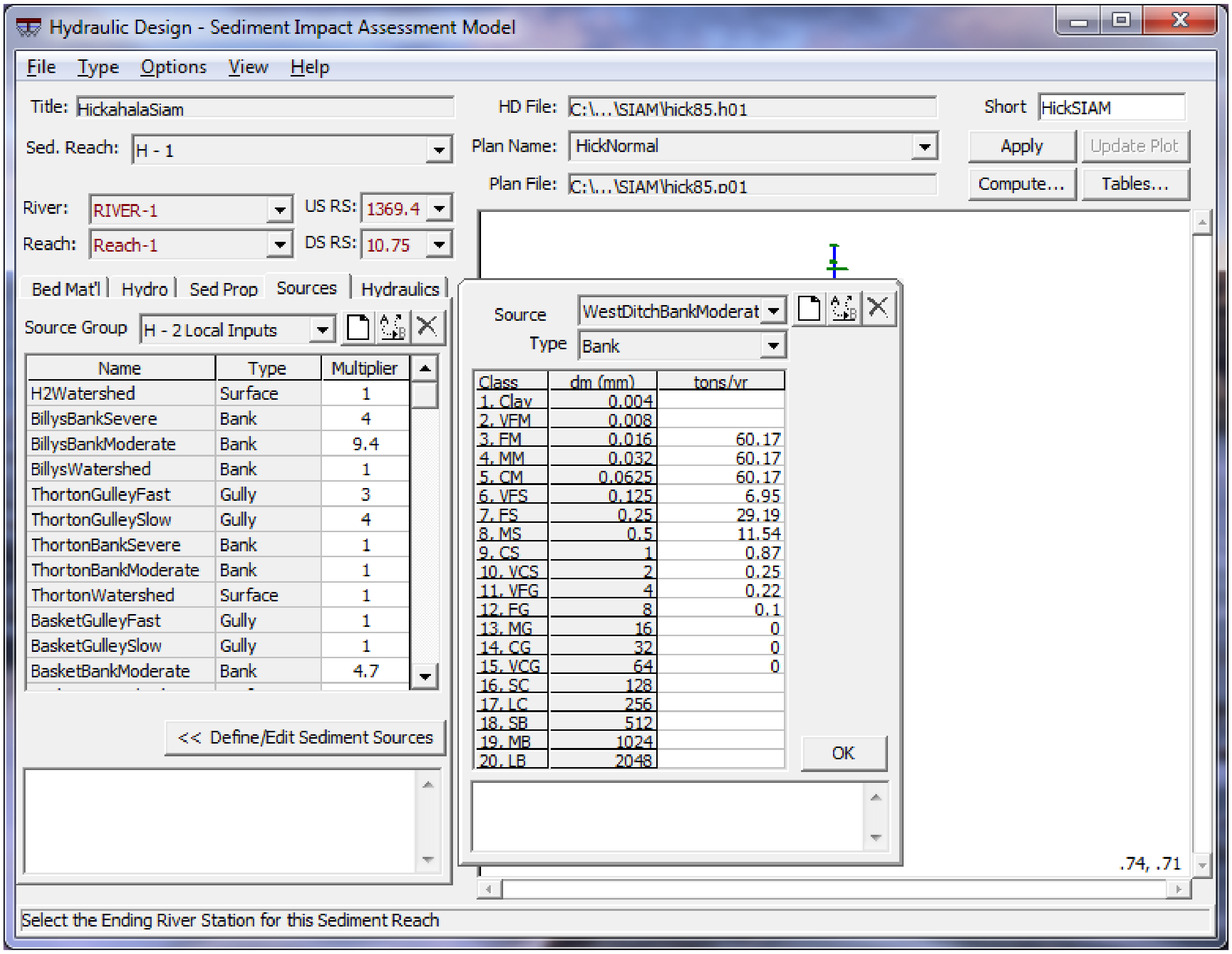
Sediment Sources

In order to compare capacity to supply, sediment supply data must be entered. In SIAM sediment annual source information is entered for each sediment reach. This information is specified on the **Sources** tab. (Figure 5-6) Each **Sediment Reach** requires a **Source Group**, a collection of sediment source records. A given Sediment Source Group record can be used exclusively for one sediment reach or can be shared by more than one sediment reach.

Before sediment supply information can be selected for a **Source Group** source templates must be created. Sediment source records can be created or edited by selecting the **Define/Edit Sediment Sources** button. An inset window will appear for source definition. Press the "new record" button and name the source template. In addition to naming the source, a source **Type** also must be selected. A source can be labeled: gully, bank, surface erosion or other. This is only a grouping descriptor and has no impact on the computations.

Once the sediment load template is generated the annual load must be specified by grain size. The second column of the table displays the upper grain size diameter limit of each grain class. Annual loads in tons/year are entered in the third column (Figure 5-6).

When the sediment sources are specified, close the source editor by pressing the **OK** button or the **<< Define/Edit Sediment Sources** button, then select the appropriate source templates for each source group. A source record can be selected by clicking on the **Name** column of the **Sources** table. A drop down menu will appear populated with the source templates previously created. When a source record is selected the **Type** column will automatically populate. The **Multiplier** column defines the relative magnitude of the load. If the load record represents the load coming into the reach precisely then enter a multiplier of 1 and the numbers entered will be used.



Title: HickahalaSiam

HD File: C:\...\SIAM\hick85.h01

Short HickSIAM

Sed. Reach: H - 1

Plan Name: HickNormal

Plan File: C:\...\SIAM\hick85.p01

River: RIVER-1

US RS: 1369.4

Reach: Reach-1

DS RS: 10.75

Source Group H - 2 Local Inputs

Name	Type	Multiplier
H2Watershed	Surface	1
BillysBankSevere	Bank	4
BillysBankModerate	Bank	9.4
BillysWatershed	Bank	1
ThortonGulleyFast	Gully	3
ThortonGulleySlow	Gully	4
ThortonBankSevere	Bank	1
ThortonBankModerate	Bank	1
ThortonWatershed	Surface	1
BasketGulleyFast	Gully	1
BasketGulleySlow	Gully	1
BasketBankModerate	Bank	4.7

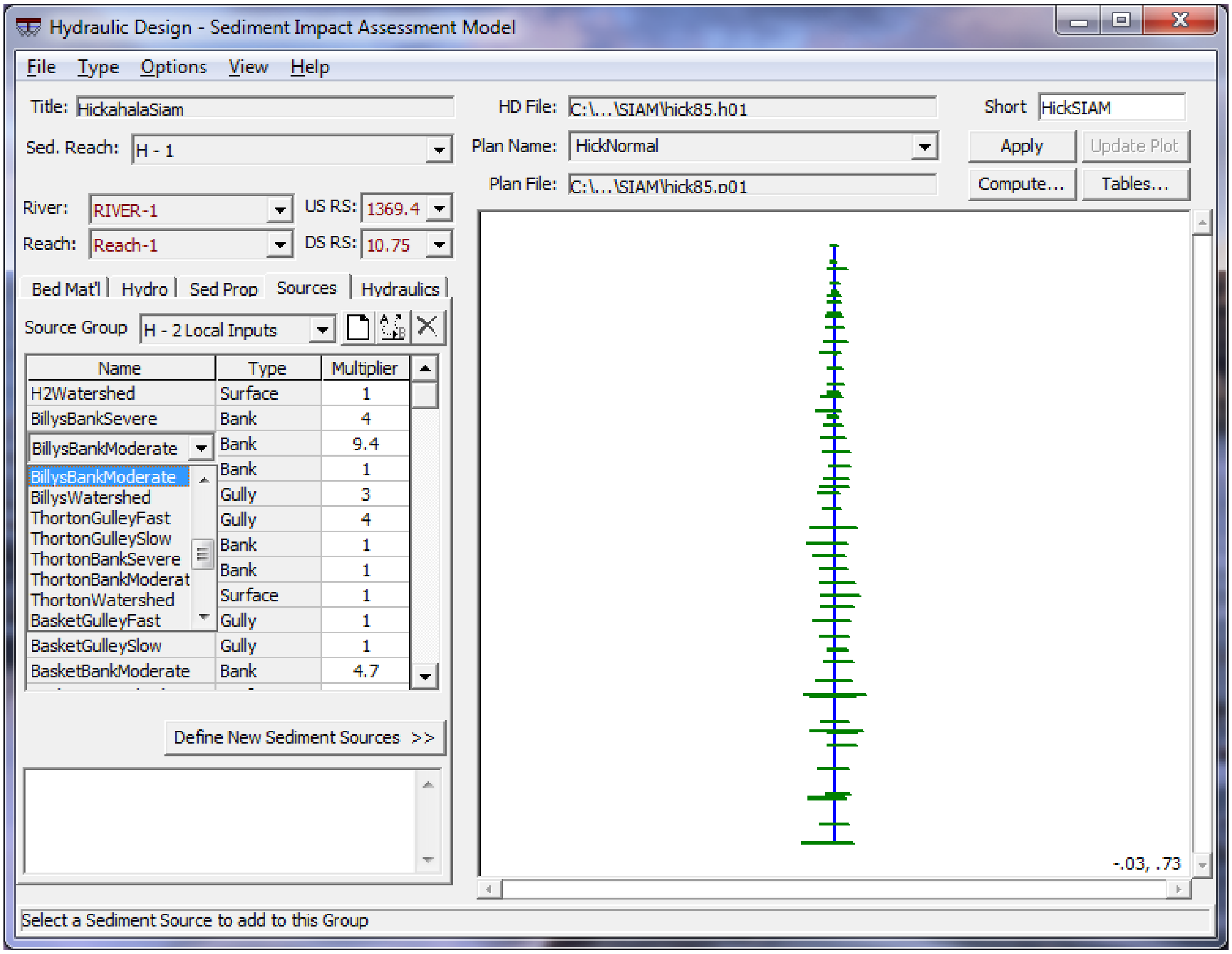
Source WestDitchBankModerat

Type Bank

Class	dm (mm)	tons/yr
1. Clay	0.004	
2. VFM	0.008	
3. FM	0.016	60.17
4. MM	0.032	60.17
5. CM	0.0625	60.17
6. VFS	0.125	6.95
7. FS	0.25	29.19
8. MS	0.5	11.54
9. CS	1	0.87
10. VCS	2	0.25
11. VFG	4	0.22
12. FG	8	0.1
13. MG	16	0
14. CG	32	0
15. VCG	64	0
16. SC	128	
17. LC	256	
18. SB	512	
19. MB	1024	
20. LB	2048	

Select the Ending River Station for this Sediment Reach

Figure 5-6: Define new sediment sources on the sources tab.



Title: HickahalaSiam

Sed. Reach: H - 1

River: RIVER-1

Reach: Reach-1

US RS: 1369.4

DS RS: 10.75

HD File: C:\...\SIAM\hick85.h01

Plan Name: HickNormal

Plan File: C:\...\SIAM\hick85.p01

Short HickSIAM

Source Group H - 2 Local Inputs

Name	Type	Multiplier
H2Watershed	Surface	1
BillysBankSevere	Bank	4
BillysBankModerate	Bank	9.4
	Bank	1
	Gully	3
	Gully	4
	Bank	1
	Bank	1
	Surface	1
	Gully	1
BasketGulleySlow	Gully	1
BasketBankModerate	Bank	4.7

BillysBankModerate
BillysWatershed
ThortonGulleyFast
ThortonGulleySlow
ThortonBankSevere
ThortonBankModerat
ThortonWatershed
BasketGulleyFast

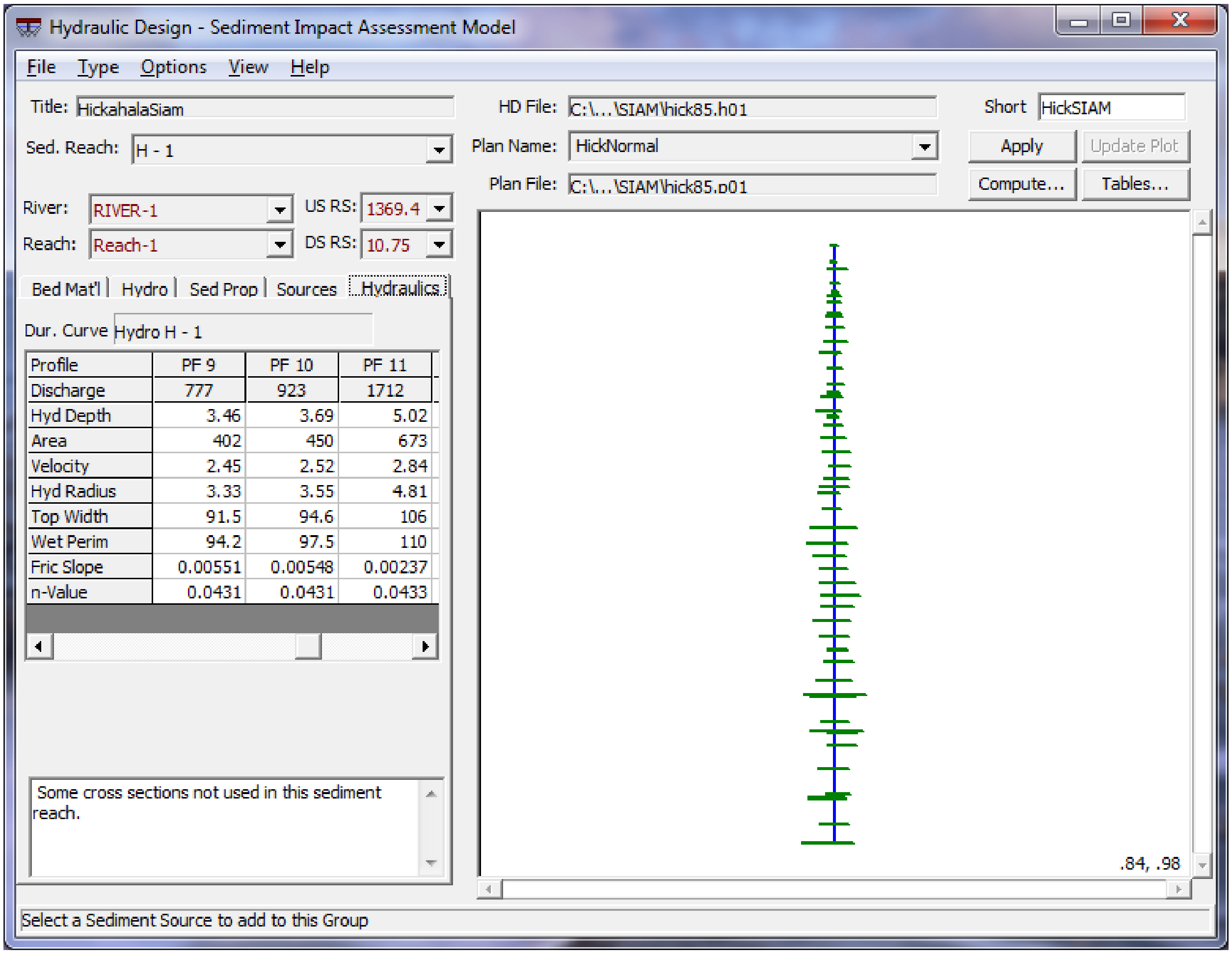
Select a Sediment Source to add to this Group

Figure 5-7: Source selection.

However, if the load was entered per linear bank foot or per watershed acre (see note at the bottom of the load template in (Figure 5-6) then the material entering the reach will be the source record multiplied by the multiplier entered. For example, in Figure 5-7 the coarse bank material is entered in annual load generated by each linear foot of bank. In Figure 5-7 this load is then multiplied by the length of exposed banks in the sediment reach. Additionally, a negative multiplier can also be entered, which will remove material from the sediment reach.

Hydraulics

The final tab is the **Hydraulics** tab. HEC-RAS computes this information and populates the table on this tab automatically. For each **Hydro** record, HEC-RAS computes a single set of hydraulic parameters for each sediment reach from the associated backwater profile, based on a reach weighted average of the included cross sections. The parameters in the grid are all sediment reach length-weighted values taken from the *channel* (not the full cross section) and are automatically updated if the bounding cross sections of the sediment reach are changed (Figure 5-8). Values cannot be changed directly on the grid by the user.



Title: HickahalaSiam

Sed. Reach: H - 1

River: RIVER-1

Reach: Reach-1

US RS: 1369.4

DS RS: 10.75

HD File: C:\...\SIAM\hick85.h01

Plan Name: HickNormal

Plan File: C:\...\SIAM\hick85.p01

Short: HickSIAM

Dur. Curve: Hydro H - 1

Profile	PF 9	PF 10	PF 11
Discharge	777	923	1712
Hyd Depth	3.46	3.69	5.02
Area	402	450	673
Velocity	2.45	2.52	2.84
Hyd Radius	3.33	3.55	4.81
Top Width	91.5	94.6	106
Wet Perim	94.2	97.5	110
Fric Slope	0.00551	0.00548	0.00237
n-Value	0.0431	0.0431	0.0433

Some cross sections not used in this sediment reach.

Select a Sediment Source to add to this Group

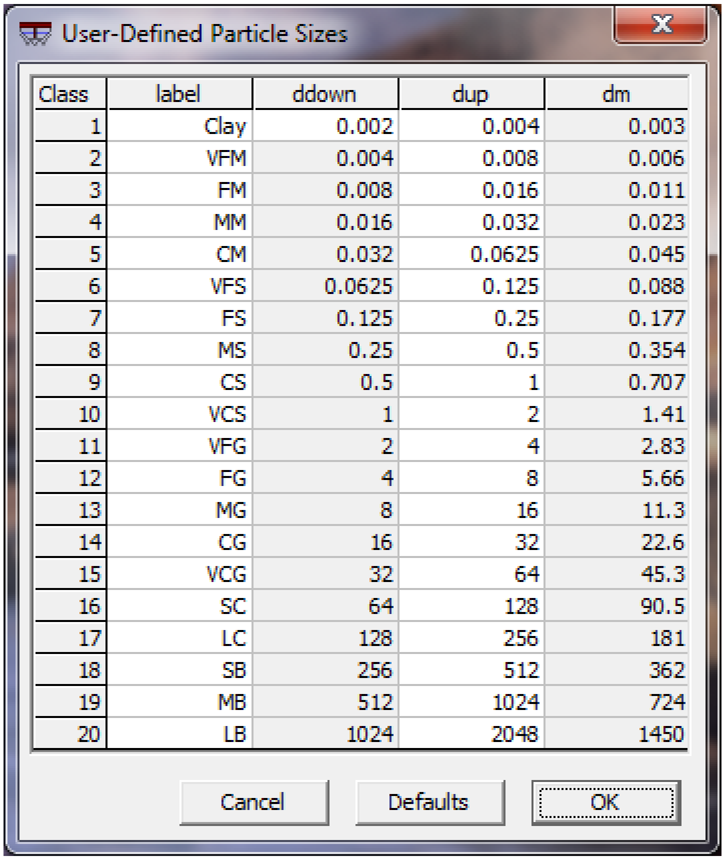
Figure 5-8: Average hydraulic properties populated by HEC-RAS.

Options

Several user capabilities are available in the **Options** menu. These options provide analysis flexibility in several aspects of the computations.

User Defined Particle Sizes

The grain size bins used by default in HEC-RAS are based on a standard log base 2 scale based on the American Geophysical Union (AGU). This option allows the user to redefine the particle size class ranges to either simplify the analysis or provide more detail in a certain grain size range. The user can enter in the upper and lower bound of the first grade class and the upper bound of the rest of the grade classes (Figure 5-9). Lower bounds automatically adjust to eliminate gaps. The grain class labels can also be edited. Edited grain class names and sizes will appear in the corresponding dialogs. If the Defaults button is selected, all of the grid entries will return the AGU default values.



Class	label	ddown	dup	dm
1	Clay	0.002	0.004	0.003
2	VFM	0.004	0.008	0.006
3	FM	0.008	0.016	0.011
4	MM	0.016	0.032	0.023
5	CM	0.032	0.0625	0.045
6	VFS	0.0625	0.125	0.088
7	FS	0.125	0.25	0.177
8	MS	0.25	0.5	0.354
9	CS	0.5	1	0.707
10	VCS	1	2	1.41
11	VFG	2	4	2.83
12	FG	4	8	5.66
13	MG	8	16	11.3
14	CG	16	32	22.6
15	VCG	32	64	45.3
16	SC	64	128	90.5
17	LC	128	256	181
18	SB	256	512	362
19	MB	512	1024	724
20	LB	1024	2048	1450

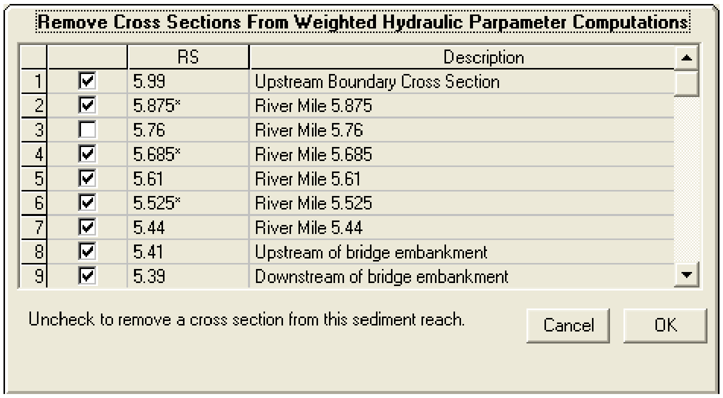
Figure 5-9: Variable grain class boundary editor.

Multiple Transport Functions

The multiple transport functions option allows the user to specify distinct transport functions for different grain classes. A more detailed description of this feature is included on page 5.

Remove Cross Section from Sediment Reach

It may occasionally be desirable to omit one or more cross sections within a defined sediment reach from the hydraulic parameters averaging and sediment transport computation. If the hydrodynamics at a cross section are spurious and non-typical they may be omitted by de-selecting them in the editor depicted in Figure 5-10.



Remove Cross Sections From Weighted Hydraulic Parpameter Computations

		RS	Description
1	☑	5.99	Upstream Boundary Cross Section
2	☑	5.875*	River Mile 5.875
3	☐	5.76	River Mile 5.76
4	☑	5.685*	River Mile 5.685
5	☑	5.61	River Mile 5.61
6	☑	5.525*	River Mile 5.525
7	☑	5.44	River Mile 5.44
8	☑	5.41	Upstream of bridge embankment
9	☑	5.39	Downstream of bridge embankment

Uncheck to remove a cross section from this sediment reach.

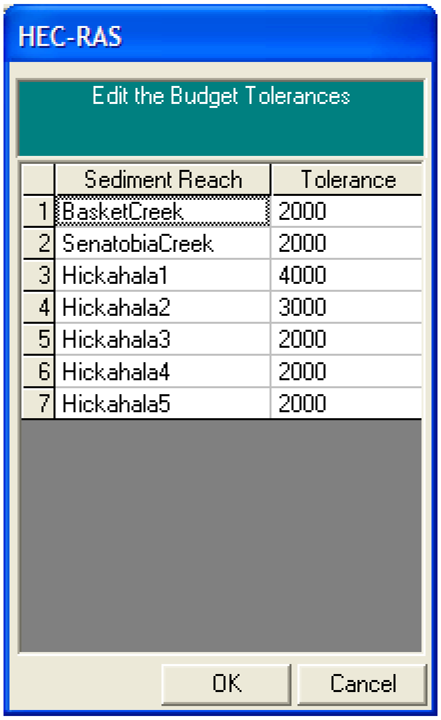
Figure 5-10: Cross section de-selection editor.

Set Budget Tolerances

When SIAM displays output, results are color coded in three categories: sediment deficit, surplus or equilibrium. Since the supply will never precisely equal the capacity, equilibrium is a range of acceptable deficit or surplus. This acceptable zone is strongly site and project specific and therefore must be entered by the user. The budget tolerance editor (Figure 5-11) allows the user to set a range of acceptable fluctuation (in tons/year) that will be displayed as equilibrium for each reach.

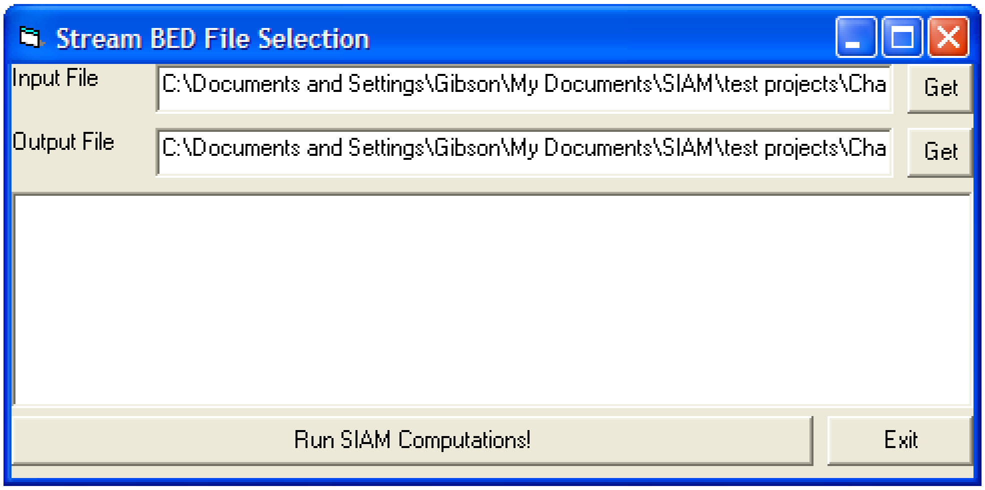
Command Buttons

Four command buttons can be found in the upper right corner of the dialog. The **Apply** button will store the entries on the current window into memory. The **Compute** button launches a computational window depicted in Figure 5-12. To execute the SIAM computations press the **Run SIAM Computations** button. Computation times are generally short. Very complex models will run in several seconds. Finally, the **Tables** button provides access to SIAM output after an analysis is conducted.



	Sediment Reach	Tolerance
1	BasketCreek	2000
2	SenatobiaCreek	2000
3	Hickahala1	4000
4	Hickahala2	3000
5	Hickahala3	2000
6	Hickahala4	2000
7	Hickahala5	2000

Figure 5-11: Sediment budget tolerance editor.



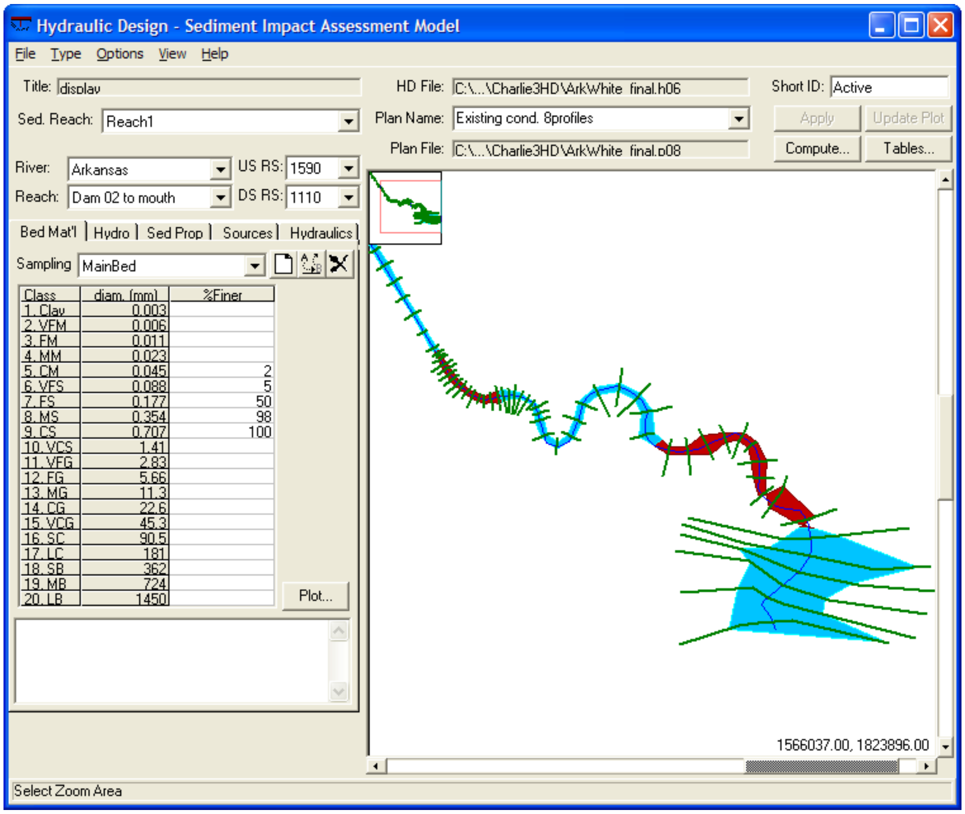
Input File C:\Documents and Settings\Gibson\My Documents\SIAM\test projects\Cha

Output File C:\Documents and Settings\Gibson\My Documents\SIAM\test projects\Cha

Figure 5-12: SIAM computation window.

Model Output

Once SIAM has completed computations it will update the inset schematic display to reflect the results. Sediment reaches for which a deficit is calculated are colored red while surplus reaches are colored blue and those that fall within the equilibrium tolerance will be green. (Figure 5-13) The quantitative local balance for each sediment reach can be queried by clicking on the colored region.



Title: display

Sed. Reach: Reach1

River: Arkansas

Reach: Dam 02 to mouth

US RS: 1590

DS RS: 1110

HD File: C:\...\Charlie3HD\ArkWhite final.h06

Plan Name: Existing cond. 8profiles

Plan File: C:\...\Charlie3HD\ArkWhite final.p08

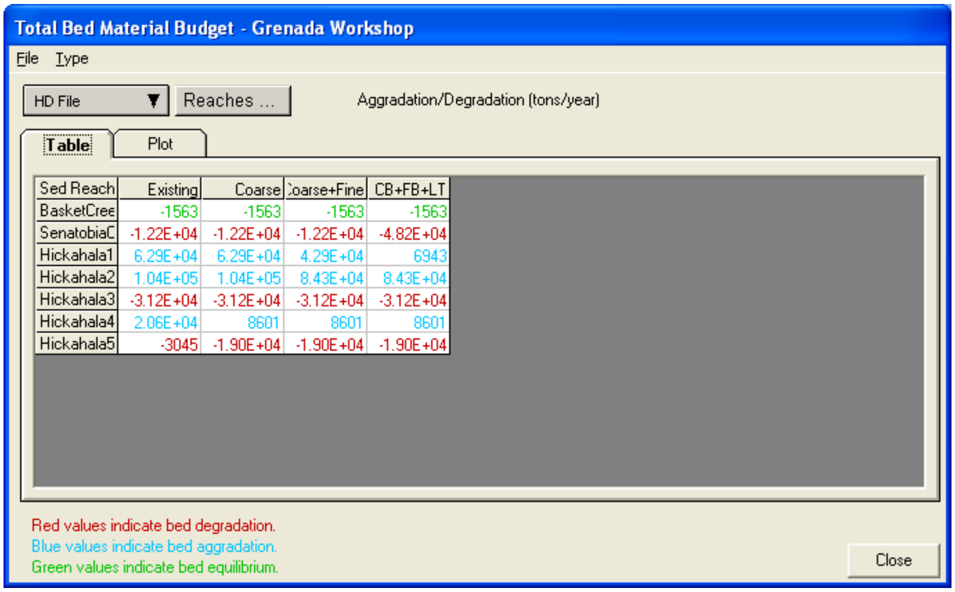
Short ID: Active

Sampling: MainBed

Class	diam. (mm)	%Finer
1. Clay	0.003	
2. VFM	0.006	
3. FM	0.011	
4. MM	0.023	
5. CM	0.045	2
6. VFS	0.088	5
7. FS	0.177	50
8. MS	0.354	98
9. CS	0.707	100
10. VCS	1.41	
11. VFG	2.83	
12. FG	5.66	
13. MG	11.3	
14. CG	22.6	
15. VCG	45.3	
16. SC	90.5	
17. LC	181	
18. SB	362	
19. MB	724	
20. LB	1450	

Figure 5-13: Plan view surplus and deficit display.

Plots and tables are available by pushing the **Table** button above the display. The standard output is **Local Balance** which reports the annualized sediment surplus or deficit for each sediment reach. Output can be viewed in tabular (Figure 5-14) or graphical format (Figure 5-15). All plots are bar graphs. In either tabular or graphical form multiple HD files and reaches can be selected or deselected too look at different scenarios or simplify the plot. Lists of the available reaches and HD files are available by pressing the **HD File** and **Reaches** buttons.



Sed Reach	Existing	Coarse	:oarse+Fine	CB+FB+LT
BasketCree	-1563	-1563	-1563	-1563
SenatobiaC	-1.22E+04	-1.22E+04	-1.22E+04	-4.82E+04
Hickahala1	6.29E+04	6.29E+04	4.29E+04	6943
Hickahala2	1.04E+05	1.04E+05	8.43E+04	8.43E+04
Hickahala3	-3.12E+04	-3.12E+04	-3.12E+04	-3.12E+04
Hickahala4	2.06E+04	8601	8601	8601
Hickahala5	-3045	-1.90E+04	-1.90E+04	-1.90E+04

Red values indicate bed degradation.
Blue values indicate bed aggradation.
Green values indicate bed equilibrium.

Figure 5-14: Tabular local balance output.

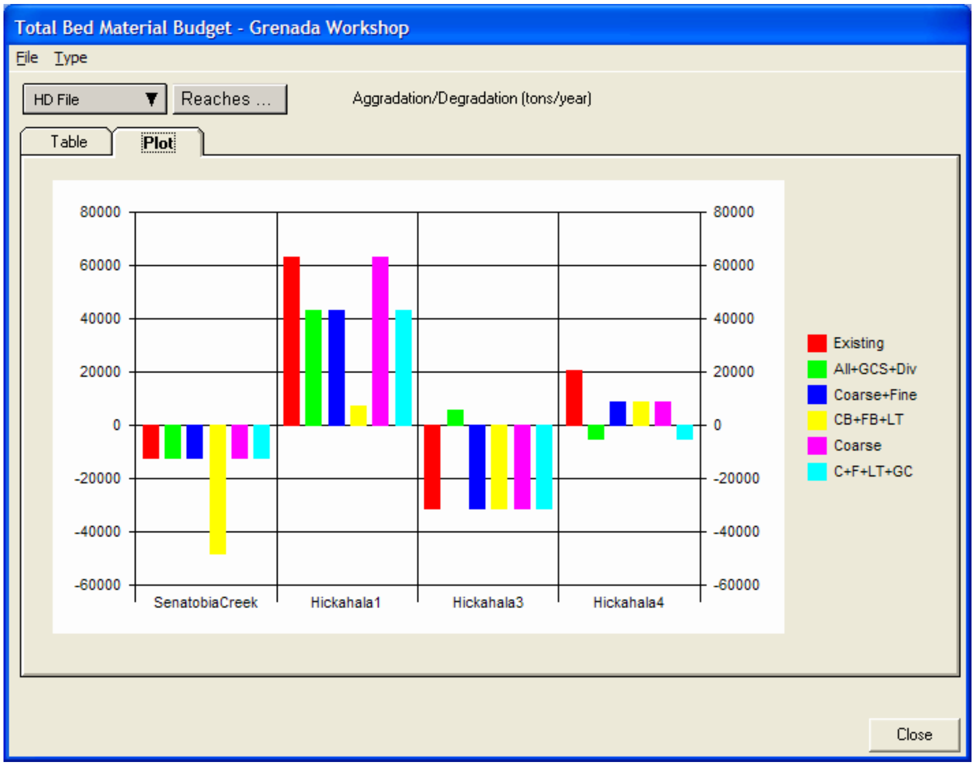


Figure 5-15: Graphical local balance Output.

The following output options are available from the **Type** menu:

Local Balance: the annualized surplus or deficit for a given reach

Sediment Transport Potential: the transport potential computed for each grain size as if it comprised 100% of the bed material. These numbers are prorated by their relative abundance in the bed to compute transport capacity.

Supply and Balance: a summary plot that reports local supplies and the capacity which are compared to compute the local balance (also reported). It also breaks the supply into bed supply and wash supply components.

Then there are several tables and plots where output is reported by grain size. Reaches can be activated or deactivated for these output options but because of the additional dimension multiple HD files cannot be viewed simultaneously. The grain size specific outputs are:

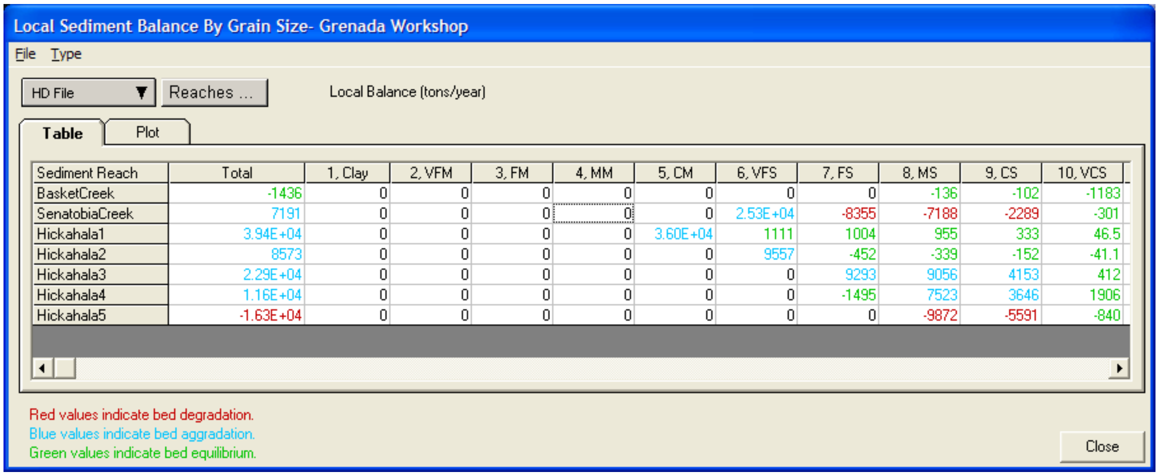
Local Supply: sums the total annual sources applied to each sediment reach by grain size.

Annual Capacity: reports the computed, cumulative, annual capacity for each reach and breaks it down into the capacity contribution of each grain class.

Wash Material and **Bed Material**: summarize the total wash and bed material supplies for each reach and the relative contributions of each grain class.

Local Balance: reports the same local balance output as depicted in **Error! Reference source not found.** except it also depicts the local balance for each grain class (**Error! Reference source not found.**). It is of note in this figure that different grain classes can report deficits and surpluses in the same reach.

Normalized Local Balance: Since longer reaches will generally have exaggerated local balances when compared to shorter reaches, the normalized local balance divides the result from each sediment reach by the reach's channel distance. Therefore, local balance is reported per linear channel foot, making it easier to compare reaches of different lengths.



Local Balance (tons/year)

Sediment Reach	Total	1, Clay	2, VFM	3, FM	4, MM	5, CM	6, VFS	7, FS	8, MS	9, CS	10, VCS
BasketCreek	-1436	0	0	0	0	0	0	0	-136	-102	-1183
SenatobiaCreek	7191	0	0	0	0	0	2.53E+04	-8355	-7188	-2289	-301
Hickahala1	3.94E+04	0	0	0	0	3.60E+04	1111	1004	955	333	46.5
Hickahala2	8573	0	0	0	0	0	9557	-452	-339	-152	-41.1
Hickahala3	2.29E+04	0	0	0	0	0	0	9293	9056	4153	412
Hickahala4	1.16E+04	0	0	0	0	0	0	-1495	7523	3646	1906
Hickahala5	-1.63E+04	0	0	0	0	0	0	0	-9872	-5591	-840

Red values indicate bed degradation.
Blue values indicate bed aggradation.
Green values indicate bed equilibrium.

Figure 5-16: Local balance by grain size.

Notes on Program Applicability and Limitations

SIAM *is not* a sediment routing model. A mobile bed model will update hydraulics in response to sediment deficits and surpluses generally resulting in mitigated rates of erosion or deficit over time, as the channel adjusts its morphology. SIAM does not update the bed and, therefore, does not account for changing capacities in response to erosion or deposition.

Therefore, SIAM should be used as a screening tool for sediment budget assessment. The numbers reported should be treated cautiously and interpreted as general trends of surplus and deficit *not* volumes of eroded or deposited material. One of the advantages of SIAM is the ease with which sensitivity, management or design alternatives can be evaluated. SIAM should be used to assess the impact of a wide range of alternatives in order to select the best few for more detailed modeling and analysis.

CHAPTER 6

References

Adkinson, E. (1996) The Feasibility of Flushing Sediment from Reservoirs, HR Wallingford, Report OD 137, 99p

Barkau, Robert L., 1992. UNET, One-Dimensional Unsteady Flow Through a Full Network of Open Channels, Computer Program, St. Louis, MO.

Binkley, D., G.G. Ice, J. Kaye, and C.A. Williams, 2004. Nitrogen and Phosphorus Concentrations in Forest Streams of the United States. Journal of the American Water Resources Association, 40(5), 2004, pp. 1277-1291.

Briaud, Jean-Louis. (2008). "Case Histories in Soil and Rock Erosion: Woodrow Wilson Bridge, Brazos River Meander, Normandy Cliffs, and New Orleans Levees," *Journal of Geotechnical and Geoenvironmental Engineering, Vol. 134, No. 10*, Zachry Dept. of Civil Engineering, Texas A&M Univ., College Station, TX

Brownlie, W. (1983). "Flow Depth in Sand-Bed Channels." *J. Hydraul. Eng.*, 109(7), 959–990.

Brown and Barnwell, 1987. The Enhanced Stream Water Quality Models QUAL2E and QUAL2E-UNCAS: Documentation and Users Manual. Environmental Research Laboratory. Office of Research and Development. U.S. Environmental Protection Agency, Athens Georgia 30613.

Brunner, Gary W., August 1994. "Improved Hydraulic Features of the HEC River Analysis System," presented at the ASCE Hydraulic engineering conference, Buffalo, NY

Brunner, Gary W. and John H. Hunt, 1995. A Comparison of the One-Dimensional Bridge Hydraulic Routines from: HEC-RAS, HEC-2, and WSPRO, Research Document No. 41, Hydrologic Engineering Center, U.S. Army Corps of Engineers, September 2009, Davis, CA.

Brunner, Gary W., June 1996. "HEC-RAS (River Analysis System)," presented at the ASCE North American Water and Environmental Congress, Anaheim, CA.

Brunner, Gary W., June 1996. "Computing Bridge Scour With HEC-RAS," presented at the ASCE North American Water and Environmental Congress, Anaheim, CA.

Brunner, Gary W., Mark R. Jensen, and Steven S. Piper, 2000. Unsteady Flow Routing with the Hydrologic Engineering Center River Analysis System (HEC-RAS), Watershed Management and Operations Management, ASCE, EWRI, June 2000, Fort Collins, CO.

Brunner, Gary W. and Mark E. Forest, 2002. Unsteady Flow Routing With HEC-RAS – Truckee River, Joint Federal Interagency Conference, April 2002, Las Vegas, NV

Brunner, Gary W., 2003. Dam and Levee Breaching With HEC-RAS, World Water & Environmental Resources Congress, ASCE, EWRI, June 2003, Philadelphia, PA.

Brunner, Gary W. and Stanford S. Gibson, 2005. Sediment Transport Modeling in HEC-RAS, World Environmental & Water Resources Congress, ASCE, EWRI, May 2005, Anchorage, AL.

Brunner, Gary W. and Cameron T. Ackerman, 2012. "HEC-RAS Modeling for Operation of the Birds Point - New Madrid Floodway, Mississippi River Flood of 2011", World Environmental & Water Resources Congress, ASCE, EWRI, May 2012, Albuquerque, NM.

Brunner, Gary W., 2014. Using HEC-RAS for Dam Break Studies, Training Document No. 39, Hydrologic Engineering Center, U.S. Army Corps of Engineers, August 2014, Davis, CA.

Brunner, Gary W., Steven S. Piper, Mark R. Jensen, and Ben Chacon, 2015. Combined 1D and 2D Hydraulic Modeling within HEC-RAS, World Environmental & Water Resources Congress, ASCE, EWRI, May 2015, Austin, TX.

Bureau of Public Roads (BPR), 1965. Hydraulic Charts for the Selection of Highway Culverts, Hydraulic Engineering Circular No. 5, U.S. Department of Commerce.

Bureau of Reclamation, 1977. Design of Small Dams, Water Resources Technical Publication, Washington D.C..

Bureau of Reclamation, 1998. Prediction of Embankment Dam Breach Parameters, Dam Safety Research Report DSO-98-004, Dam Safety Office, U.S. Department of the Interior.

Cantelli, A., Paola, C., and Parker, G. (2005) Experiments on upstream-migrating erosional narrowing and widening of an incisional channel caused by dam removal," WATER RESOURCES RESEARCH, VOL. 40, W03304, doi:10.1029/2003WR002940.

Carpenter, S.R., N.F. Caraco, D.L. Correll, R. W. Howarth, A.N. Sharpley, and V.H. Smith (1998) Nonpoint Pollution of Surface Waters With Phosphorus and Nitrogen Ecological Applications, 8(3), 1998, pp. 559-568.

Copeland, R. and Lombard, L. (2009) Numerical Sedimentation Investigation Mississippi River Vicksburg to Pilots Station 94p.

Cui, Y., Parker, G., Braudrick, C., Dietrich, W., and Cluer, B. (2005) "Dam Removal Express Assessment Models (DREAM). Part 1: Model development and validation," Journal of Hydraulic Research 0(0) 1–17.

Copeland, R (1993) Numerical Modeling of Hydraulic Sorting and Armoring in Alluvial Rivers, PhD Thesis, The University of Iowa, 284 p.

Dietrich, E. W. (1982). "Settling velocity of natural particles," *Water Resources Research*, 18 (6), 1626-1982.

Echevarria, W. (2012) *Analysis of Sediment Transport following Removal of the Springville Dam*.

Federal Emergency Management Agency, 1985. Flood Insurance Study Guidelines and Specifications for Study Contractors, FEMA 37, Washington D.C., September 1985.

Federal Highway Administration, 1978. Hydraulics of Bridge Waterways, Hydraulic Design Series No. 1, by Joseph N. Bradley, U.S. Department of Transportation, Second Edition, revised March 1978, Washington D.C..

Federal Highway Administration, 1985. Hydraulic Design of Highway Culverts, Hydraulic Design Series No. 5, U.S. Department of Transportation, September 1985, Washington D.C.

Ferguson. R.I. 1986. "River loads underestimated by rating curves," Water Resources Research, Vol. 22, No.1, pp74-76, January.

Fread, D.L., 1988 (revised 1991). BREACH: An Erosion Model For Earth Dam Failures, National Weather Service, NOAA, Silver Springs Maryland.

Fread, D.L., Ming Jin and Janice M. Lewis, 1996. An LPI Numerical Solution for Unsteady Mixed Flow Simulation, North American Water Congress, Anehiem, CA June 22-28, 1996, American Society of Civil Engineers.

FHWA, 1996. Evaluating Scour at Bridges, Federal Highway Administration, HEC No. 18, Publication No. FHWA-IP-90-017, 2nd Edition, April 1993, Washington D.C.

Froehlich, D.C., 1988. Analysis of Onsite Measurements of Scour at Piers, Proceedings of the ASCE National Hydraulic Engineering Conference, Colorado Springs, CO.

Froehlich, D.C., 1989. Local Scour at Bridge Abutments, Proceedings of the 1989 National Conference on Hydraulic Engineering, ASCE, New Orleans, LA, pp. 13-18.

Froehlich, D.C., 1995. Embankment Dam Breach Parameters Revisited, Water Resources Engineering, Proceedings of the 1995 ASCE Conference on Water Resources Engineering, San Antonio, Texas, August 14-18, 1995.

Garbrecht, J. and Gary W. Brunner, "Hydrologic Channel-Flow Routing for Compound Sections," ASCE Journal of Hydraulic Engineering, Vol. 117, No. 5, May 1991.

Gibson, S. (2010) *Simulating Hydraulic Conductivity Evolution Due to Sediment Dynamics in the Russian River.* U. S. Army Corps of Engineers - Hydrologic Engineering Center, 93p.

Gibson, S., Pak, J., & Fleming, M. (2010). Modeling watershed and riverine sediment processes with HEC-HMS and HEC-RAS. *EWRI Watershed Management 2010: Innovations in Watershed Management*, 1340-1349.

Gibson, S. and Boyd, P. (2014) "Modeling Long Term Alternatives for Sustainable Sediment Management Using Operational Sediment Transport Rules," *Reservoir Sedimentation –* Scheiss et al. (eds), 229-236.

Gibson, S., Simon, A., Langendoen, E., Bankhead, N., and Shelley, J. (2015) "A Physically-Based Channel-Modeling Framework Integrating HEC-RAS Sediment Transport Capabilities and the USDA-ARS Bank-Stability and Toe-Erosion Model (BSTEM)," Federal Interagency Sediment Conference, SedHyd Proceedings.

Gibson, S. and Pridal, D. (2015) "Negotiating Hydrologic Uncertainty in Long Term Reservoir Sediment Models: Simulating Arghandab Reservoir Deposition with HEC-RAS," Federal Interagency Sediment Conference, SedHyd Proceedings.

Hem, John D. (1985) Study and Interpretation of the Chemical Characteristics of Natural Water. Third Edition. U.s. Geological Survey Water-Supply Paper 2254.

Hunt, John, Gary W. Brunner, and Bruce E. Larock. "Flow Transitions in Bridge Backwater Analysis," ASCE Journal of Hydraulic Engineering, Vol. 125 No. 9, September 1999.

Hydrologic Engineering Center, 1991. HEC-2, Water Surface Profiles, User's Manual, U.S. Army Corps of Engineers, Davis CA.

Hydrologic Engineering Center, 1993. UNET, One-Dimensional Unsteady Flow Through a Full Network of Open Channels, User's Manual, U.S. Army Corps of Engineers, Davis, CA.

Hydrologic Engineering Center, 1994. HECDSS, User's Guide and Utility Programs Manual, U.S. Army Corps of Engineers, Davis CA.

Hydrologic Engineering Center, 1995. RD-41, A Comparison of the One-Dimensional Bridge Hydraulic Routines from: HEC-RAS, HEC-2, and WSPRO, U.S. Army Corps of Engineers, Davis CA., September 1995

Hydrologic Engineering Center, 1995. RD-42, Flow Transitions in Bridge Backwater Analysis, U.S. Army Corps of Engineers, Davis CA., September 1995

Johnson, Billy, and T. Gerald, 2006. Development of a Distributed nutrient Sub-Model (NSM Version 1.0) for Watersheds – Kinetic Process Descriptions. Environmental Laboratory. U.S. Army Engineer Research and Development Center. Vicksburg, MS. 39180. ERDC/EL TR-06-X September 2006

Laursen, E.M., 1960. Scour at Bridge Crossings, ASCE Journal of Hydraulic Engineering, Vol. 89, No. HY 3.

Laursen, E.M., 1963. An Analysis of Relief Bridges, ASCE Journal of Hydraulic Engineering, Vol. 92, No. HY 3.

Leonard, B. P., 1991. The ULTIMATE Conservative Difference Scheme Applied to Unsteady One-Dimensional Advection, Computer Methods in Applied Mechanics and Engineering, vol 88, pp 17-74.

Leonard, B.P., 1979. A Stable and Accurate convective Modelling Procedure Based on Quadratic Upstream Interpolation, Computer Methods in Applied Mechanics and Engineering, vol 19, pp 59-98.

Little, C. and Biedenharn, D. (2014) Mississippi River Hydrodynamic and Delta Management Stuey (MRHDM) – Geomorphic Assement, ERDC/CHL TR 14-5, 309p.

Martin, J.L., and S. C. McCutcheon, 1999. Hydrodynamics and Transport for Water Quality Modeling. CRC Press, Boca Raton, Florida.

McDonald, Thomas C. and Jennifer Langridge-Monopolis, 1984. Breaching Characteristics of Dam Failures, Journal of Hydraulic Engineering, vol. 110, No. 5, pp 567-586.

Meybek, Michel, 1982. Carbon, Nitrogen, and Phosphorus Transport by World Rivers. American Journal of Science, Vol. 282, April, 1982, P. 401-450.

Microsoft Corporation, 2007. Microsoft Windows Vista, User's Manual, Redmond WA.

Morris, G., Annandale, G., and Hotchkiss, R. (2008) "Reservoir Sedimentation," *Sedimentation Engineering: Processes, Measurements, Modeling, and Practices*, ASCE Manuals and Reports on Engineering Practice No. 110, 579-612.

Parker, G. (2008) "Transport of Gravel and Sediment Mixtures," *Sedimentation Engineering: Processes, Measurements, Modeling, and Practices*, ASCE Manuals and Reports on Engineering Practice No. 110, 165-252.

Richardson, E.V., D.B. Simons and P. Julien, 1990. Highways in the River Environment, FHWA-HI-90-016, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C.

Shelley, J. and Gibson, S. (2015) “Modeling Bed Degradation of a Large, Sand-Bed River with In-Channel Mining with HEC-RAS,” Federal Interagency Sediment Conference, SedHyd Proceedings.

Thomas, W. and Chang, H. (2008) “Computational Modeling of Sediment Processes,” *Sedimentation Engineering: Processes, Measurements, Modeling, and Practices*, ASCE Manuals and Reports on Engineering Practice No. 110, 649-682.

U.S. Army Corps of Engineers, 1965. Hydraulic Design of Spillways, EM 1110-2-1603, Plate 33.

van Rijn, L. (1984). ”Sediment Transport, Part III: Bed forms and Alluvial Roughness.” J. Hydraul. Eng., 110(12), 1733–1754.

Wong, M. and Parker, G. (2006). ”Reanalysis and Correction of Bed-Load Relation of Meyer-Peter and Müller Using Their Own Database.” J. Hydraul. Eng., 132(11), 1159–1168.

Wunderlich, W.O. 1972. Heat and mass transfer between a water surface and the atmosphere, TN Report 14, Tennessee Valley Authority Water Resources Research Engineering Laboratory, Norris, TN.