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Hydrologic Engineering Center

HEC-RAS Two-Dimensional Sediment Transport User's Manual

December 2020

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HEC-RAS

Two-Dimensional Sediment Transport Technical Reference Manual

December 2020

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Chapter 1

Introduction

The Corp's Hydrologic Engineering Center River Analysis System (HEC-RAS) is designed to simulate one-dimensional (1D) steady, unsteady flow. The latest release of HEC-RAS V6.0 also simulates unsteady two-dimensional horizontal (2D) sediment transport, and bed change, sorting, and layering. Sediment transport is computed with a non-equilibrium total-load formulation. The total-load transport equation is solved with implicit Finite-Volume methods on the same unstructured polygonal mesh as the flow solver. Sediment transport is coupled to the flow model at the time step level. One powerful feature of the 2D flow solvers is that they use the subgrid topographic variations directly into the model thus improving the accuracy of the solution and permitting the use of relatively coarse meshes resulting in reduced computational times. The sediment transport model is designed to work within the subgrid framework of the flow model, and computes subgrid erosion and deposition rates, bed elevations, gradations, and bed layering.

This document discusses how to utilize the 2D sediment user-interface, the model input and output, and how-to setup and run a 2D sediment transport model in HEC-RAS. The document is intended as supplemental to the 1D Sediment Users Manual as many concepts and features are covered in detail in that document. Most of the 1D sediment capabilities are supported in 2D sediment and many new features have been added to 2D sediment which are not available yet in 1D sediment. Some of the new sediment features include variable density bed sorting and layering model, flocculation, consolidation, hiding and exposure effects, multiple new transport potential formula. However, as a beta release, there are still several computational and user-interface limitations and known issues including the inability to hot-start sediment, the inability to couple 1D and 2D sediment, the inability to modify terrains based on computed bed change, inability to visualize subgrid output directly in HEC-RAS, the inability to specify avalanching parameters in the user-interface, and the inability to specify subsidence in 2D areas. Lastly, the 2D sediment transport feature in HEC-RAS V6.0 is a beta feature and should not be used for design purposes.

Chapter 2

Performing a 2D Sediment Transport Analysis

2.1 Best Practices for a 2D Sediment Model

Sediment models are often more sensitive to hydraulic modeling choices that fixed bed models. Adding sediment to a hydraulic model that runs and generates reasonable results often exposes model problems hidden by the robustness of the hydraulic equations or approximations that were sufficient for hydraulic analysis but not for sediment modeling.

2.1.1 Hydraulic Warm Up

<u>One of the most important hydraulic parameters for sediment modeling is the **hydraulic warm-up period**</u>. Unless the prototype starts dry and pushes a wetting front through the domain, it is essential to use a hydraulic warm up period for the a 2D sediment model. A hydraulic model can often pass through a wetting phase at the beginning of a simulation without affecting the final results (this is not best practice but can produce acceptable results in some cases). If the sediment model runs without a warmup period, it will scour as the wetting front initialized the model and bias the result.

HEC-RAS will only run hydraulics during the first half of the warmup period, and then will add sediment warm up during the second half. Choose a warmup period that wets the mesh fully during the first half. HEC-RAS does not populate a warmup period by default. Define this parameter by selecting **Options→Computational Options and Tolerances…** and selecting the **2D Flow Options** tab.

Define the **Initial Conditions Time (hrs)** and the **Ramp Up Fraction** (the portion of the Initial Conditions Time the model will take to gradually get up to the full warm up flows – often 0.1). Run the hydraulic model (without sediment) to make sure this time is sufficient to reach an initial steady-state flow condition.

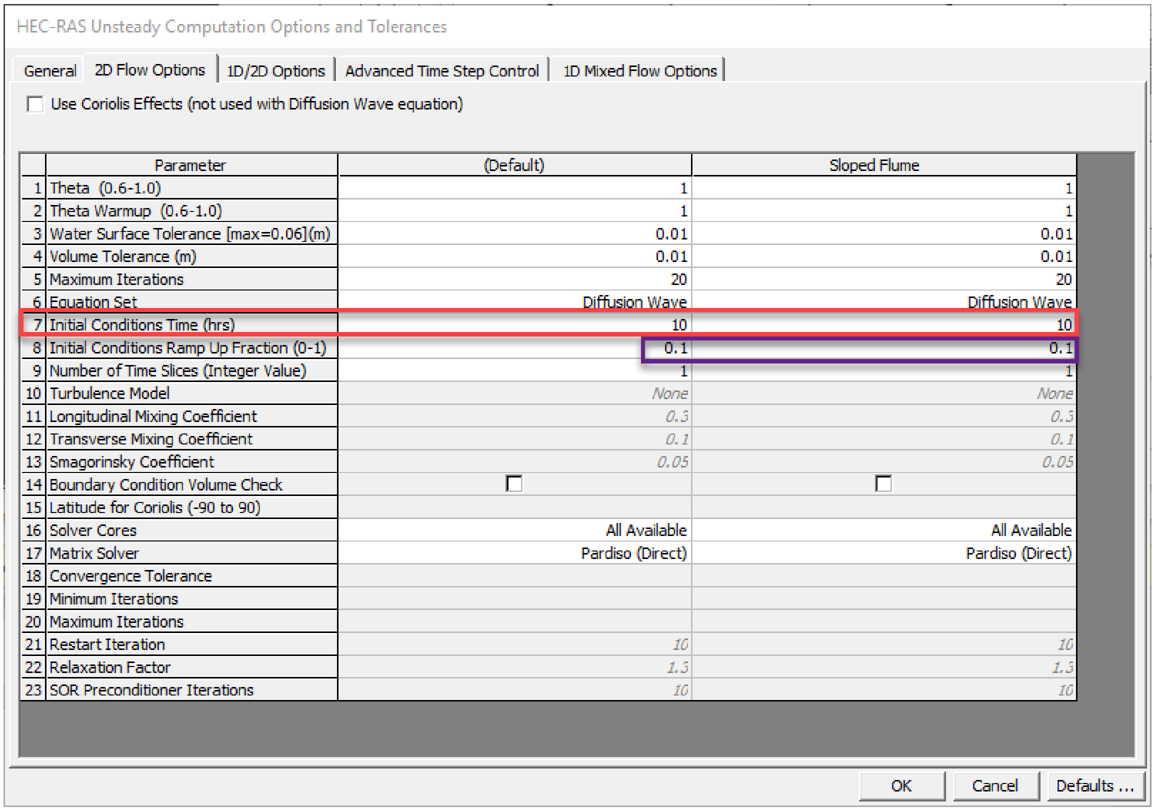


Figure 2-1. HEC-RAS Unsteady Computation Options and Tolerances editor.

2.1.2 Computational Mesh

Although HEC-RAS can compute on highly irregular meshes, poor mesh quality will decrease the accuracy of the numerical solution and can lead to poor convergence and numerical instabilities. Mesh quality affects both the flow and sediment, but it is especially important when simulating sediment transport.

Mesh Alighnment

With 2D flow and sediment transport, the HEC-RAS will produce better results if the mesh is oriented or aligned with the flow. This reduces numerical diffusion and improved computational accuracy. In the example below, a refinement region is used to increase the spatial resolution (25 ft) within the channel. The refinement region allows for a more resolution within the channel while maintaining coarse resolution outside of the channel, thus reducing the total number of computational cells and computational costs. The refinement region also aligns the channel banks which also improves the model results. However, the issue with this approach is the that the cells are not aligned with the flow producing more numerical diffusion. In addition, the regions in between the square or rectangular cells within the refinement polygon and the boundaries of the refinement polygon can have relatively irregular cells and relatively poor mesh quality.

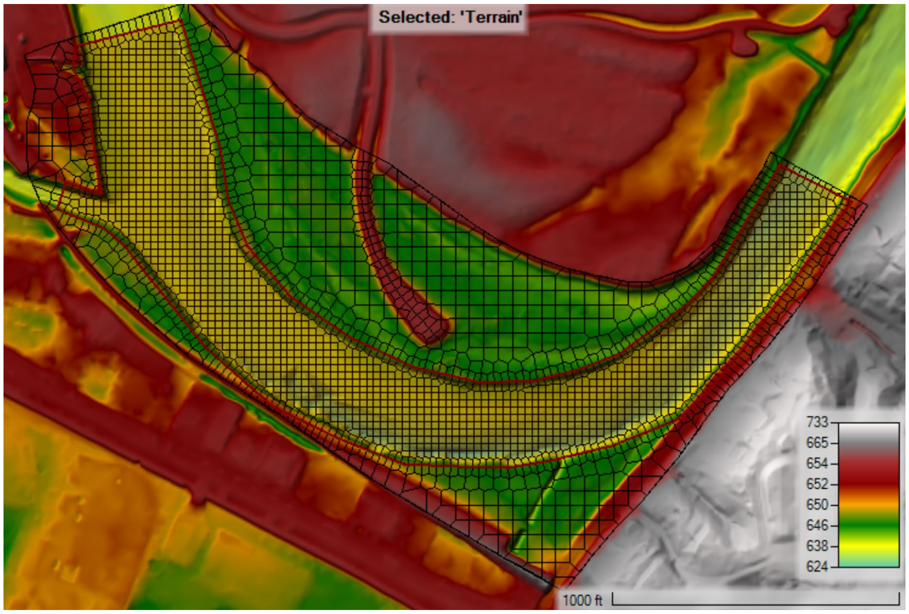


Figure 2-2. Example of a computational mesh with a simple refinement region within the channel.

To improve the mesh alignment with the flow, a break line is inserted along the centerline of the channel as shown in the figure below. The breakline is added with 6 repeat points and a 30-ft spacing.

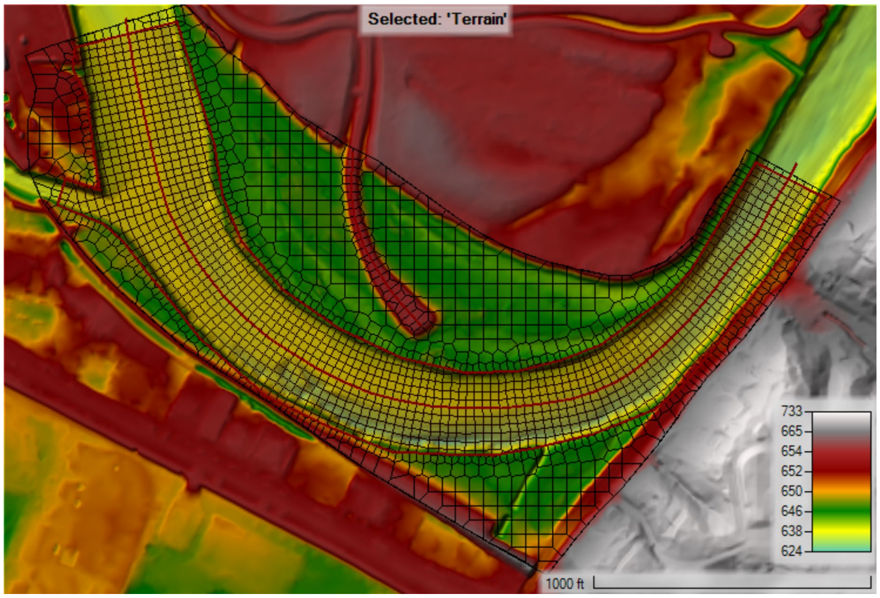


Figure 2-3. Example computational mesh with cells in the channel aligned with the direction of flow.

Small Faces

When building a mesh avoid having cells with small faces. This is because small faces can increase run times and introduce instabilities in both the hydraulic and sediment model. Small faces increase the number of faces and therefore the computational time and memory. In addition, small faces often have poor mesh quality.

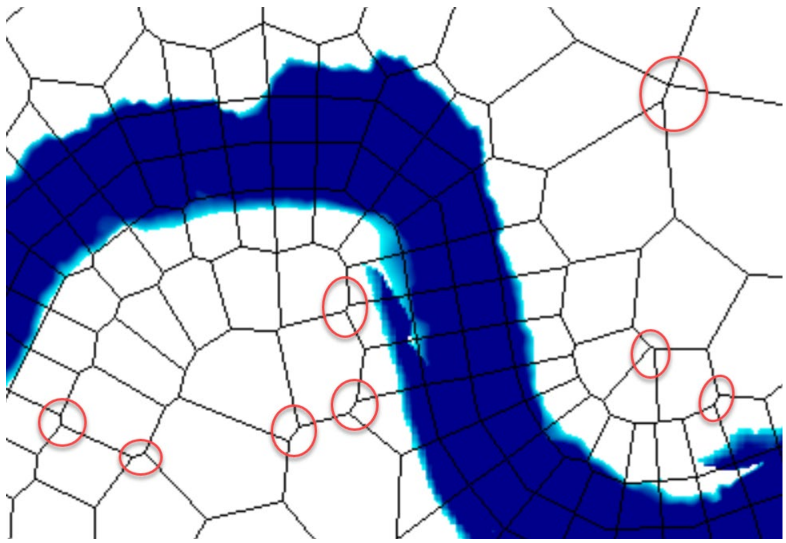
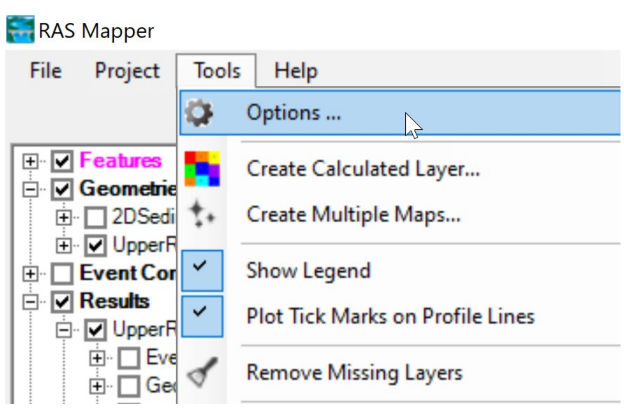


Figure 2-4. Example computational mesh with small faces indicated by ellipses.

HEC-RAS has a feature which detects small faces and snaps together the face nodes (also referred to as face points in HEC-RAS). The tolerance parameter for the maximum face length is based on the ratio between the face length and the distance between adjacent computational points. The tolerance parameter can be modified by the user in RAS Mapper by

1. Select the menu **Tools**.

2. Click on **Options...**. This will open The RAS Mapper Options window



3. On the left side under **Project Settings**, select **Mesh Tolerances**.
4. Modify the value next to **Minimum Face Length Tolerance (Percent)** by manuall typing a value or using the above and down arrows.
5. Click **Apply**
6. Click **OK** to the window
7. If necessary recompute 2D meshes.

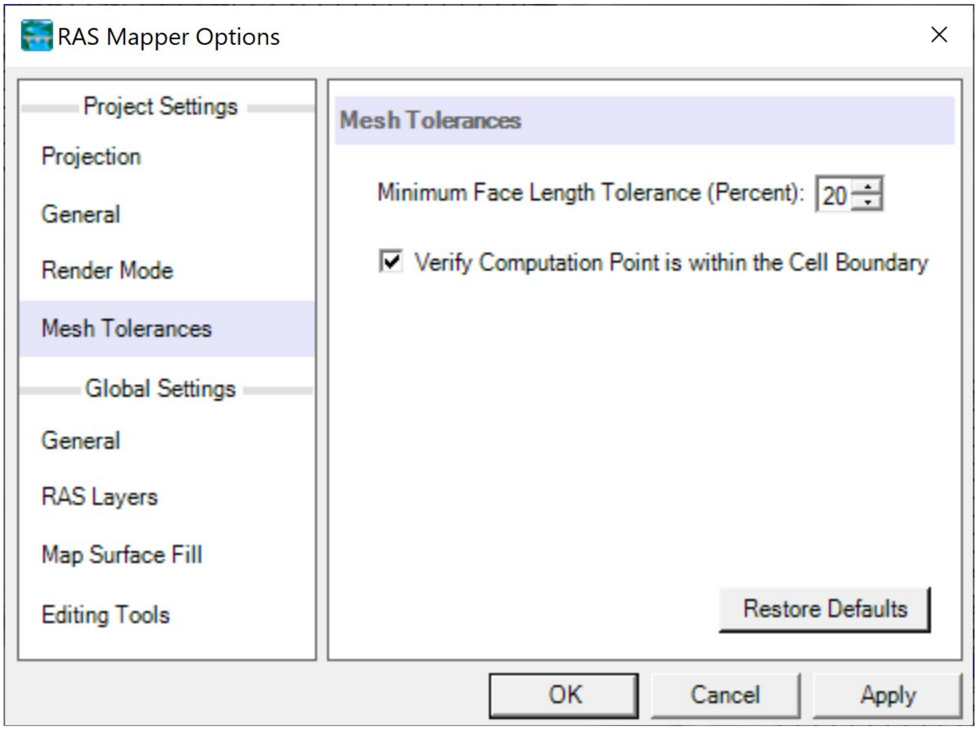


Figure 2-5. Mesh Tolerances section of the RAS Mapper Options window.

An example two meshes with Minimum Face Length Tolerances of 5% (red) and 20% (black) are shown in the figure below. In general the differences between the two meshes occur at transition areas between resolution and near breaklines.

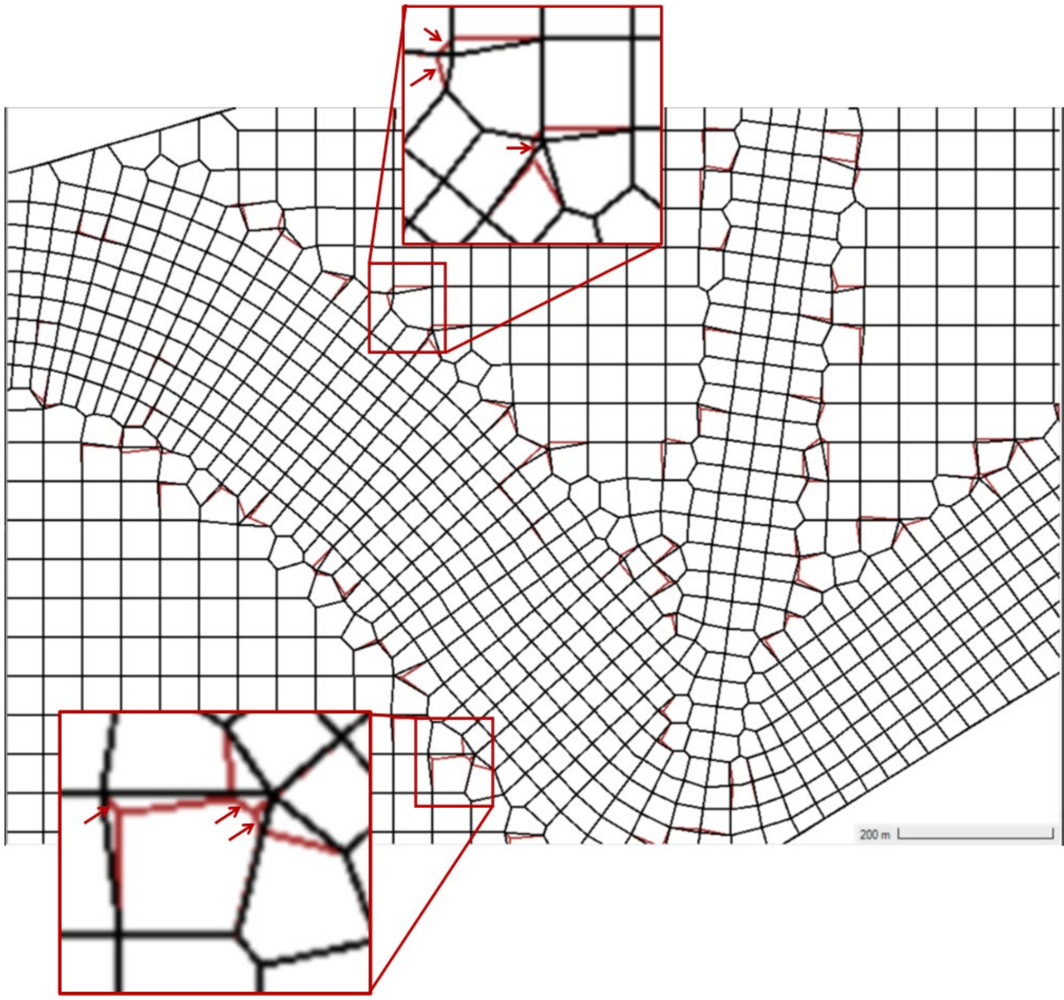


Figure 2-6. Example computational meshes with Minimum Face Length Tolerances of 5% (red) and 20% (black).

2.1.3 Hydraulic Equations

2D sediment runtimes can be be long, so it can be attractive to select the Diffusion Wave Equation (DWE) to try to reduce the runtime. However, with the DWE sediment models of rivers often develop a distinctive pattern, eroding a deep sub-channel and depositing in the rest of the channel (see figure below). This is not a credible result. Most 2D river sediment transport models should be run with one of the Shallow Water Equations (SWE). The DWE should only be used for watershed or flooding type applications.

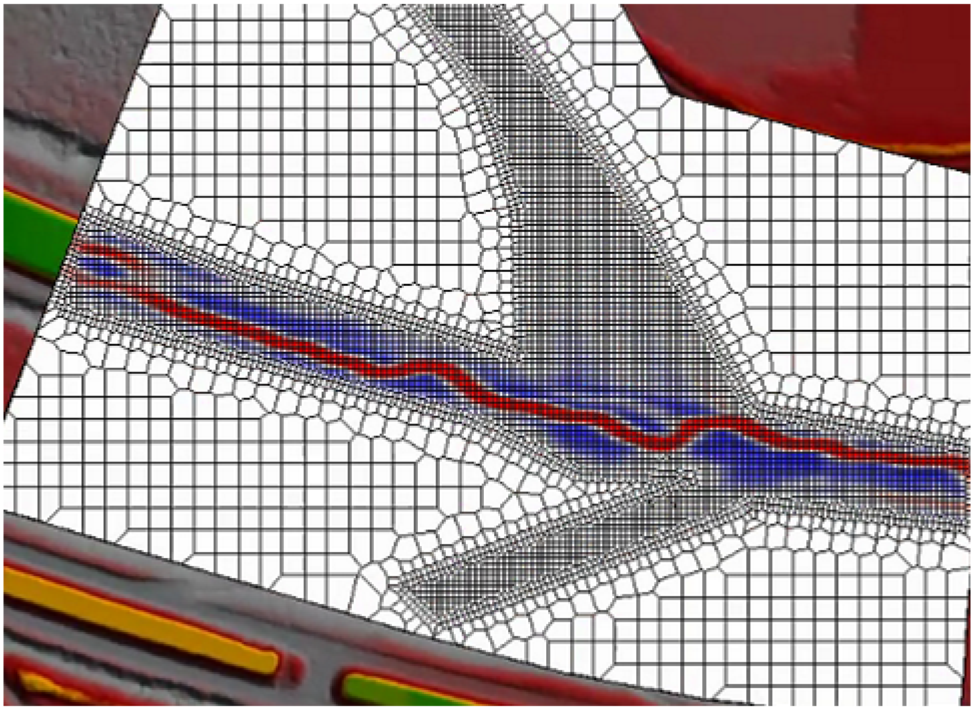


Figure 2-7. Example of an erroneous bed change result for a river using the Diffusion-Wave Equation.

2.1.4 Time Step

The time step is the most common issue with 2D sediment models that do not run. Modelers usually try to run the 2D sediment model with time steps that are too large. The model setup should obey (or at least respect*) the Courant condition, which roughly means that the water should pass though one cell per time step.

Users can calculate a limiting Courant condition for their model using the smallest cell and estimating a maximum current velocity and then choose a fixed time step that satisfies this condition. However, recent versions of HEC-RAS make time step selection much easier.

The Advanced Time Step Control under the Unsteady Computation Options and Tolerances includes options for dynamic time steps that will change during the simulation. The option to Adjust Time Step Based on Courant is the most widely used and is becoming standard practice for 2D modeling. Define a maximum and minimum Courant condition and then the maximum halving or doubling steps allowed from the base time step, and the model will compute the appropriate time step throughout the model.

The Implicit Finite Volume solver in HEC-RAS 1D and 2D is not Courant limited. So the Courant Condition is more of a stability guideline and time-step selection support, than the hard limit it can be in other, explicit, solvers. Therefore, modelers sometimes set their max Courant condition closer to 2, without introducing computational issues or instabilities.

2.2 Sediment Data

2D sediment transport models in HEC-RAS require four files: an unsteady flow file, a geometry file, a sediment file, and a plan file to tie them together. Sediment data should be specified after the geometry. Some mandatory sediment parameters are specified spatially and thus require knowledge of the geometry. If the geometry changes, the sediment data may 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 Unsteady Flow Analysis option, calibrating the bottom roughness and if necessary, the turbulence coefficients. It is recommended to identify hydraulics model problems before adding the bed change complexity. Only add sediment data after crafting a careful, robust, hydraulic model.

This document focuses on the 2D sediment data. However, many of the 2D sediment parameters and data inputs are the same as 1D. 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 2-8. The sediment data editor has four tabs: **Initial Conditions and Transport Parameters,** Sediment **Boundary Conditions**, the **USDA-ARS Bank Stability and Toe Erosion Model (BSTEM),** and **2D Sediment (Beta)**. The first two and last tabs are mandatory for 2D simulations. The third (BSTEM) is only for bank process computations and is not required for a sediment transport model.

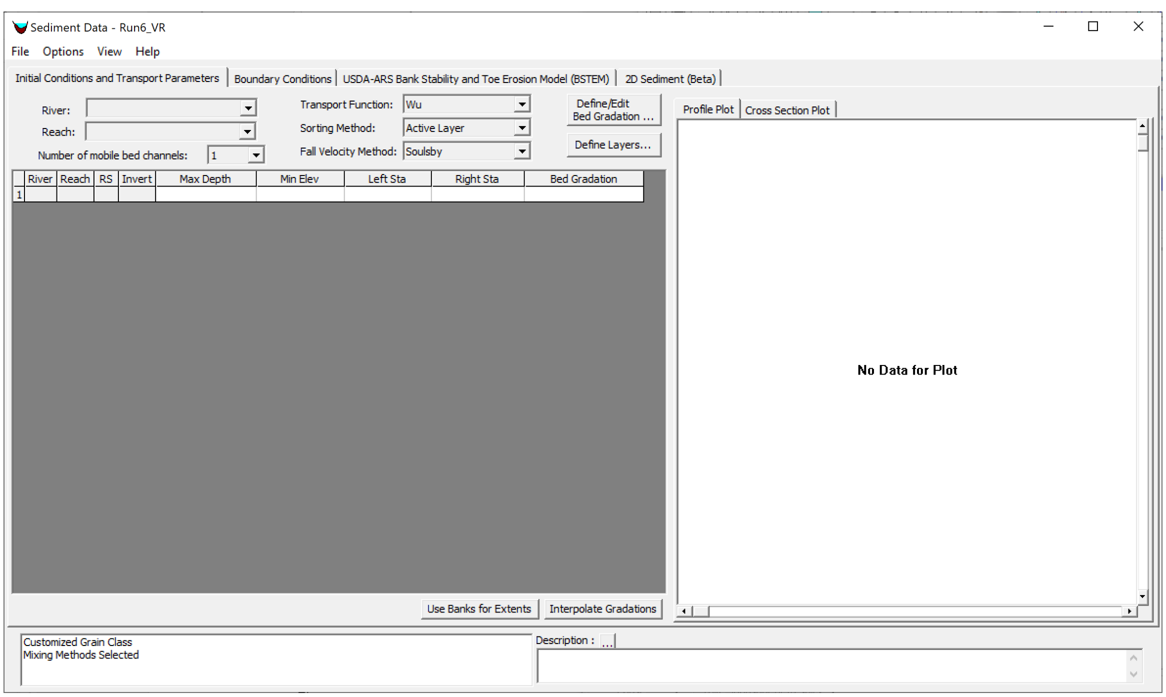


Figure 2-8. Sediment Data editor.

2.2.1 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. It is also used to specify sediment data for 1D cross-sections. However, if the model does not include cross-sections, then that information may be left empty.

Transport Function

Select a **Transport Function** from the drop-down box near the top of the editor. HEC-RAS 6.0 includes the following eleven transport functions:

1. Ackers and White (Ackers and White 1973; Day 1980; Proffitt and Sutherland 1983)
2. England and Hansen (Engelund-Hansen 1967)
3. Laursen-Copeland formula (Laursen 1968)
4. Meyer-Peter and Müller (1948)
5. Toffaleti (1968)
6. MPM-Toffaleti (Meyer-Peter and Müller 1948; Toffaleti 1968)
7. Yang (sand and gravel eqns.)
8. Wilcock and Crowe (2003)
9. Soulsby-van Rijn (Soulsby 1997)
10. van Rijn (1984a,b; 2007a,b)
11. Wu et al. (2000)

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 bed change.

Sorting Method

Transport functions compute transport potential without accounting for 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. The **Sorting Method** drop down menu in the **Sediment Data** editor only applies to 1D sediment transport. The 2D sediment transport model always uses a method similar to the **Active Layer** method for 1D except that it can have any arbitrary number of layers. The active layer thickness is set equal to the d90 by default or a factor of the d90.

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

Fall Velocity Methods

The same sediment fall velocity formulas are available for 2D and 1D sediment transport. The options include:

1. Rubey (1933)
2. Toffaleti (1968)
3. Van Rijn (1993)
4. Report 12 (Default method in HEC-6)
5. Dietrich (1982)
6. Soulsby (1997)
7. Wu and Wang (2006)

The fall velocity formula used to compute free particle settling velocity for both cohesive and noncohesive sediments. Depending on the concentration and whether the user has selected flocculation, cohesive sediments may also settle as flocs. Hindered settling of noncohesive particles may also be simulated if selected by the user. In general, the fall velocity formula should not be used as a model calibration parameter for morphology change since the results are not very sensitive to the formula. Preference for the formulas is generally based on the transport formula used, the range of grain classes, and/or the parameters utilized by the fall velocity formulas. For example, the Wu and Wang formula considers the particle shape.

Bed Gradations

Bed gradations are specified in the same manner as for 1D models. Instead of requiring users to input bed gradations for each cell individually, HEC-RAS uses a **Bed Gradation Template** concept similar to that in the Channel Modification Editor. **Sediment Bed Material Types** are defined in a **Sediment Bed Material Layer** in RAS Mapper. The **Sediment Bed Material Types** are regions defined as polygons in RAS Mapper in a **Sediment Bed Material Layer**. The polygons can be overlapping to override regions. **Sediment Bed Material Layer Types** are the associated to **Bed Gradation Templates**, **Non-erodible Surfaces**, or **Bed Layer Groups** within the **2D Bed Gradations (Beta)** tab of the **Sediment Data** editor. **Bed Layer Groups** consist of one or more bed layers. Each layer is assigned a **Bed Gradation Template** or a **Non-erodible Surface**. The connectivity between these elements utilized for specifying the sediment bed material are described in the schematic below.

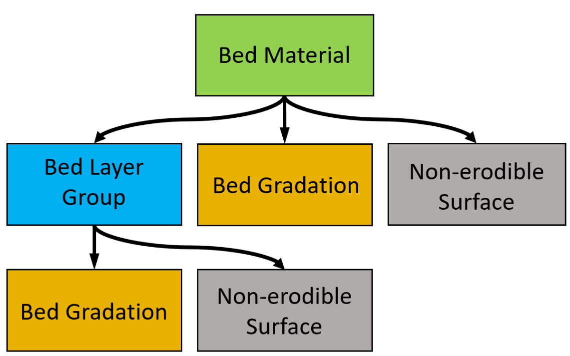


Figure 2-9. Bed Gradation Template editor.

Non-erodible surfaces are surfaces such as bedrock or structures which cannot be eroded. Non-erodible surfaces may be associated with a **Sediment Bed Material** are specified within a **Bed Layer Group**. Non-erodible surfaces are specified at computational cells and are not enforces at computational faces.

Defining Bed Material Layers in RAS Mapper

Users will associate bed gradations, layer groups, or non-erodible surfaces with **Sediment Bed Material Layers** defined in RASMapper. In order to define gradations in the sediment editor, the user must define **Sediment Bed Material Layers** in RAS Mapper first.

Sediment Bed Material Layers are independent of specific model geometries or terrains. Like **n-value Layers** or **Land Cover Layers** (see 2D Hydraulic Manuals). Create new **Sediment Bed Material Layers** by right clicking on the Map Layer node in RASMapper.

To Define Bed Material Layers, follow these five steps:

1. Create a New/Empty RAS Layer
2. Import or Draw Polygons in the Created RAS Layer
3. Give the Polygon Classifications Sediment Material Names that will show up in the Sediment Editor
4. Go to Manage Geometry Associations and associate the Bed Material Layers with geometry files
5. Associate each Bed Material Classification with a bed gradation, bed layers, or define it as a non-erodible surface, in the 2D sediment editor.

Defining these bed material layers have two main workflows, which are not mutually exclusive. Users will generally import a pre-existing shape file or draw overlapping polygons. Often users will do both, importing a base bed material shape file, but then drawing in channel features, sand bars, and/or non-erodible features on top of them as new layers.

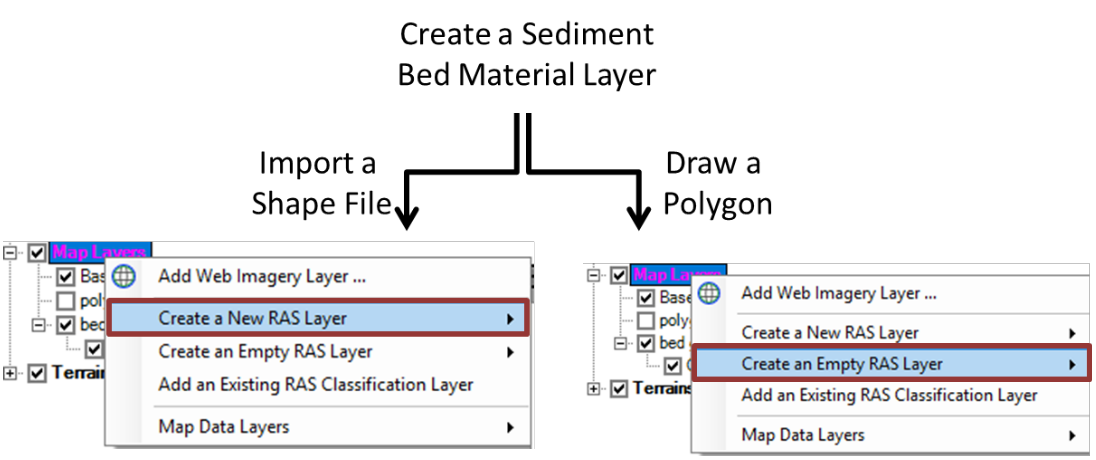


Figure 2-10. Crating a Bed Material Layer in RASMapper.

The Sediment Bed Material Layer will show up under the **Map Layers** tree in RASMapper.

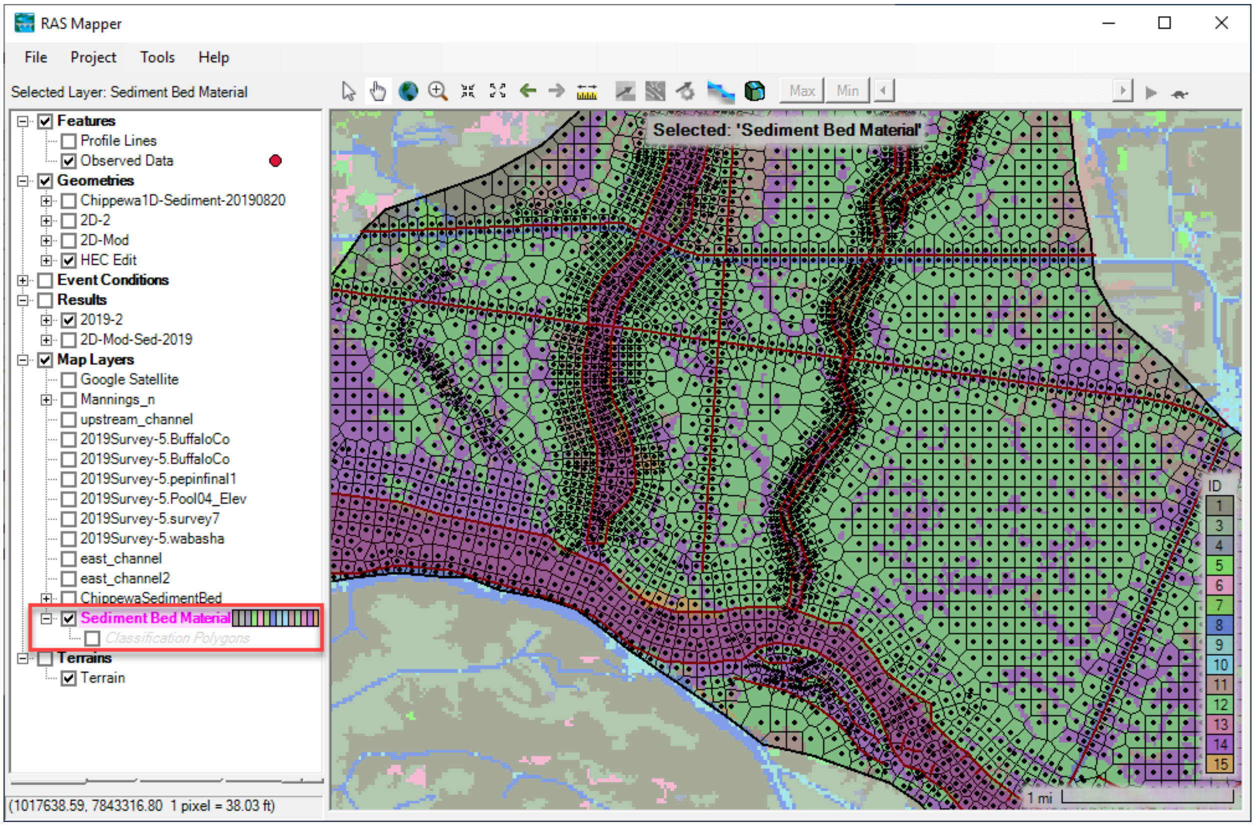


Figure 2-11. Sediment Bed Material Layer underlying a 2D mesh and in the RASMapper tree under Map Layers.

Whether you create your **Sediment Bed Material Layer** by importing a shape file, creating polygons, or both, there are two additional steps before the bed materials are ready for the sediment model.

RAS Mapper will create a **Classification Polygons** node under your map layer and will add a feature to the geo-referenced database for each polygon you import or create. You will have to give each of these polygons a (preferably descriptive) name which will show up in the sediment editor, where you will associate the polygon(s) that share this classification with a **Bed Material** or **Bed Layer Group**.

Name the layer classifications by right clicking on the **Classification Polygons** node (in editable mode) and selecting **Layer Properties.** Then select the **Features** tab and give each of the Layer Classifications a Name that will show up in the Sediment Data editor.

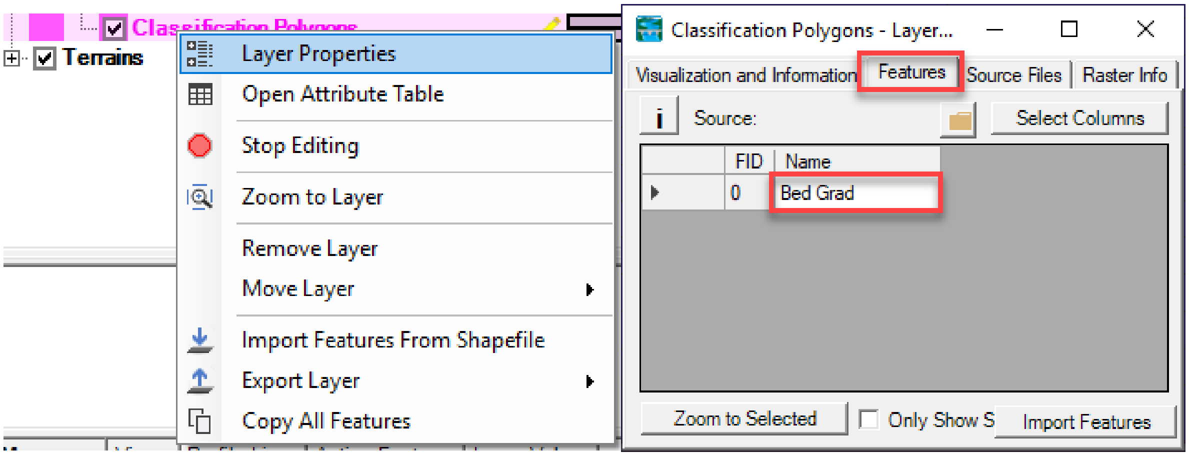
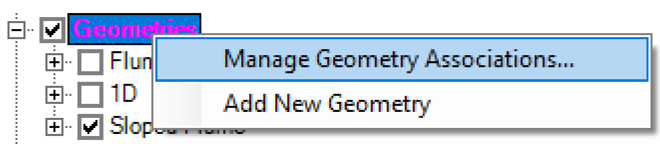


Figure 2-12. Give the layer classifications names that will show up in the sediment editor under Layer Properties.

When the **Sediment Bed Material Layer** and Classifications are complete, **Stop Editing** and save.

Before these layers and classifications become available in the Sediment Data editor, however, they must be associated with a geometry file. Just like n-values, Land Cover, and Terrains must be associated with a geometry file, **Sediment Bed Material Layer Groups** must be matched to one-or-more geometries to connect the Mapper classifications to the other files in HEC-RAS.

Right Click on the **Geometries** node in RAS Mapper and Select **Manage Geometry Associations…**



Select the **Sediment Bed Material Layer** that goes with each **Geometry**.

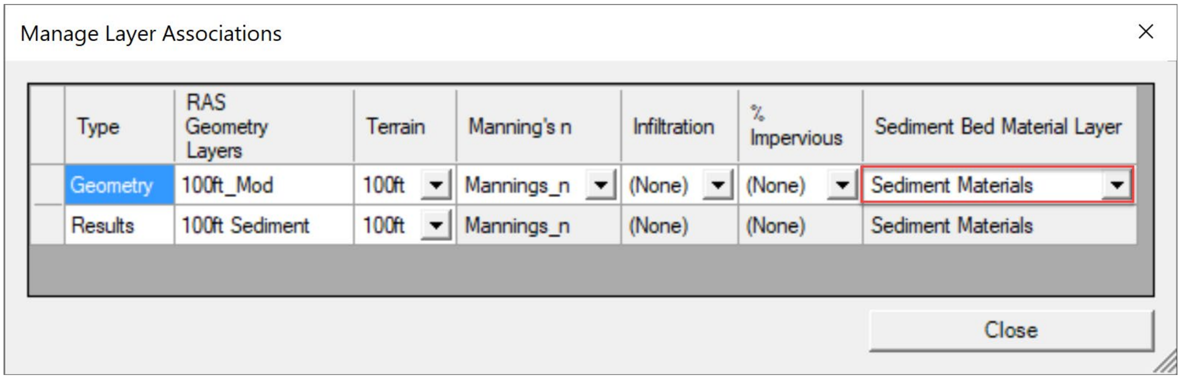


Figure 2-13. RAS Mapper **Manage Layer Associations** editor.

It is worth noting, that this associates the Bed Gradation Layers with the geometry, not the sediment file. Sediment files depend on geometry files for some of their data structures (e.g. cross sections in 1D). The sediment file will inherit the bed gradation layers and classifications from the active geometry file.

These layer classifications will become available in the **2D Sediment** tab of the Sediment Data Editor (see the 2D gradation selection section).

Bed Gradation Templates

Bed Gradation Templates contain the sediment grain class sizes, grain fractions by weight, and optionally bulk cohesive parameters. Users define sediment **Bed Gradations Templates** in a database with no spatial data. They can be considered simply as a database of different sediment types. In many applications, **Bed Gradation Templates** will correspond to individual bed samples taken in the project. Templates are created and edited by pressing the **Define/Edit Bed Gradation** button, which will launch the dialog depicted in Figure 17-17.

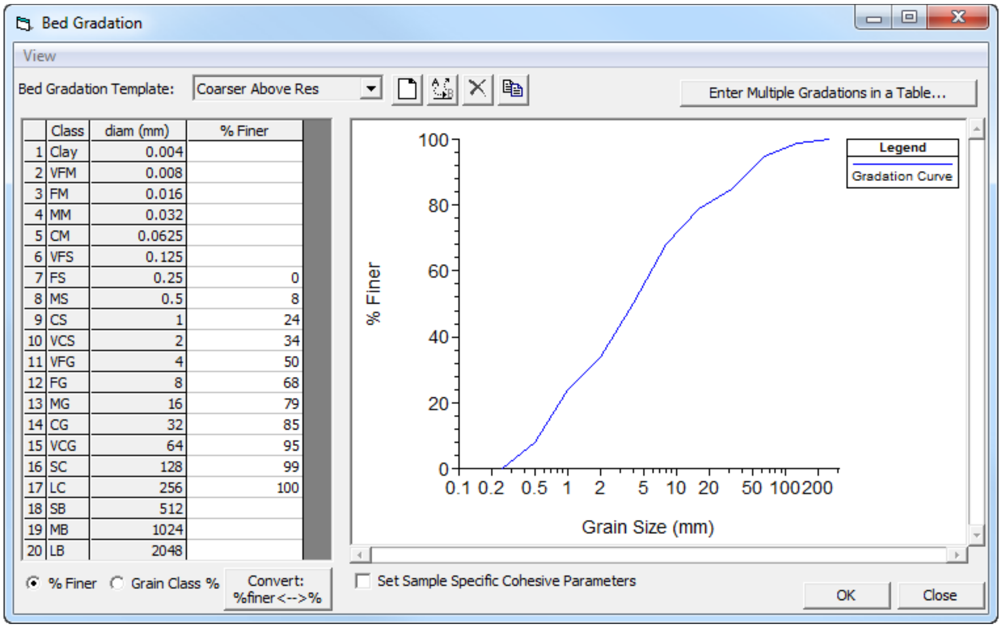


Figure 2-14. Bed Gradation Template editor.

Multiple bed gradations may be entered for 2D sediment models in the same as for 1D sediment models.

To create a **Bed Gradation Template**, 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 by clicking on the Enter Multiple Gradations in a Table... button and entering the data in the **Multiple Bed Gradation Table**.

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 values. (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 Layer Groups

User specified **Bed Layer Groups** allow the user to specify vertical bed layers with different bed gradations and different bulk properties. **Bed Layer Groups** are specified by selecting the button 

in the main **Sediment Data** editor which will open the **Define Gradation Layers** editor (Figure 2-15).

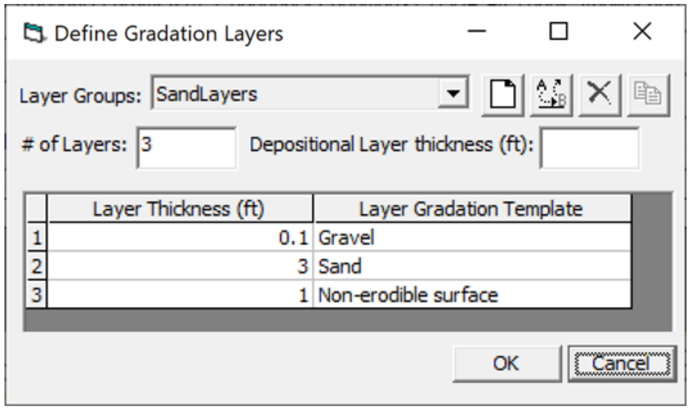


Figure 2-15. Example of a Bed Layer Group definition in the Define Gradation Layers editor.

In HEC-RAS 2D sediment transport, the depositional layer thickness is not utilized. The parameter is only utilized for 1D sediment transport.

The layer thickness specified for non-erodible surfaces is not actually used. Bed gradations are specified for each computational cell. Faces do not have bed gradations and only bed elevations. All subareas within a cell have the same **Sediment Bed Material**. Therefore, if a **Bed Layer Groups** is assigned to a cell, the bed layers will be at different elevations for the different subareas. For example, the figure below shows a computational which has been assigned a **Bed Layer Group** three layers. In the example below, the cell has three subareas. The bed layers have the same thickness in each subarea but start at a different elevation.

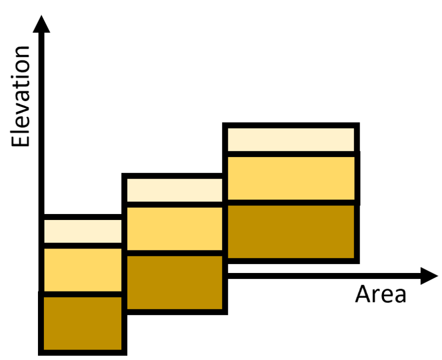


Figure 2-16. Example of a Bed Layer Group assigned to a computational cell.

2.2.2 Associated Bed Gradation Templates with Bed Material Layers

Once the user has created **Bed Gradation Templates**, and a **Sediment Bed Materials Layer** in RAS Mapper these can be associated in the **2D Bed Gradations (Beta)** tab of the **Sediment Data** editor.

After user defines the sediment **Bed Gradation 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. A single bed sample is frequently associated with multiple **Sediment Bed Material Layers**. 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.

The drop-down list always includes all of the user specified bed gradations and layer groups as well as a **non-erodible** option. If the **Bed Material Layer** represents a hard surface, engineered element (e.g. bank protection, wing wall, bed rock, or river engineering element), selecting the non-erodible option will allow the model to deposit on top of them, but not erode below the starting terrain surface.

A simple example of a dataset is shown below which only has one **Bed Material Type** and one **Bed Gradation**. Simple datasets like this are most easily created by starting with an empty **Sediment Bed Materials Layer** in **RAS Mapper** and creating polygons for different regions of different bed composition. Each polygon corresponds to a Bed Material Type and can then be associated with a **Gradation** in the **2D Bed Gradations** tab of the **Sediment Data** editor.

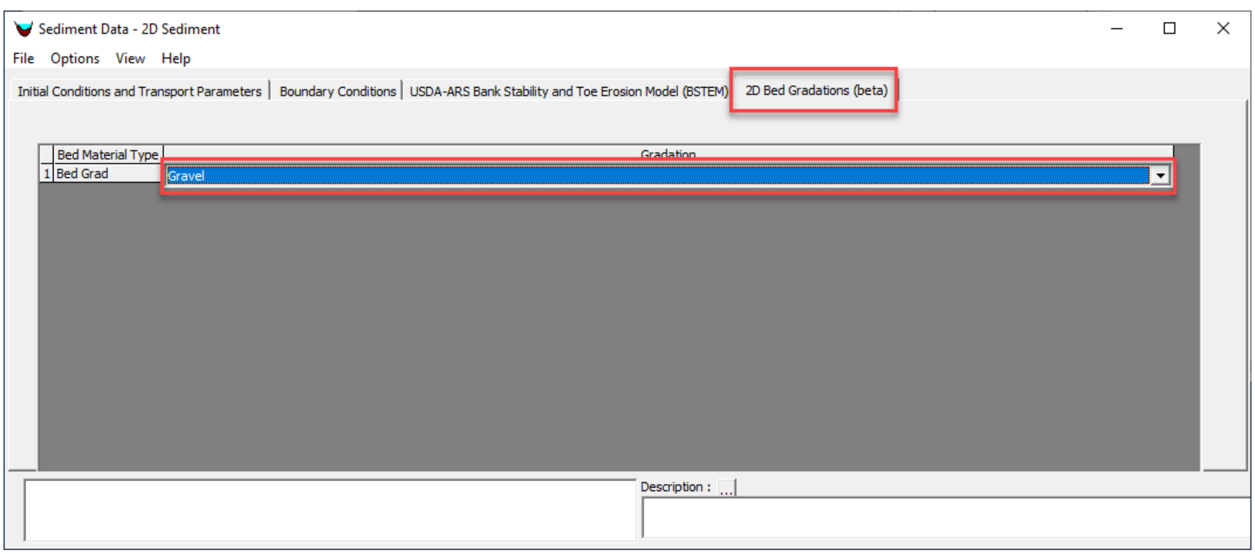


Figure 2-17. Simple, single gradation, 2D sediment specification with one Bed Gradation associated with one Bed Material Type.

A more complicated dataset is shown in the figure below for which the **Sediment Bed Material Layer** was created by importing a shape file. The shape file defines the polygon types in RAS Mapper with integers, that show up under **Bed Material Type**. The user then defined and associated bed gradations with these **Sediment Bed Material** classifications. Users can rename these imported polygons under the **Layer Properties→Features** menu of the RAS Mapper Layer.

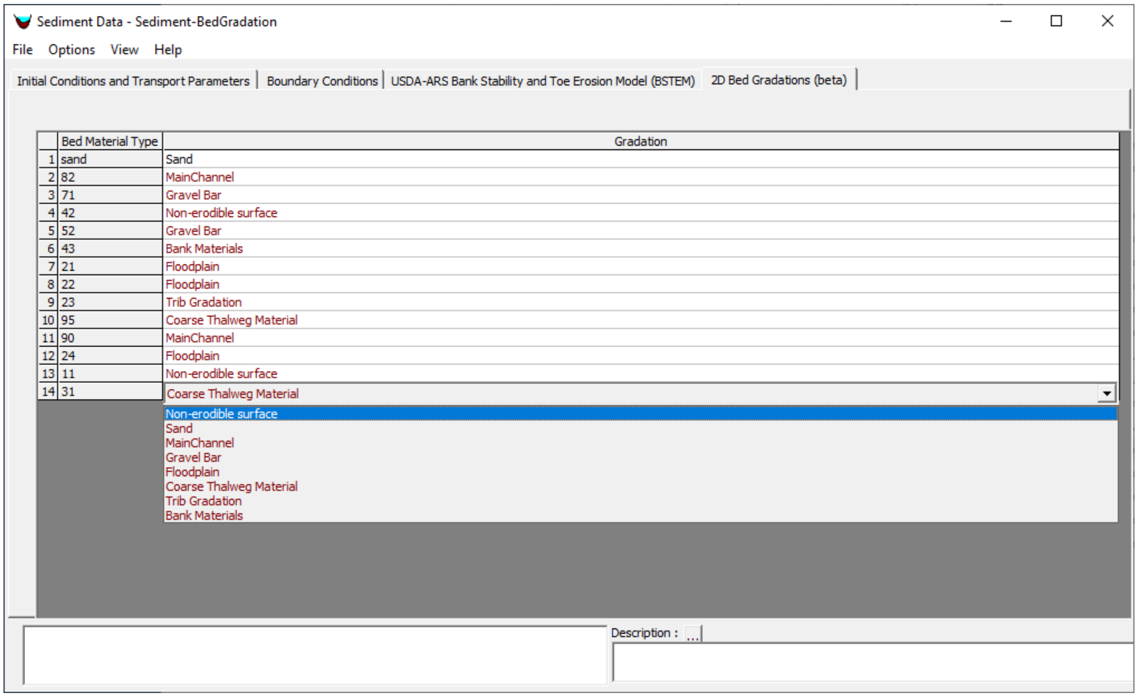


Figure 2-18. More detailed bed material specification, where the Bed Material Layer was imported from a shape file.

2.2.3 Sediment Boundary Conditions

The second tab on the **Sediment Data** editor defines sediment boundary conditions (see figure below). The editor automatically lists external model boundaries. HEC-RAS requires a boundary condition at all external boundaries. If any external boundary (i.e. boundary condition line) is left unspecified, then an equilibrium sediment load boundary condition is assumed. The types of boundary conditions which may be specified in a 2D sediment model are:

1. Rating curve
2. Sediment load series
3. Equilibrium load
4. Clear water (no sediment)

The other boundary condition options available from the interface (which are mostly associated with 1D flow splits) are not allowed at 2D sediment transport boundaries. Only inflow sediment boundary conditions are required. When the model computes flow out of the domain the sediment can simply leave the domain. At 2D boundaries that where flux is always out of the domain, users can select the equilibrium boundary condition may or simply leave the sediment boundary condition empty. Any boundary condition lines left empty are assigned an **Equilibrium Load** boundary condition. This is necessary so a boundary condition type is available if the flow were to reverse direction even locally during the simulation.

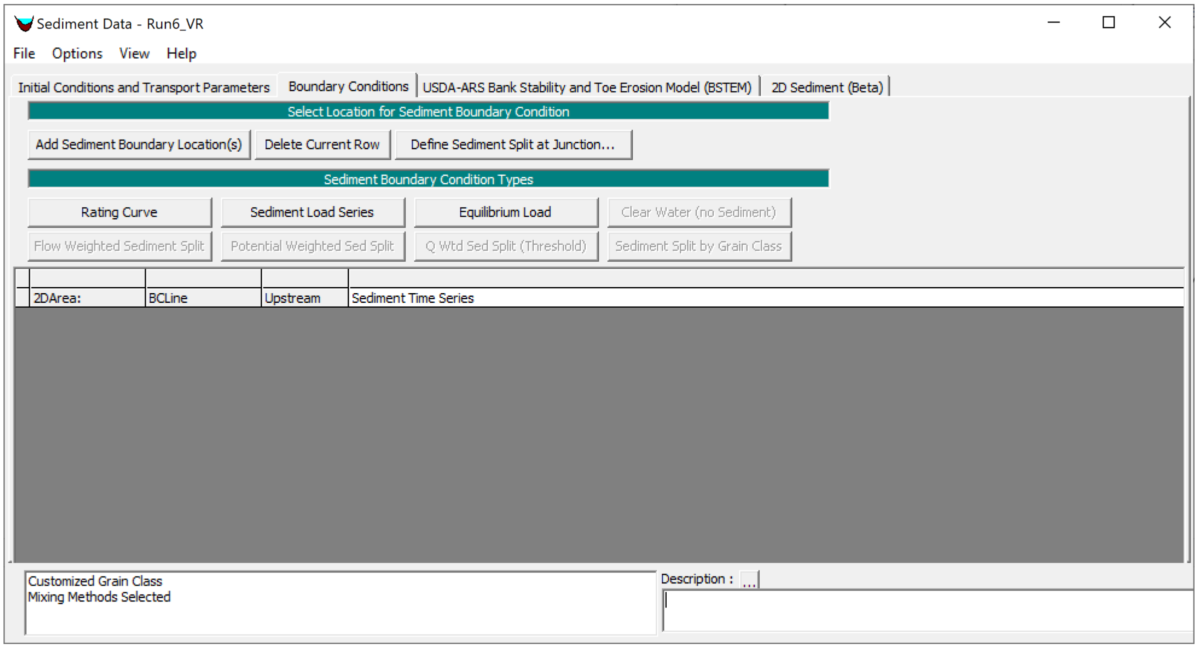


Figure 2-19. Boundary Conditions tab in the Sediment Data editor.

Rating Curve

The rating curve specifies the sediment load in tons/day or sediment concentration in mg/l as a function of flow discharge. The fractional composition of the incoming sediment load is specified for each grain class. The fractional loads are then specified to each cell using the cell sediment capacity as a weighting function. For 2D sediment transport, the user has the option to no specify the fractional bed-load composition. In this case, the cell sediment capacities (equilibrium concentrations) are used to compute the fractional sediment loads at each cell. This option is useful when the rating curve sediment gradations are not known.

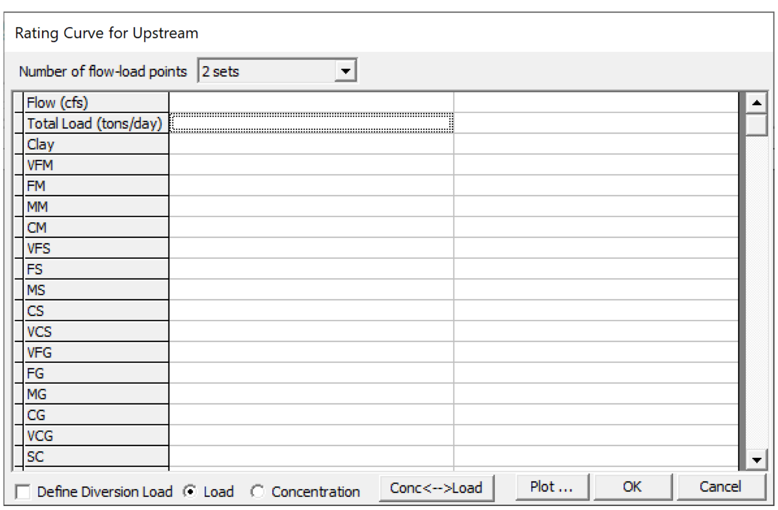


Figure 2-20. Sediment Rating Curve editor.

Sediment Load Series

The **Sediment Load Series** boundary condition specifies the sediment load in tons per time increment (see figure below). The sediment gradation may be specified with a **Gradation Rating Curve** or if this data is left empty, the gradation is determined by weighting the local (cell) equilibrium sediment loads. The **Gradation Rating Curve** specifies the gradation of the inflow sediment as a function of total load in tons/day. It is important to keep in mind that any grain specified in the gradation curve is automatically added to the computed grain classes.

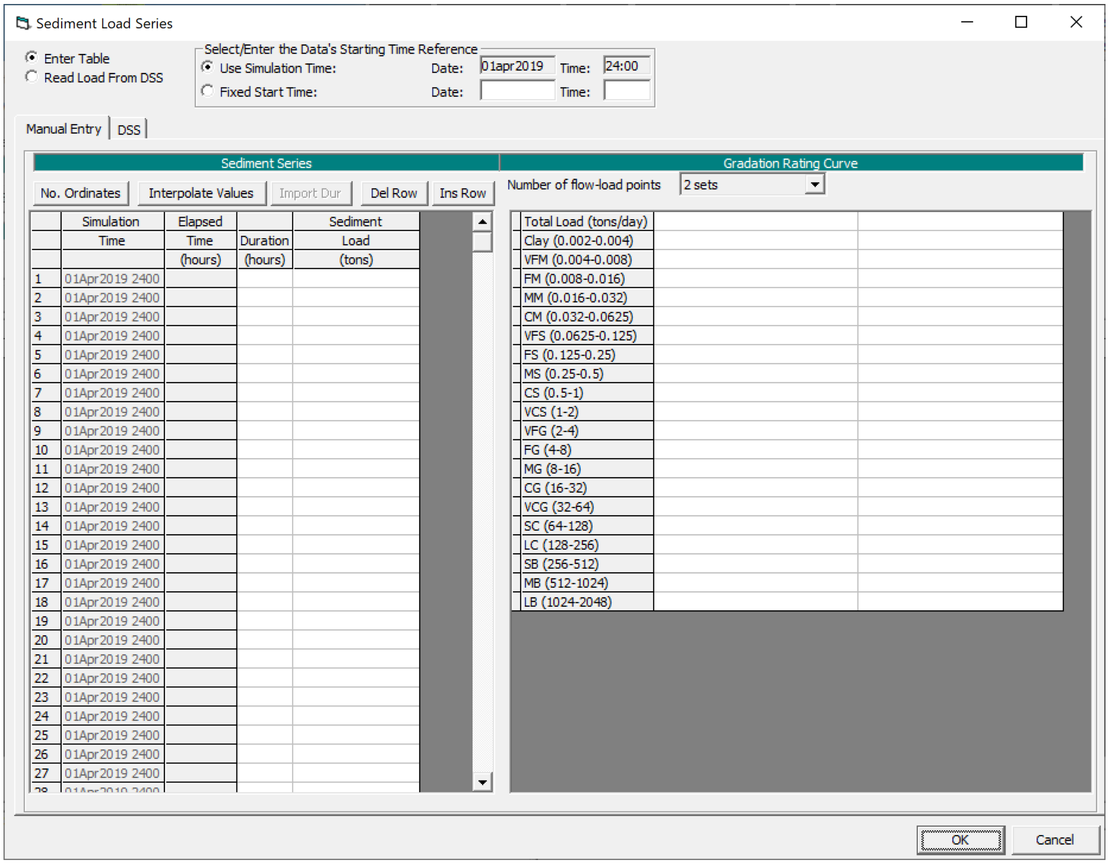


Figure 2-21. Sediment Load Series editor.

Equilibrium Load

The **Equilibrium Load** boundary condition specifies the inflow sediment load as the equilibrium sediment load. The equilibrium sediment load is computed as the equilibrium sediment concentrations at the boundary cells times the face flows. This approximation essentially assumes a zero-gradient concentration normal to the boundary. The equilibrium boundary condition should be used whenever data is not available or when first setting up a model to quickly get simulation results or to compare results from other boundary condition types which may be suspect.

Clear Water

The **Clear Water** boundary condition specifies a zero load/concentration at the boundary. This boundary is not very commonly used except for very specific situations.

Unsteady Temperature

Temperature is the only data the unsteady flow editor required 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 (see figure below).

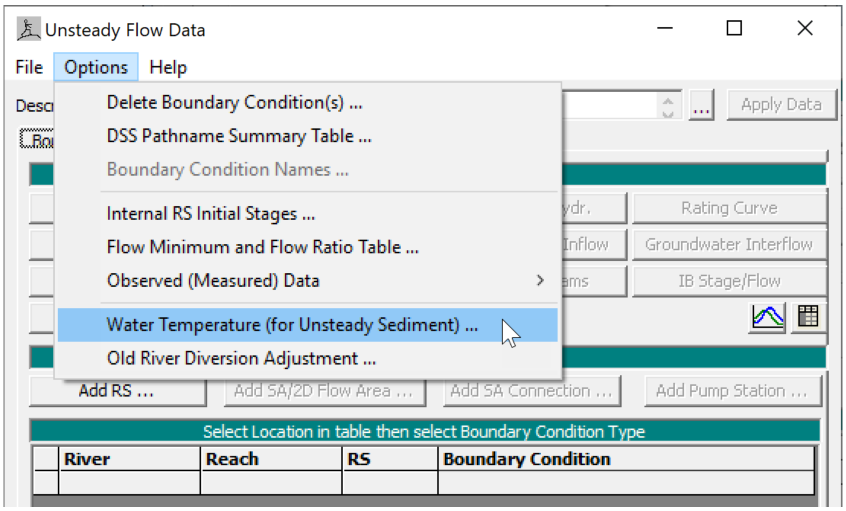


Figure 2-22. Opening the Unsteady Temperature editor from the Unsteady Flow Data editor.

The **Unsteady Temperature** time series editor, is similar to the unsteady flow and stage editors (see figure below). In the absence of temperature data in the unsteady flow file, HEC-RAS will assume 55.4ºF. The water temperature is used to compute the water kinematic and dynamic viscosities, and the water density which are then used by the sediment transport model.

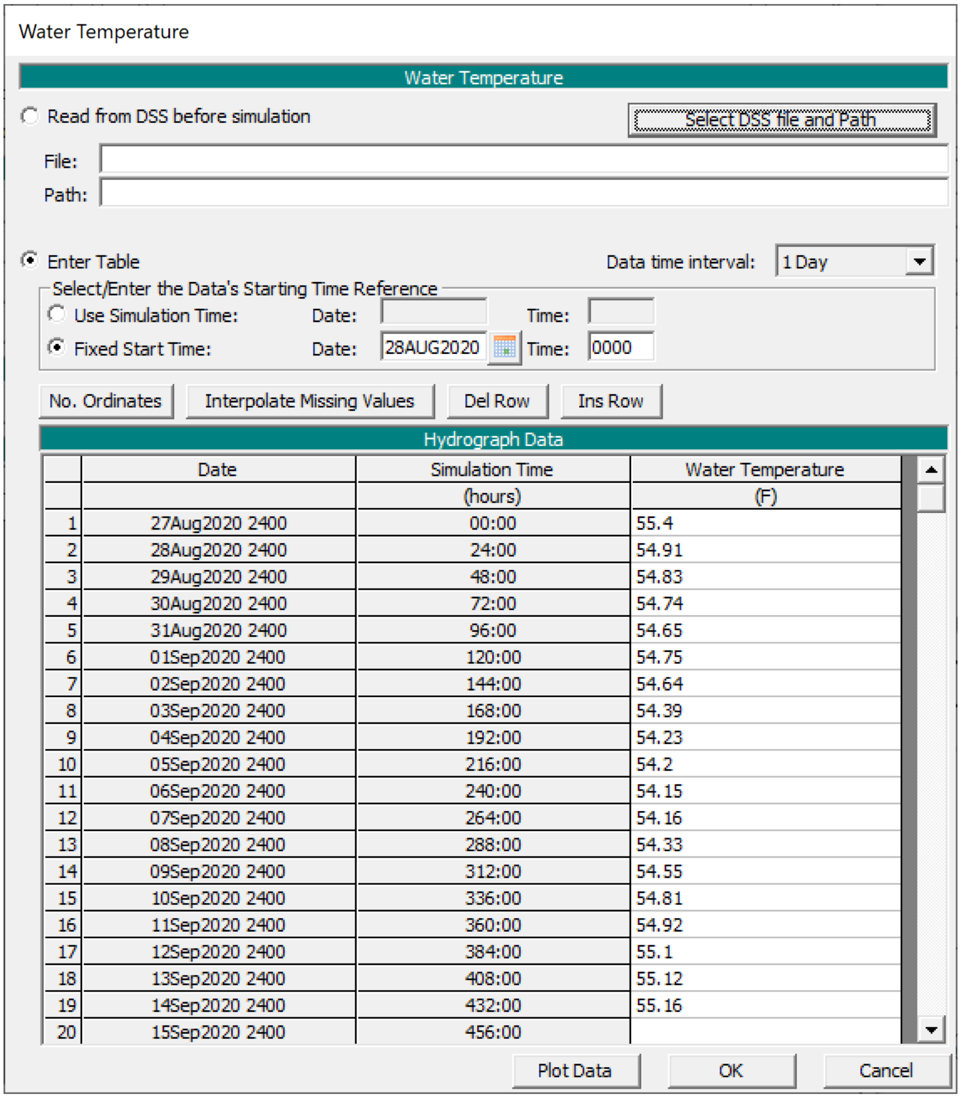


Figure 2-23. Specifying a temperature time series.

2.2.4 User-Defined 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.

The user may change the size range for the grain classes by going to the Sediment Data editor and selecting **Options | User Defined Grain Classes...** (see figure below).

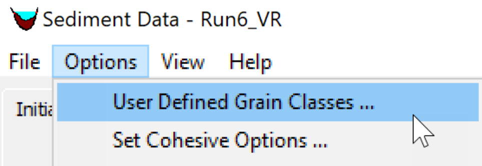
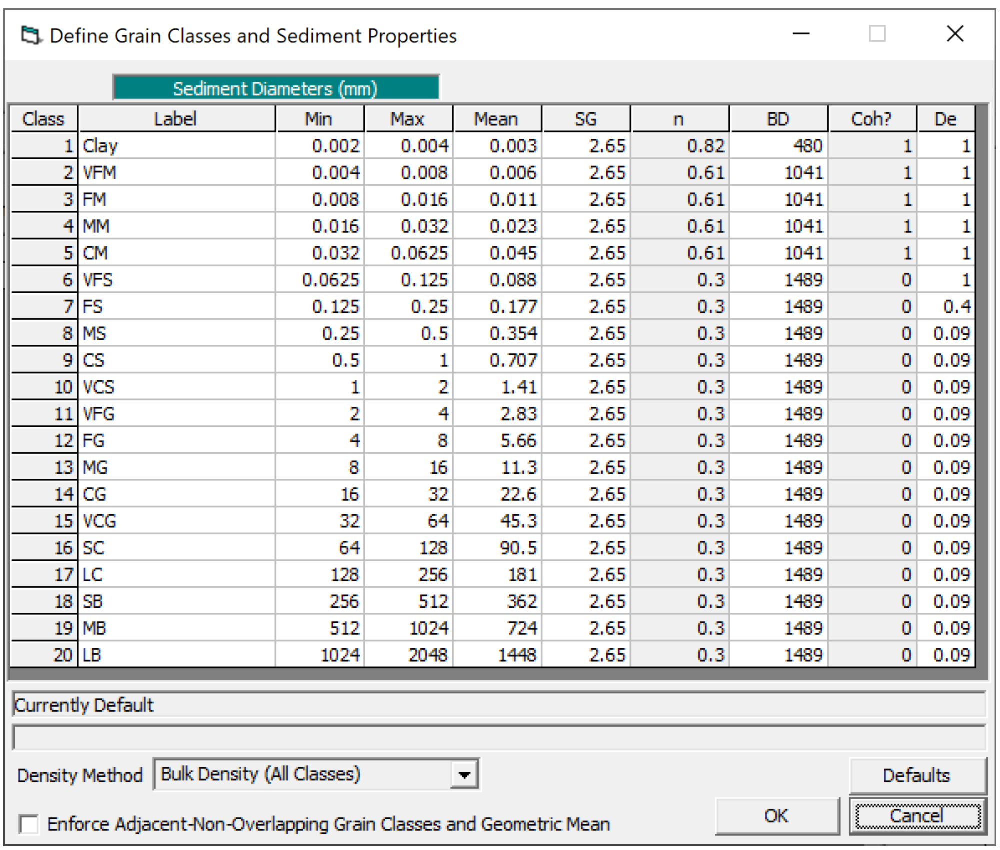


Figure 2-24. Opening the User Defined Grain Classes editor from the Sediment Data editor.

In the **User Defined Grain Classes** editor (see figure below), the user may change the diameter limits, names of the grain classes, and sediment properties including the Specific Gravity (SG), Porosity (n), dry Bulk Density (BD). The label (name) for each grain class may be changed in the table. The labels are used in the sediment output to identify variables associated with each grain class such as fractional concentrations and particle fall velocities. It is important to note that for 2D sediment transport, not all the grain-classes in the **User Defined Grain Classes** editor are used. Only the grain classes which exist in the **Sediment Bed Gradations** and/or the sediment boundary conditions are used. This saves computational time and memory since only the grain classes which need to be computed are used. Therefore, the number of grain classes in 1D and 2D sediment may be different.



Class	Label	Min	Max	Mean	SG	n	BD	Coh?	De
1	Clay	0.002	0.004	0.003	2.65	0.82	480	1	1
2	VFM	0.004	0.008	0.006	2.65	0.61	1041	1	1
3	FM	0.008	0.016	0.011	2.65	0.61	1041	1	1
4	MM	0.016	0.032	0.023	2.65	0.61	1041	1	1
5	CM	0.032	0.0625	0.045	2.65	0.61	1041	1	1
6	VFS	0.0625	0.125	0.088	2.65	0.3	1489	0	1
7	FS	0.125	0.25	0.177	2.65	0.3	1489	0	0.4
8	MS	0.25	0.5	0.354	2.65	0.3	1489	0	0.09
9	CS	0.5	1	0.707	2.65	0.3	1489	0	0.09
10	VCS	1	2	1.41	2.65	0.3	1489	0	0.09
11	VFG	2	4	2.83	2.65	0.3	1489	0	0.09
12	FG	4	8	5.66	2.65	0.3	1489	0	0.09
13	MG	8	16	11.3	2.65	0.3	1489	0	0.09
14	CG	16	32	22.6	2.65	0.3	1489	0	0.09
15	VCG	32	64	45.3	2.65	0.3	1489	0	0.09
16	SC	64	128	90.5	2.65	0.3	1489	0	0.09
17	LC	128	256	181	2.65	0.3	1489	0	0.09
18	SB	256	512	362	2.65	0.3	1489	0	0.09
19	MB	512	1024	724	2.65	0.3	1489	0	0.09
20	LB	1024	2048	1448	2.65	0.3	1489	0	0.09

Figure 2-25. User Defined Grain Classes editor.

The grain size classes can be viewed as analogous so the grid resolution. The table below shows typical specific gravity ranges for different common minerals and rocks.

Table 2-1. Specific gravity ranges for different minerals and rocks.

Material	Specific Gravity
Quartz	2.6 – 2.7
Limestone	2.6 – 2.8
Basalt	2.7 – 2.9
Magnetite	3.2 – 3.5
Coal	1.3 – 1.5

The grain specific gravity should not be used as calibration parameter. It is a parameter of the sediment particles and should be specified as accurately as possible. However, in general the results are generally not very sensitive to the specific gravity for natural sediments in rivers.

Density Methods

The **Density Method** refers to the methods used to specify the grain class dry density/porosity/unit weight:

1. Bulk Density (All Classes)
2. Porosity (All Classes)
3. UW-Cohesive/Porosity-Cohesionless

The default **Density** Method is **Bulked Density** (**BD**). To specify a different **Density Method**, the user may select one of the options in the drop down menu as shown in the figure below.

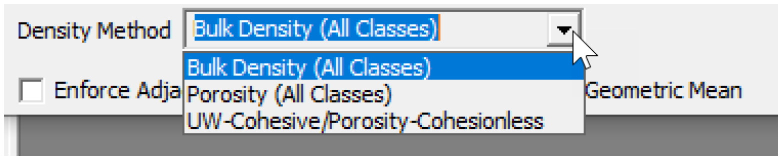


Figure 2-26. Selecting the Density Method in the Define Grain Classes and Sediment Properties editor.

Depending on the choice selected the appropriate columns will be enabled or grayed out in the **User-defined Grain Classes** editor. If the **Bulk Density** method is selected the **BD** (for dry bulk density) column is enabled. The program computes a grain class porosity from the specific gravity (column labeled **SG**) which may not be the same as the values in the grayed-out porosity (column labeled **n**). If the **Porosity (All Classes)** method is selected, the specific gravity and porosity columns are enabled. The program internally computed a dry bulk density from the specific gravity and porosity, which may not be the same as that which is displayed in the editor. The last option is the **UW-cohesive/Porosity-Cohesionless** method. In this method the dry bulk density is specified for cohesive grain classes, and the porosity is specified for the cohesionless (noncohesive) grain classes.

The treatment of the dry bulk density in HEC-RAS 2D sediment is different from that of HEC-RAS 1D. In 2D the bulk density is treated as a property of the sediment mixture and there is not always a one-to-one relationship between the grain class fractions and the bulk density. This is necessary to simulate processes such as packing and consolidation.

If all the utilized grain class (cohesive and noncohesive) have the same bulk density and consolidation is not enabled, a constant bulk density is assumed, which significantly simplifies the computations. If the specified bulk densities or porosities for the noncohesive grain classes are variable, a variable bed density model is utilized with the bed porosities calculated from the Colby (1963) formula. The variable bed density model is more computationally expensive because it requires several more calculations and steps during the simulation. If the dry densities or porosities are left empty, then the Wooster et al. (2008) porosity formula is utilized based on the sediment sorting. Dry densities generally vary between 300 to 1,600 kg/m^3.

2.2.5 Cohesive Options

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, to flocculate 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.

In HEC-RAS, the cohesive options can be set by selecting **Set Cohesive Options…** under **Options** menu of the **Sediment Data** editor (see figure below).

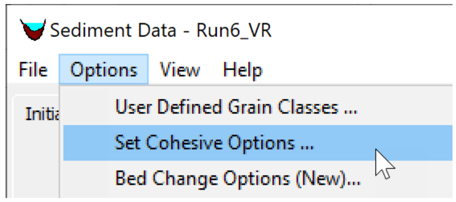


Figure 2-27. Opening the Cohesive Options editor from the Sediment Data editor.

The **Cohesive Options** editor is shown in the figure below. The editor allows the user to select how the erosion is computed for cohesive sediments.

Erosion Parameters

HEC-RAS includes three cohesive erosion methods; applying the standard transport equations, or two different implementations of the Krone and Partheniades approach. In HEC-RAS 2D sediment transport, the **HEC 6T Capacity Method** is not available. When utilizing the 2D sediment transport model, it is generally not recommended to use the transport functions for the cohesive grain classes, especially clay. If the cohesive grain classes represent a very small fraction of the bed gradation, then it is better to simply remove them from the bed gradation then it is better to model them as cohesive.

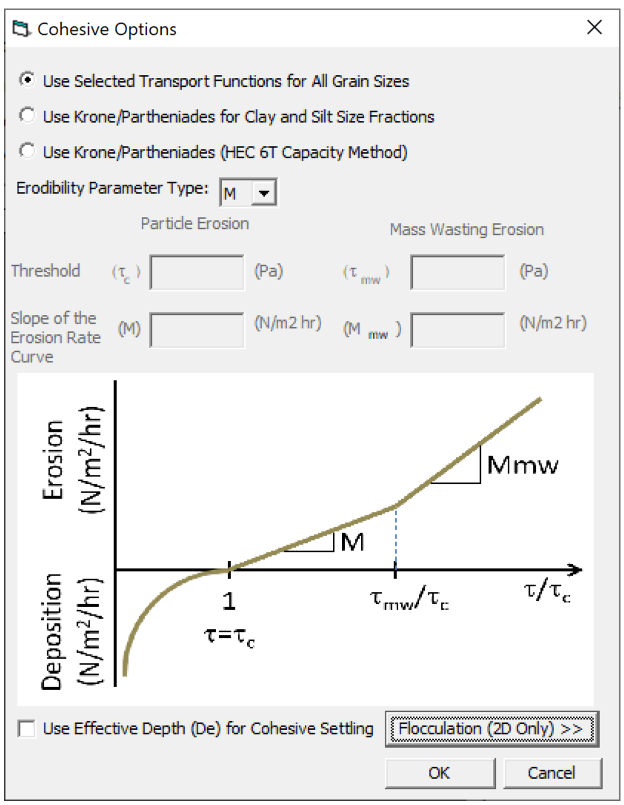


Figure 2-28. Cohesive Options editor.

The treatment of cohesive sediments and mixtures of cohesive and noncohesive sediments is slightly different for HEC-RAS 1D and 2D. HEC-RAS 1D considers the smallest five grain classes 'fine sediment'. HEC-RAS 1D applies the same cohesive erosion method selected to these grain classes. By default, the first five grain classes are the clay and silt classes, and are all finer than 0.0625 mm. However, if the user edits the diameters sizes for these, the cohesive erosion methods will still apply to the first five grain classes, regardless of their size. HEC-RAS 2D has diameter thresholds that determine whether a grain class forms flocs and behaves cohesively on the bed. The reason for having these separate thresholds is to allow for the erosion to be calculated with the user-selected transport function while still allowing fine grain classes to form flocs. The upper threshold for grain classes to form flocs is 0.0625 mm. The size tolerance for grain classes are behave cohesively on the bed is either set to 0.0 mm if the **Use Selected Transport Functions for All Grain Sizes** option is selected or 0.0625 mm if the Krone/Partheniades formulas are selected.

In HEC-RAS 1D if more than 20% of the active layer is cohesive, then the model considers the sediment active layer as cohesive and computes the erosion for all grain classes using the cohesive method. However, in 2D the erosion of mixed cohesive/noncohesive sediments is computed

Ariathurai (1974) parameterized Partheniades (1962) results into a formula with an erosion rate coefficient M and critical shear for erosion τ_c. M and τ_c include the stochastic nature of both the sediment bed composition and surface and the bed shear stress. The critical shear for erosion is usually in the range of 0.2 to 0.8 Pa, while M is usually in the range widely from 0.01 to 50 Pa/hr (Winterwerp and van Kesteren 2004). Dahl et al. (2018) obtained good results in simulating the lower Mississippi river using τ_c = 0.02 lb/ft^2, τ_{mw} = 0.04 lb/ft^2, M = 0.05 lb/ft^2/hr, and M = 0.03 lb/ft^2/hr.

Flocculation

The settling velocity of cohesive particles is computed using a flocculation settling velocity. The flocculation settling velocity takes into account the formation and destruction of flocs as a function of the sediment concentration. HEC-RAS has two methods for estimating the settling velocity of flocs (see figure below). The first is the method of Hwang (1989). The method represents the settling velocity as 4 separate zones: (1) free settling, (2) flocculation, (3) hindered settling, and (4) negligible settling. The method requires 4 empirical coefficients.

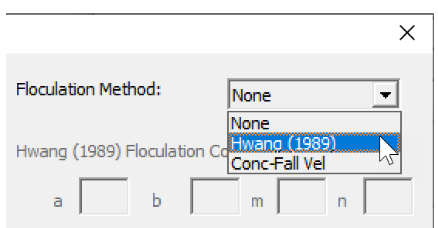


Figure 2-29. Selecting the Hwang (1989) floc settling velocity formula.

Example coefficient values for the Hwang (1989) formula are shown in the table below.

Table 2-2. Example coefficient values for the Hwang (1989) formula from literature.

Reference	**Location**	a	b	m	n
Krone (1962)	San Francisco Bay, CA	0.048	25.0	1.00	0.40
Owen (1970)	Severn River, UK	0.100	10.0	1.30	1.0
Nichols (1984)	James River, VA	0.039	3.8	1.32	1.52
Hwang (1989)	Lake Okeechobee, FL	0.080	3.5	1.88	1.65
Costa (1989)	Hangzhou Bay, China	0.100	6.20	1.60	1.20
Marván (2001)	Ortega River, FL	0.160	4.50	1.95	1.70
Ganju (2001)	Loxahatchee River, FL	0.19	5.80	1.80	1.80

The second method available to estimate the floc settling velocity is a user-specified **Flocculation Curve**. The **Flocculation Curve** defines the settling velocity as a function of the suspended sediment concentration. An example of a user-specified flocculation curve is shown in the figure below. The free-particle settling velocity is used when it is higher than the user-specified fall velocity for concentrations less than the concentration at the peak settling velocity. When the concentration is high than the maximum concentration specified in the flocculation curve, the settling velocity corresponding to the maximum concentration is used.

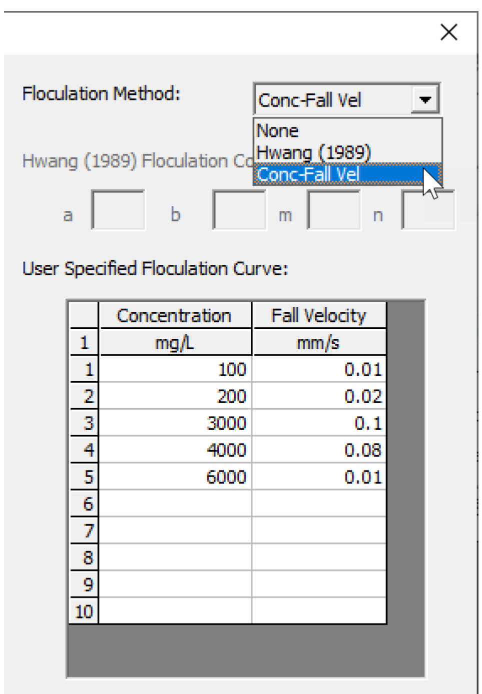


Figure 2-30. Specifying a floc settling velocity as a function of suspended sediment concentration.

In addition to taking into account the sediment concentration, HEC-RAS corrects the floc settling velocity for the water temperature by applying a correction which is a function of the water dynamic viscosity. This assumes that the user-specified curve and the coefficients in the Hwang method correspond to a standard water temperature of 55.4ºF.

Consolidation

Consolidation curves are developed for a specific bed material. Since HEC-RAS only allows the user to specify one consolidation curve, a representative consolidation curve is used for the all of the modeling domain. It is assumed that the consolidation curve was developed for cohesive sediments. Until more than one consolidation curve is added to HEC-RAS a simple correction is computed to account for the presence of noncohesive sediments which can significantly affect the consolidation curve.

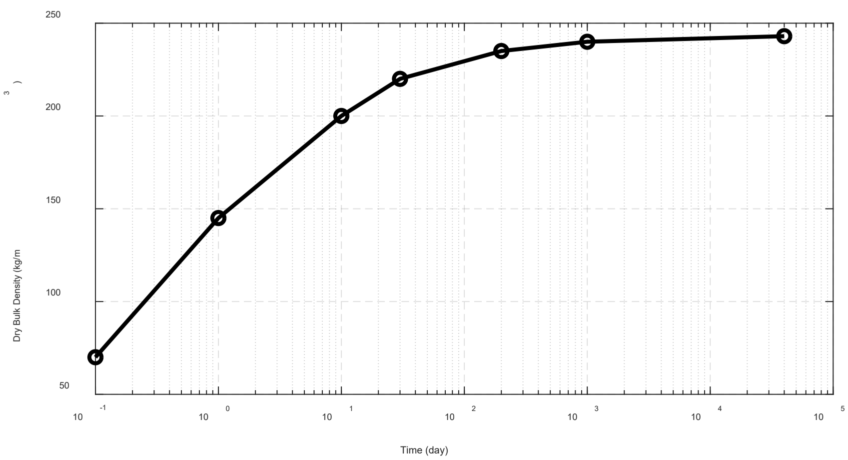


Figure 2-31. Example consolidation curve of dry bulk density as a function of time.

2.2.6 Transport Methods

The **Transport Methods** editor is where the user may select the parameters and values for several transport-related variables. These include the Load Correction Factor, Diffusion Coefficient, and adaptation parameters. To open the **Transport Methods** editor, open the **Sediment Data** editor, and select open the **Options** menu and select **Transport Methods…** (see figure below).

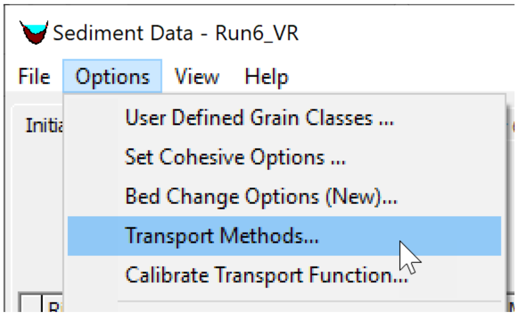


Figure 2-32. Opening the Transport Methods editor from the Sediment Data editor.

Load Correction Factor

HEC-RAS 2D sediment transport has the option to approximate the current velocity and concentration profiles with approximate semi-analytical profiles, as well as to utilize an empirical formula for the bed-load velocity (see figure below). If these options are enabled, a load correction factor is included in the temporal term of the transport equation (i.e. advection-diffusion equation). The load correction factor accounts for non-uniform vertical profiles of the concentration and current velocity as well as the bed-load velocity. Since most of the sediment concentration is typical near the bed where the current velocities are slower, the load correction factor is generally less than one and produces a temporal lag between the flow and the sediment concentrations.

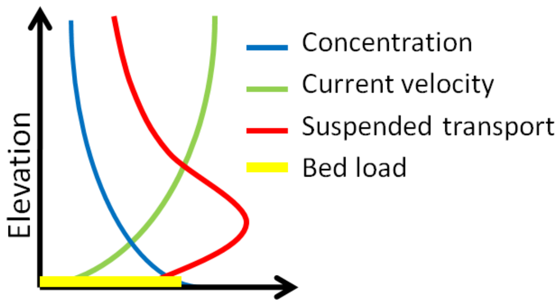


Figure 2-33. Schematic of sediment and current velocity profiles.

The load correction factor options are specified in the **Transport Model and AD Parameters** editor which can be accessed by opening the **Sediment Data** editor and selecting the menu **Options** and selecting **Transport Methods…**

The load correction factor options are specified within the section **Total-Load Correction Factor** section of the first tab of editor called **AD Parameters**. By default, HEC-RAS does not compute any load correction factors. To turn on the load correction factor the user may check the box labeled **Total-load Correction Factor**. One this checkbox is selected the user should select the methods used to compute the bed and suspended-load correction factors.

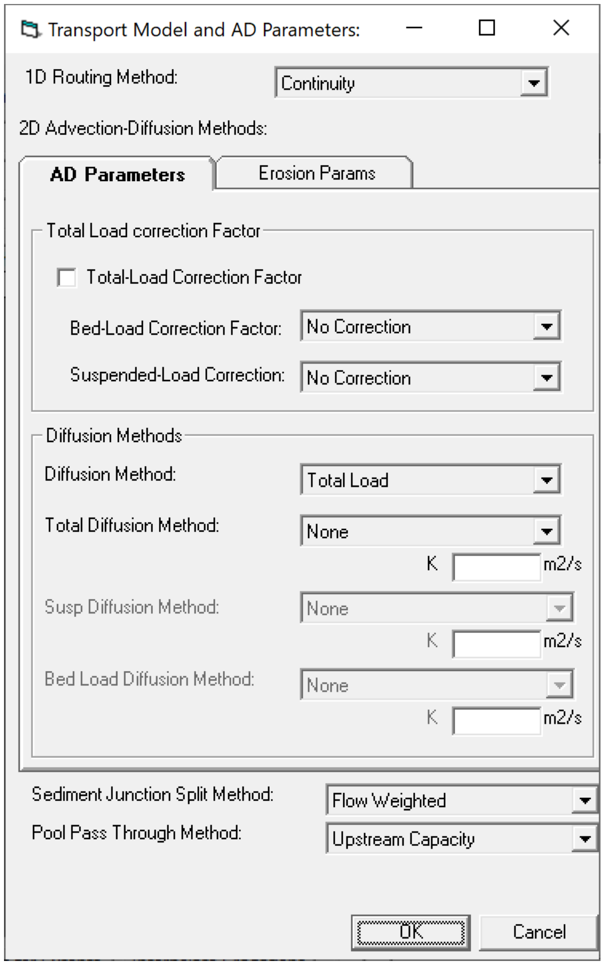


Figure 2-34. Setting the Total-load correction factor options in the Transport Model editor.

The bed-load correction factor method selects the formula for computing the bed-load velocity. The available bed-load velocity formulas are:

1. No correction
2. Van Rijn
3. Van Rijn-Wu
4. Phillips and Sutherland

Selecting **No Correction** assumes the bed-load velocity is equal to the depth-averaged velocity. The van Rijn and van Rijn-Wu are similar formulas. The only difference is that the van Rijn-Wu formula has coefficients that have been recalibrated with a larger dataset of measurements.

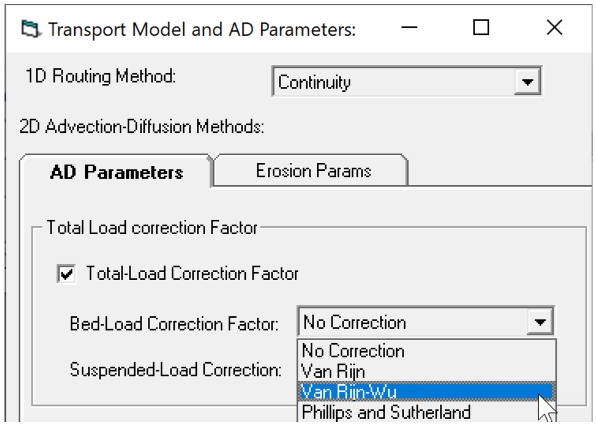


Figure 2-35. Setting the bed-load correction factor options in the Transport Model editor.

The suspended load correction factor methods select vertical sediment concentration profile. The three options are:

1. No correction
2. Rouse sediment concentration profile
3. Exponential sediment concentration profile

When selecting the Rouse and Exponential sediment concentration profiles, it is assumed that the current velocity follows a logarithmic profile. If **No Correction** is selected, the suspended-load correction factor is set to one.

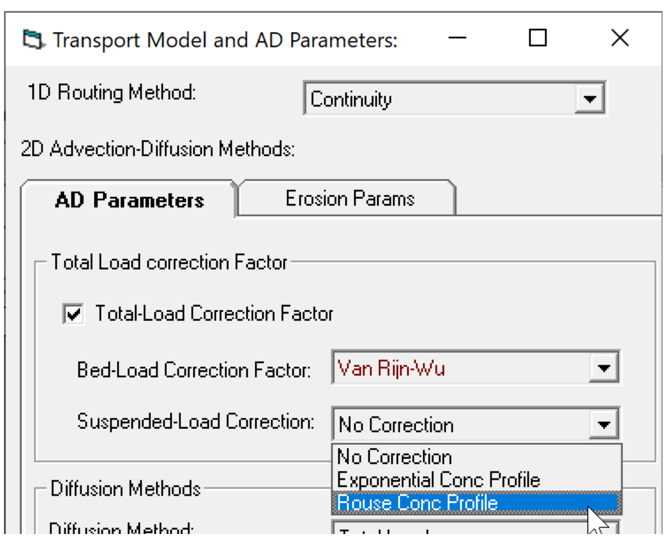


Figure 2-36. Setting the suspended-load correction factor method in the Transport Model editor.

Generally, for practical applications there is not enough data to calibrate the bed and suspended-load correction factors. Their use is a compromise between accuracy and computational time which are both relatively minor. In general, the morphology change is much more sensitive to other parameters and options such as the transport function and adaptation parameters than the load correction factors.

Diffusion Coefficient

Horizontal turbulent mixing and dispersion is modeled in HEC-RAS with a Fickian diffusion model. Turning on horizontal mixing is important in simulations with high resolution and sharp variations in sediment concentration capacities and concentrations, and when using high-resolution advection schemes. When the computational grid is relatively coarse or when using a first-order advection scheme the numerical diffusion may be so large that adding horizontal mixing is unnecessary. In general, sediment diffusion should not be used in combination with the Diffusion Wave Equation (DWE), since this can result and overly diffusive results.

The methods for computing the horizontal diffusion coefficients are in the **AD Parameters** tab of the **Transport Model and AD Parameters** editor which can be opened from the **Sediment Data** editor under **Options** and selecting **Transport Methods…** HEC-RAS has two options for the total-load diffusion coefficient.

1. Constant
2. Weighted bed-load and suspended-load diffusion coefficients

The default in HEC-RAS is for total-load diffusion of zero (i.e. no horizontal diffusion).

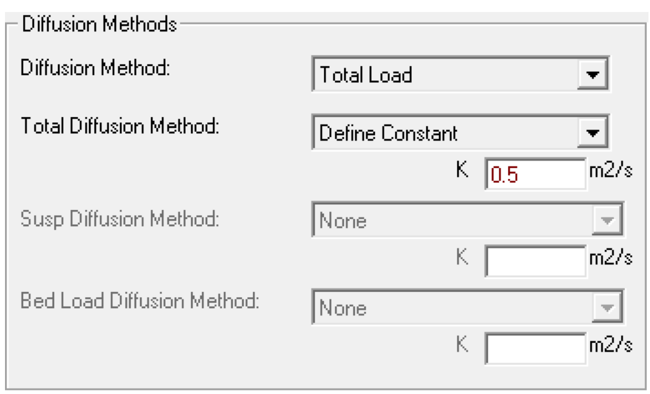


Figure 2-37. Specifying a constant total-load diffusion coefficient.

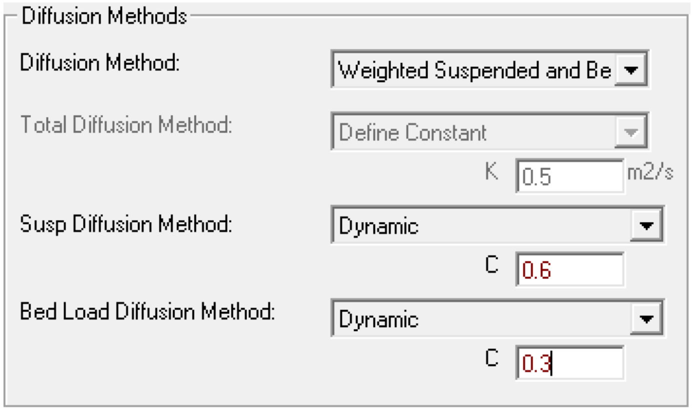


Figure 2-38. Specifying a total-load diffusion coefficient based on weighted bed and suspended load coefficients.

Erosion Parameters

The **Erosion Parameters** tab of the **Transport Model and AD Parameters** editor contains the settings for the noncohesive sediment transport erosion formulation. The total-load sediment erosion is computed as a function of the total-load adaptation coefficient. In HEC-RAS there are two methods for computing total-load adaptation coefficient:

1. Total-load length
2. Weighted bed-load and suspended-load adaptation coefficients

The total-load adaptation length computes the total-load adaptation length as a function of the unit discharge and sediment fall velocity (see figure below). The total-load adaptation length is the simplest and most computationally efficient of the two options.

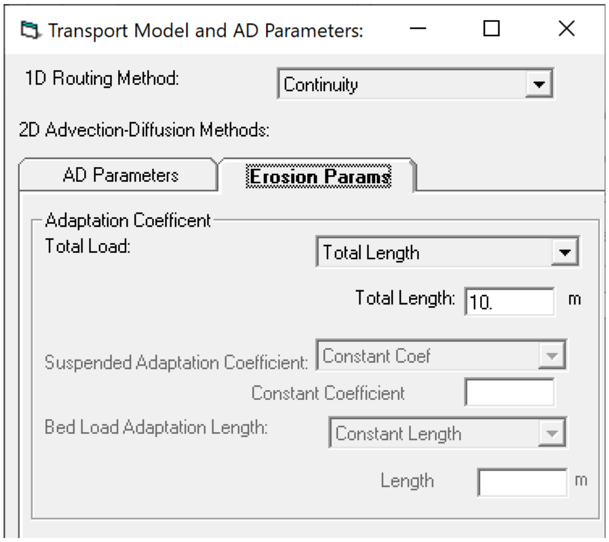


Figure 2-39. Specifying a total-load adaptation length.

The weighted bed-load and suspended adaptation coefficients requires specifying methods for the bed-load and suspended-load adaptation coefficients and computing the fraction of suspended sediments. However, it is the most physically accurate method.

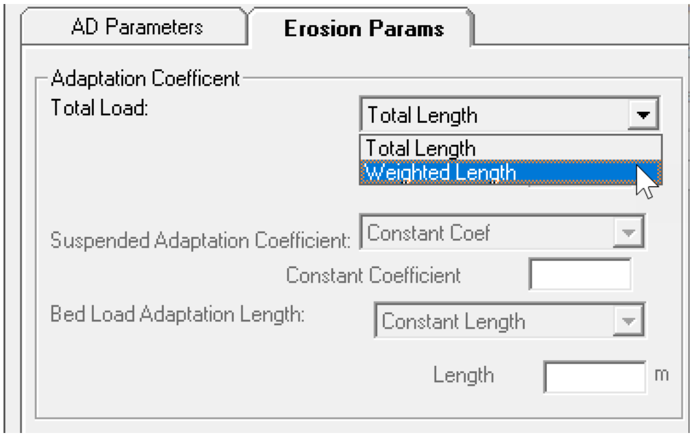


Figure 2-40. Specifying a weighted total-load adaptation length.

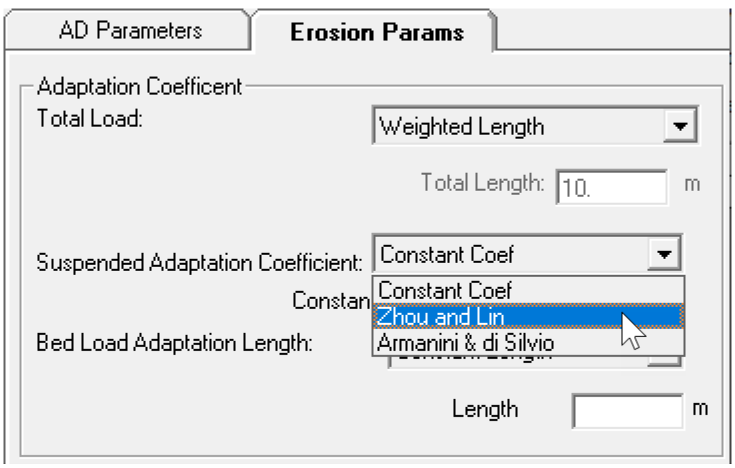


Figure 2-41. Specifying a suspended-load adaptation coefficient.

When first setting up a sediment transport model, it is recommended to use a constant total load adaptation length for simplicity. Once the user has a stable model producing reasonable results, it is recommended to perform a sensitivity of the adaptation length by adjusting the adaptation length. In many cases, the results are not found to be sensitive. This is usually for relatively coarse grid simulations under mild to moderate forcing. However, if the results are found to be sensitive to the adaptation length then more tests are necessary in determining to optimal adaptation method and parameters.

2.2.7 Transport Function Calibration and Modification

The **Transport Function Calibration and Modification** editor allows the user to scale or calibrate different transport formula in various ways. It is opened from the **Sediment Data** editor by opening the **Options** menu and selecting **Calibrate Transport Function** (see figure below).

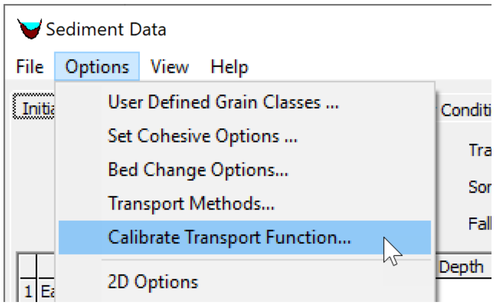


Figure 2-42. Opening the Transport Function Calibration and Modification editor from the Sediment Data editor.

The preferred method for calibrating the transport function is by means of the scaling factors. The total-load scaling factor is applied the same to all the transport functions. The mobility factor multiplies by the threshold for incipient motion (albeit a critical shear, reference shear, or Shields number). Therefore, a mobility factor larger than 1 reduces the mobility of a sediment. The option is also available to calibrate specific coefficients and exponents of several transport formula.

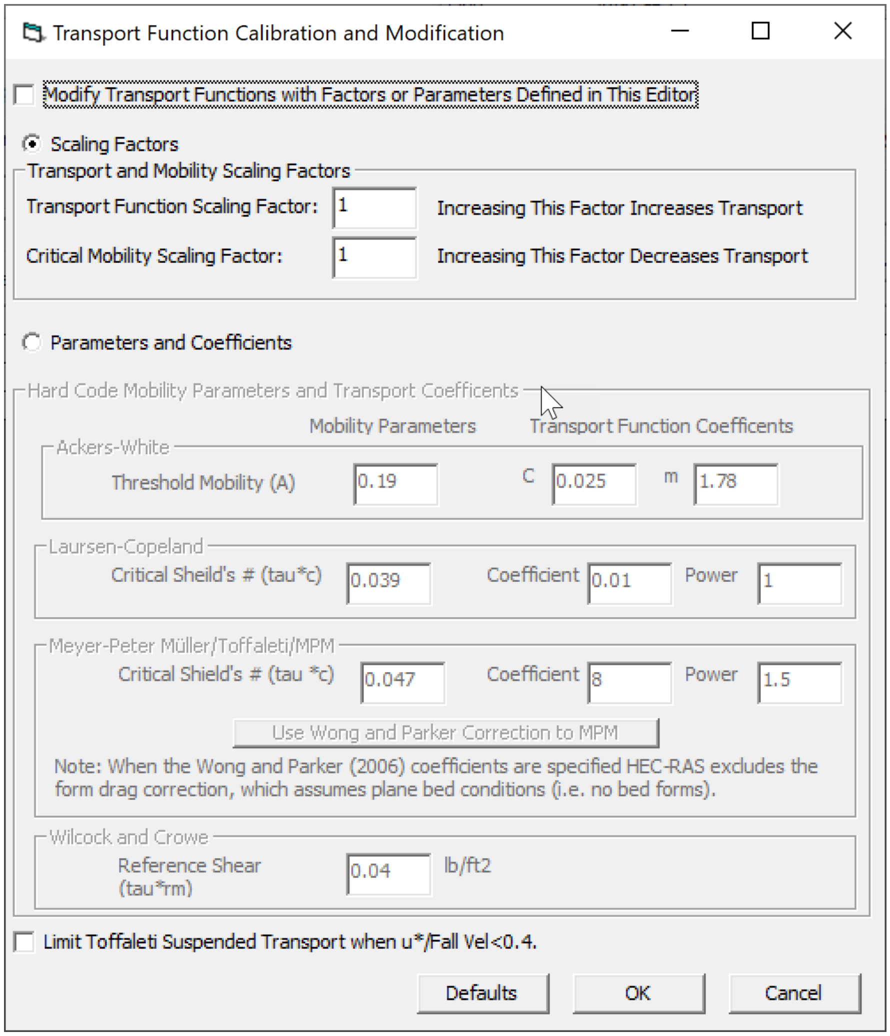


Figure 2-43. Transport Function Calibration and Modification editor.

2.2.8 2D Options

There are several sediment transport options which are only available in 2D. The goal is for both 1D and 2D sediment transport to have the same options but for now the 2D only options have been places in a single editor called **2D Options** which is available from the **Sediment Data** editor under the **Options** menu (see figure below).

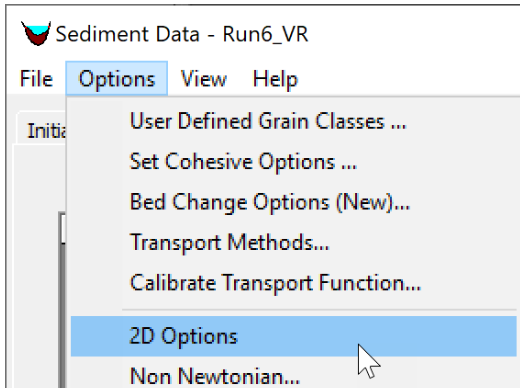


Figure 2-44. Opening the 2D Options editor from the Sediment Data editor.

The 2D Sediment Options editor is shown in the figure below. The editor is used to specify the options for sheet and splash erosion, the morphologic acceleration factor, the base bed-slope coefficient, and hindered settling.

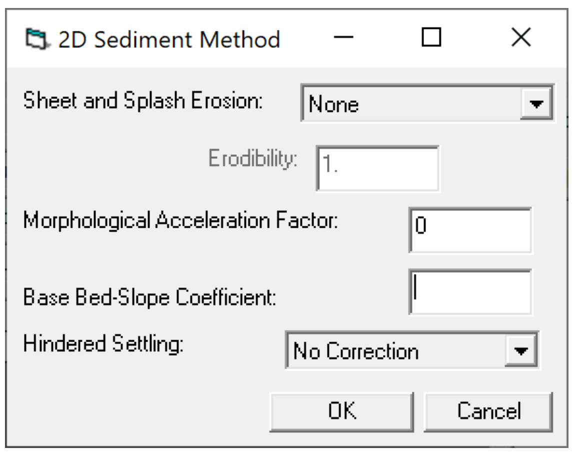


Figure 2-45. 2D Options editor.

Sheet and Splash Erosion

The first option available in the editor is the **Sheet and Splash Erosion**. The 2D sediment transport model has the option to use the Wei et al. (2009). The formulation has an erodibility coefficient which for simplicity is set to a single value in HEC-RAS. The units of the erodibility coefficient are $kg{\cdot}m^{-3.644}{\cdot}s^{0.644}$. Wei et al. (2009) reported values for the sheet and splash erosion coefficient between 1124 and 2555 $kg{\cdot}m^{-3.644}{\cdot}s^{0.644}$ for 3 grassland rangeland plots in Arizona (all variables in the International System of Units). However, its value can vary by orders of magnitude for different soil types and cover characteristics.

Morphologic Acceleration Factor

The **Morphologic Acceleration Factor** is a parameter which can be used to turn off the bed change or as the name implies, to accelerate the bed change. The factor is directly multiplied by the mass bed exchange rates at every time step. A value of zero will turn off the bed elevation and bed composition change.

The **Morphologic Acceleration Factor** can be utilized in several ways. The first and most obvious is to simply turn off updating the bed elevation and bed composition by setting it to a value of zero. This saves computational time and is useful for idealized situations are when debugging a problem with a sediment model.

Another way the factor can be used is as a scaling factor to the morphological change. In other words, the factor can be used to simulate a time period which represents the morphological change of a time period equal to the simulation period times the **Morphologic Acceleration Factor**. This approach is commonly used in coastal applications with tidal boundary conditions. As an example, a 5-year simulation can be run with **Morphologic Acceleration Factor** of 20 to simulate 100 years of change which greatly reduces the computational time. However, it should be noted that this approach changes the order of events (i.e. storms and tidal forcing with respect to morphological features) which can have a negative impact on the accuracy of the approach.

Lastly, the **Morphologic Acceleration Factor** can also be used as a time speed-up factor. This approach is more appropriate in river applications or when simulating single events or sequences of events. As an example, a 20-day simulation can be reduced to 2 days by setting the **Morphologic Acceleration Factor** to 10 and importantly also speeding up the boundary conditions by the same factor. However, just as in the previous example, care must be taken as to not speed-up the time so much that the hydrodynamics change substantially and thereby the morphological change.

The **Morphologic Acceleration Factor** should be used with caution as it can lead to misleading results or instabilities. The best practice for using the factor is to test the validity of the factor by doing a full or partial length of a simulation with the factor and without it and compare the results. If the results agree reasonably well, then longer or alterative simulations can usually be done with the **Morphologic Acceleration Factor** thus saving time. It is generally not recommended to use a factor larger than 30 to 50, and values between but not equal to 0 and 1. The **Morphologic Acceleration Factor** can be verified by reducing its value (e.g. by a factor of 2) while also increasing the simulation time by the same factor and verifying the simulation results do not significantly change.

Since, the **Morphologic Acceleration Factor** is applied to the bed exchange rates, the approach does not change total-load transport rates or concentrations. In addition, the approach is not locally mass conservative but approximately globally conservative.

Finally, it is important to emphasis that the **Morphologic Acceleration Factor** should NOT be used as a calibration parameter. It should be used carefully and validated to make sure the results are not sensitive to the **Morphologic Acceleration Factor**. When used carefully the **Morphologic Acceleration Factor** can be a powerful and useful tool in numerical studies.

Base Bed-Slope Coefficient

The **Base Bed-Slope Coefficient** specifies the maximum value of the bed-slope coefficient. The coefficient is then reduced based on the skin and critical shear stresses. As the ratio between the skin and critical shear stress increases bed-load particles are less influenced by the bed slope. The coefficient is used to compute an additional sediment flux in the downslope direction which is a function of the bed slope, the bedload, and the bed-slope coefficient. For further details on the formulation, the user is referred to the HEC-RAS 2D Sediment Technical Reference manual (HEC 2020). The **Base Bed-Slope Coefficient** typically has a value between 0.1 and 1. Increasing the coefficient has the effect of smoothing the bathymetry. Measured bed change can be used to calibrate the base bed-slope coefficient. However, its effect is significantly less than the transport formula, transport scaling factors and mobility scaling factor. The **Base Bed-Slope Coefficient** will tend to improve model stability by smoothing out small scale instabilities. However, if the value is too large the numerical scheme can become unstable. In these situations the user can either reduce the computational time step or reduce the value of the **Base Bed-Slope Coefficient**.

Hindered Settling

Hindered settling is the condition in which the settling velocity of particles or flocs is reduced due to a high concentration of particles. Hindered settling is primarily produced by particle collisions and the upward water flow equal to the downward sediment volume flux. Hindered settling occurs to both cohesive and noncohesive particles. However, the hindered settling correction described here only applies to noncohesive particles. The hindered settling of cohesive particles is accounted for in the floc settling method. Currently, the 2D sediment has the option to use the Richardson and Zaki (1954) formula for hindered settling (see figure below). For simplicity the exponent in the Richardson and Zaki (1954) is set to 4.0 and cannot be modified in the user interface.

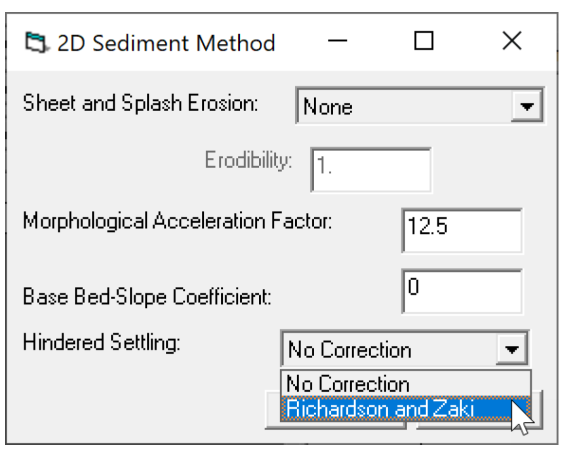


Figure 2-46. Setting the hindered settling method to the Richardson and Zaki (1954) method.

2.2.9 Bed Mixing Options

The **Bed Mixing Options** editor contains both 1D and 2D sediment bed mixing options and other parameters. The editor is opened from the **Sediment Data** editor by going to the **Options** menu and selecting **Bed Mixing Options ...** (see figure below).

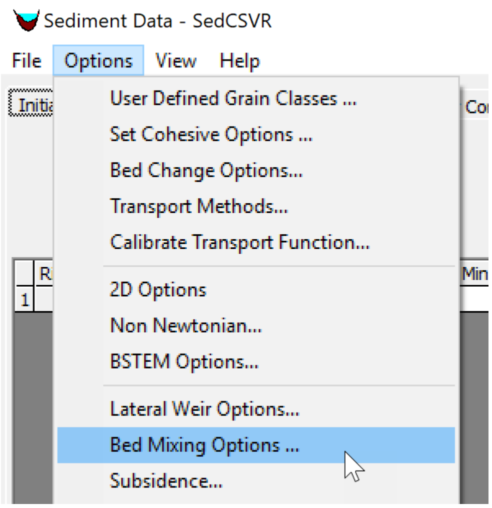


Figure 2-47. Accessing the Bed Mixing Options editor from the Sediment Data editor.

An example of the **Bed Mixing Options** editor is shown in the figure below. The sections which are applicable to 2D sediment are **Hiding Functions** and **Active Layer Options.**

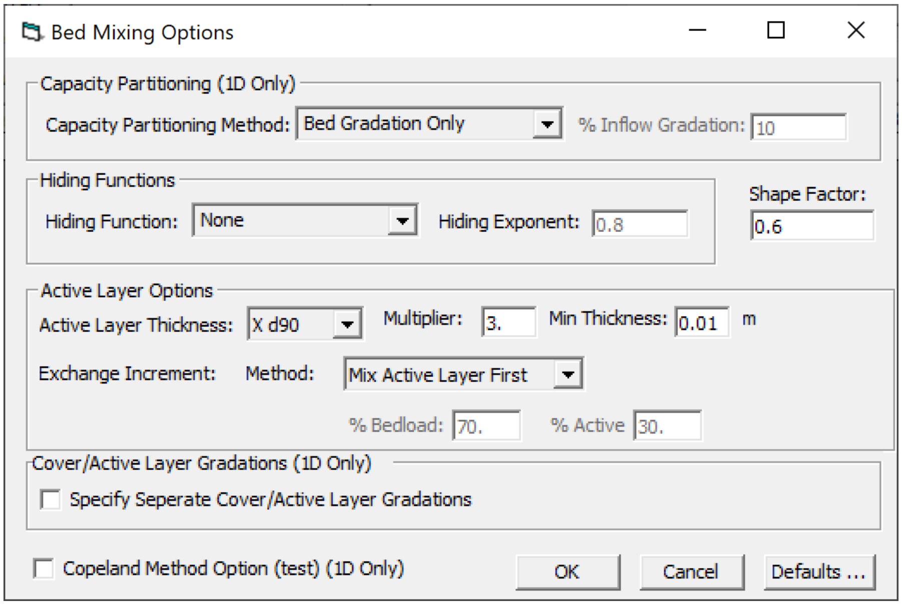


Figure 2-48. Bed Mixing Options editor.

Hiding Functions

In non-uniformly sized sediment beds, smaller particles are hidden from the flow and physically trapped by larger particles whereas larger particles are more exposed to the flow and less impeded to move freely. The hiding (and exposure) function computes a correction to the incipient motion variable such as a shear stress or velocity to account for the hiding and exposure of particles. The hiding functions available in HEC-RAS are:

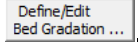
1. None (not correction)
2. Ashida and Michiue (1971)
3. Day (1980)
4. Egiazaroff (1965)
5. Hayashi et al. (1980)
6. Parker et al. (1982)
7. Proffitt and Sutherland (1983)
8. Wilcock and Crowe (2003)
9. Wu et al. (2000)

The hiding and exposure function can have a big impact on the results. Some of the hiding and exposure functions were developed for in conjunction with specific transport potential functions. For example, the Wu et al. (2000) hiding function was developed for use with bed- and suspended-load transport potential functions published in the same paper. Similarly, the Day (1980) and Proffitt and Sutherland (1983) hiding function where developed specifically for the Ackers and White (1973) transport potential formula. Lastly the Wilock and Crowe (2003) hiding function was developed specifically for the Wicock and Crowe formula (Wilcock 2001; Wilcock and Crowe 2003).

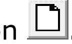
Active Layer Options

Within the **Active Layer Options** section of the **Bed Mixing Options** editor are the input options controlling the active layer thickness and the Exchange Increment Method:

2.2.10 Bed Gradations

Instead of specifying the sediment size distribution and potentially the cohesive sediment properties at every 2D computational cell (and cell subarea), HEC-RAS uses a template concept similar to that of the **Channel Modification Editor**. In HEC-RAS a **Bed Gradation Template** describes the grain size distribution and cohesive sediment properties of a sediment mixture. **Bed Gradation Template** are first defined in a database and then associated to **Sediment Bed Materials** which are specified at each computational cell within **RAS Mapper**. The **Bed Gradation** editor, is opened from the **Sediment Data** editor by clicking on the button 

. An example grain size distribution in the **Bed Gradation** editor is shown in the figure below.

To create a new **Bed Gradation** the user may click on the "New" button . Give it a name (e.g. "Nonuniform"). Enter the gradation information as shown in the figure below.

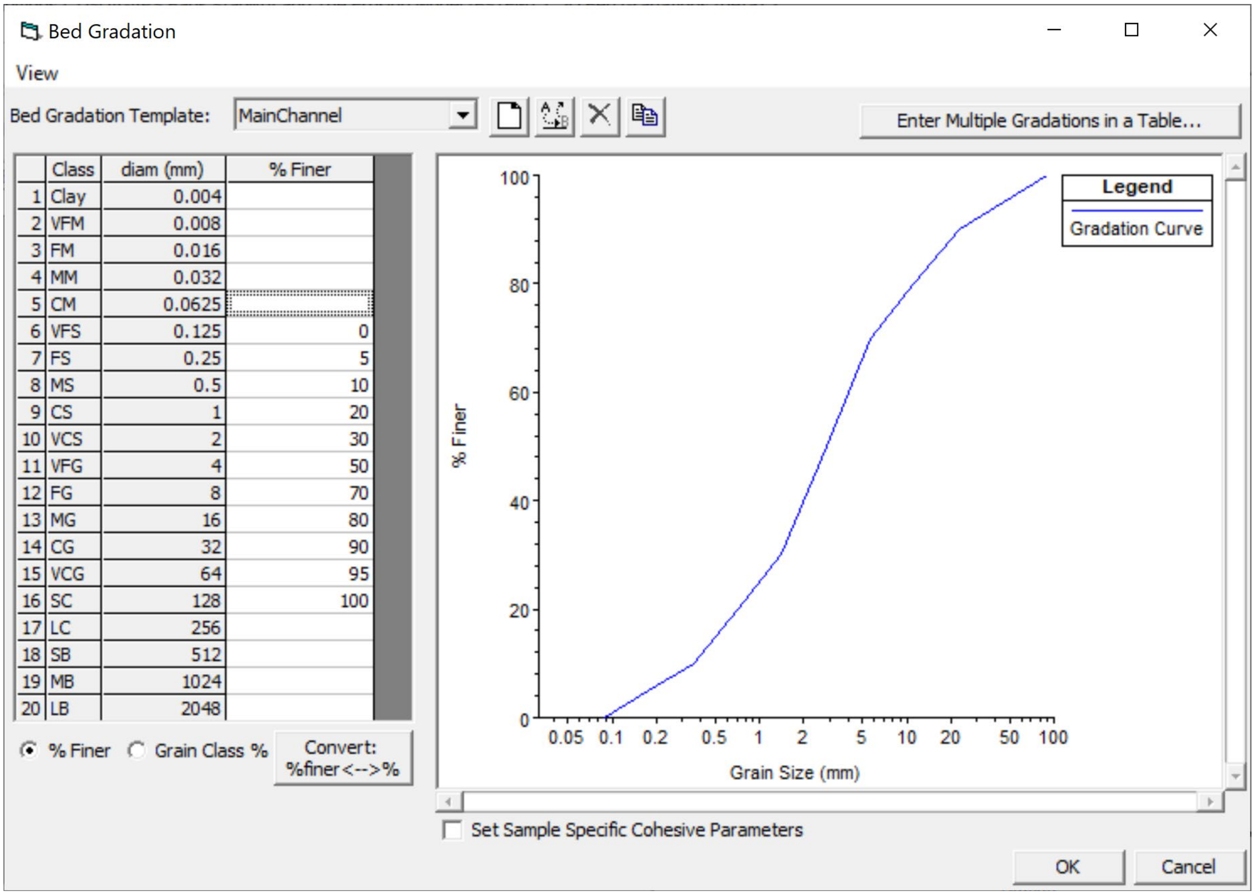
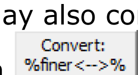


Figure 2-49. Bed Gradation editor with an example grain size distribution.

The user may enter the size distribution as percent finer values or grain class percent values. The current mode is indicated by the radio buttons under the table on the left side of the editor names **% Finer** and **Grain Class %**. The user may also convert the values in the table from one mode to the other by clicking on the button 

.

The 2D sediment transport model will only compute grain classes which are utilized in the initial bed gradations or any boundary conditions. This reduces the computational costs and speeds up the model. Consequently, it is important for the user to be mindful of how many grain classes are utilized in the input. For example, HEC-RAS has 5 cohesive grain classes. Except for the particle fall velocity, all the cohesive grain classes are treated the same, therefore using 5 cohesive grain classes or just 1 will have little impact on the results but a big impact on the computational costs.

Optionally, HEC-RAS allows users to associate bulk bed properties with bed gradations. More specifically, the sediment cohesive properties can be specified for each bed gradation. This option is activated by selecting the checkbox at the bottom of the **Bed Gradation** editor labeled **Set Sample Specific Cohesive Parameters** (see figure below).

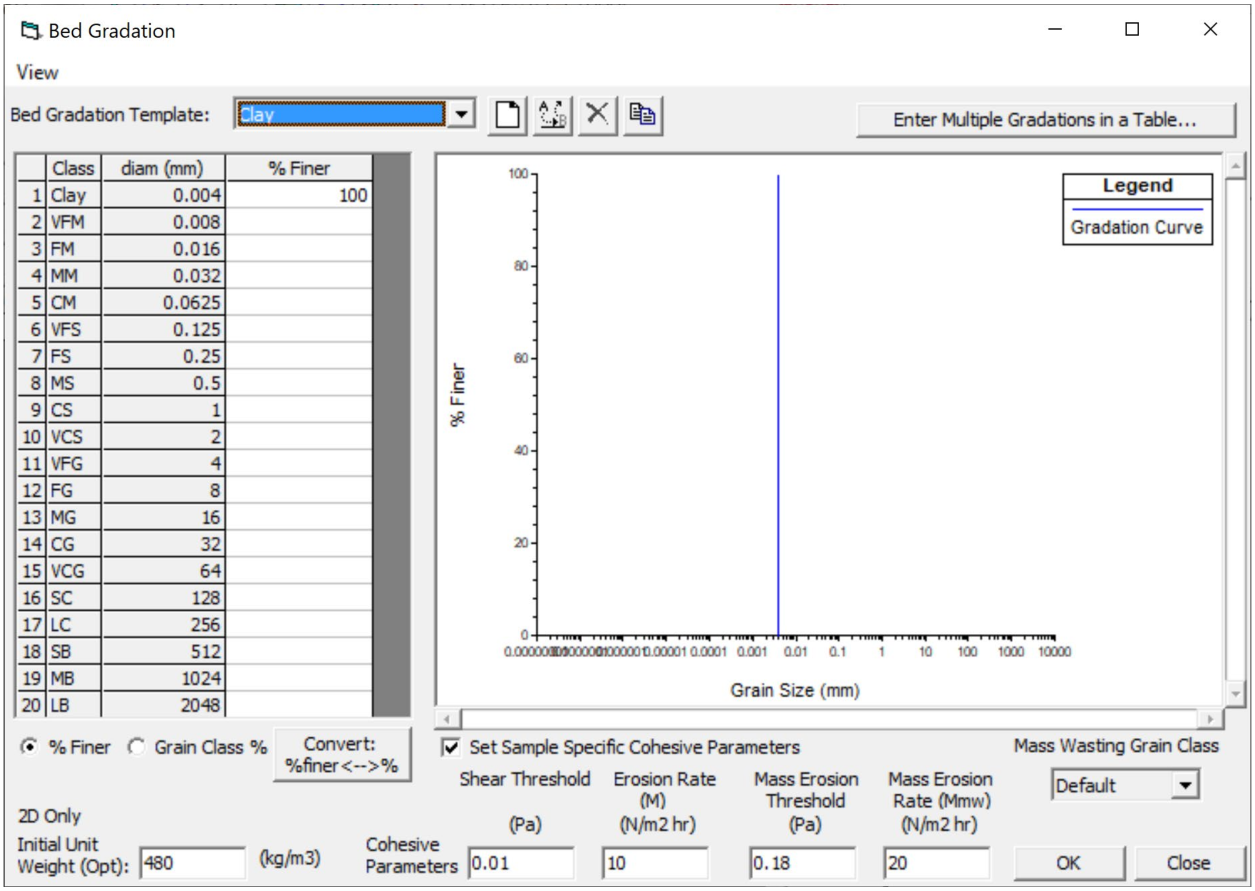
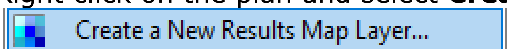


Figure 2-50. Setting sample specific cohesive parameters in the Bed Gradation editor.

2.3 Viewing Sediment Results in RAS Mapper

HEC-RAS and RAS Mapper do not write sediment results by default. The default results include Depth, Velocity, and Water Surface Elevation (WSE). Users must add sediment results to the **Results** tab like they would add any other hydraulic paramters.

Expand the **Results** node in the RAS Mapper tree. Each simulated plan has a node under **Results**. Right click on the plan and select **Create a New RAS Map Layer** to add variables. 

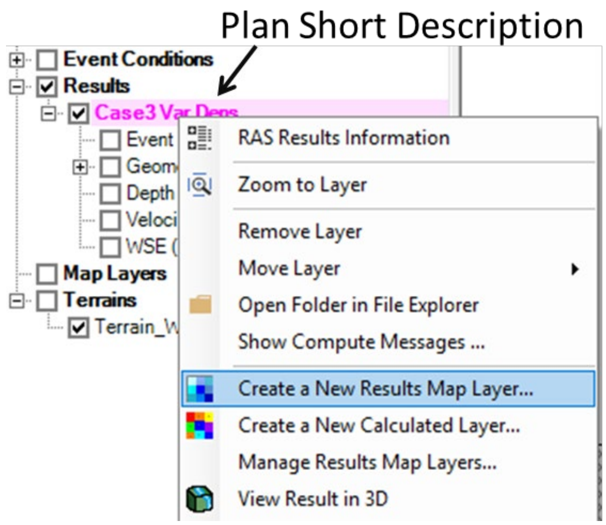


Figure 2-51. Right click on the Plan Description under Results and Select Create a New Results Map Layer to add Sediment results (or non-default hydraulic results).

The **Results Map Parameters** editor has two main **Map Types**: Hydraulics and Sediment. Expand the **Sediment** tree in the left pane of the editor to see the available sediment parameters. The figure below includes the default sediment results avialble. Select additional 2D sediment results by selecting **Customized Variables** in the **Sediment Output Options** menu.

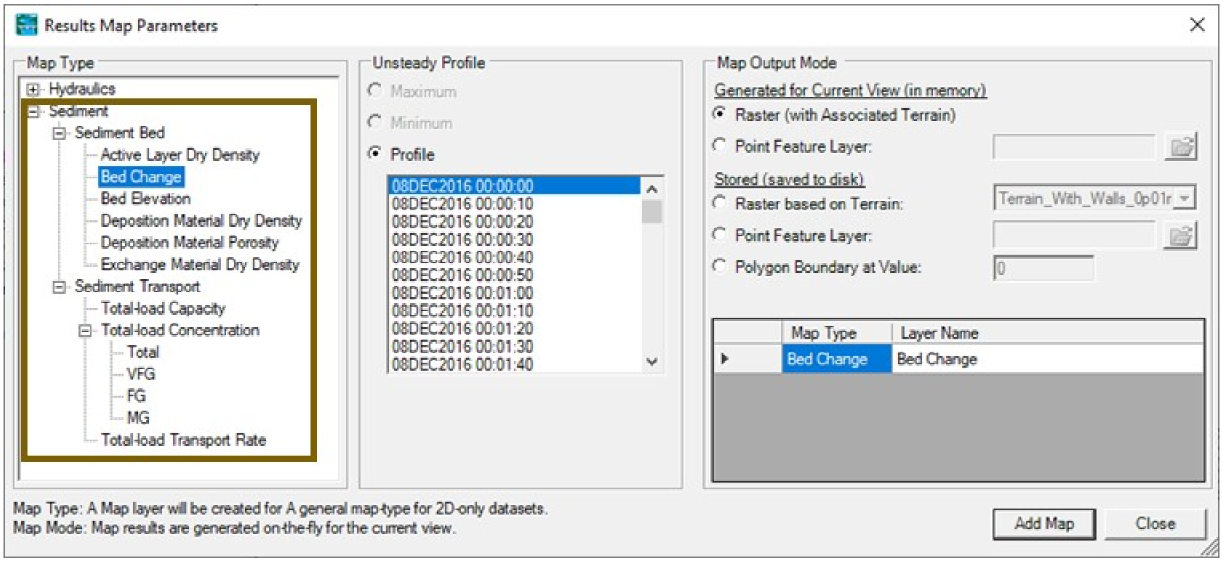


Figure 2-52. Two types of sediment results (Bed and Transport) in the Results Map Parameter editor.

2D sediment maps fall into two main catagories: **Sediment Bed Maps** and **Sediment Transport** Maps. Sediment Bed maps include results like bed change, bed elevation, bed gradation, and other bed properties. Sediment Transport includes results like concentration, capacity, and other results dynamic, water column or flux results. Any results that HEC-RAS also computes by grain class will also include an expandable tree of results (like Total-load Concentration in the example above). Select the variable node (e.g. Total-load Concentraiton in the example above) to add the Total and all the grain classes to RAS Mapper. Or, click on one of the sub nodes (e.g. Total, VFG, MG) to add only the total or only one grain class at at time. In the example bleow the user added **Bed Change** and all of the **Total-load Concentration** results but is only diplaying the Fine Gravel Concentration (FG).

Simply clicking the checkbox to turn sediment results on often does not display any results because sediment reuluts are often not initialized in the first time step.

Use the animation bar to view results through time. 

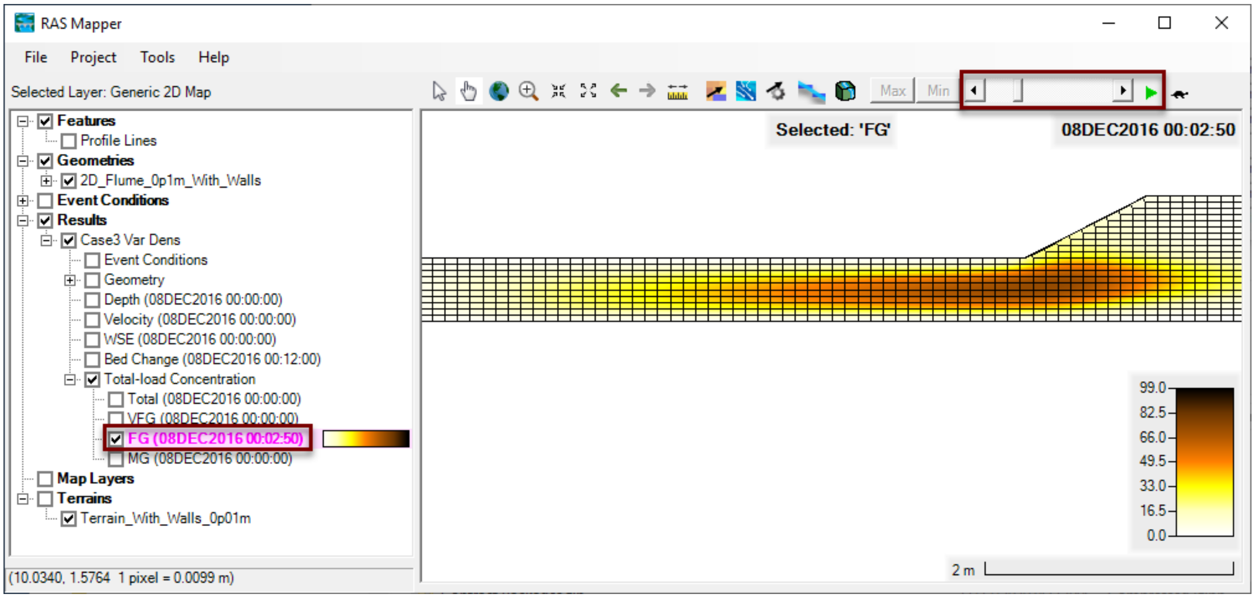
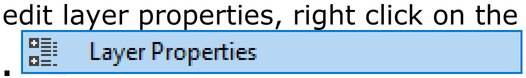


Figure 2-53. Example use of the animation bar to view sediment concentrations in time.

HEC-RAS 6.0 cannot plot cell face results yet.

Modeling Note – Subgrid Visualiation - Because the 2D model updates the bed on the subgrid scale but RAS Mapper does not display subgrid results yet, RAS Mapper will map average results over the wet, dry, or total cell. "Wet" cell results will average the bed properties and bed change properties from the sub-grid portions of the cell below the computed water surface elevation and "dry" results plot the sub-grid results for the cell above the computed water surface. Sediment bed results that are not specified as wet or dry average results ove the whole cell.

After adding the map or maps, **Close** the Parameter Selection editor. The selected map(s) should appear under the plan heading in the **Results** node (see Figure below). It is almost always useful to edit the default color ramp to visualize sediment results, and there are some standard practices for some variables. To edit layer properties, right click on the map and select **Layer Properties** (see figure below). 

This will launch the **Layer Properties** editor (see figure below). To edit the color ramp press the **Edit** button under **Surface**.

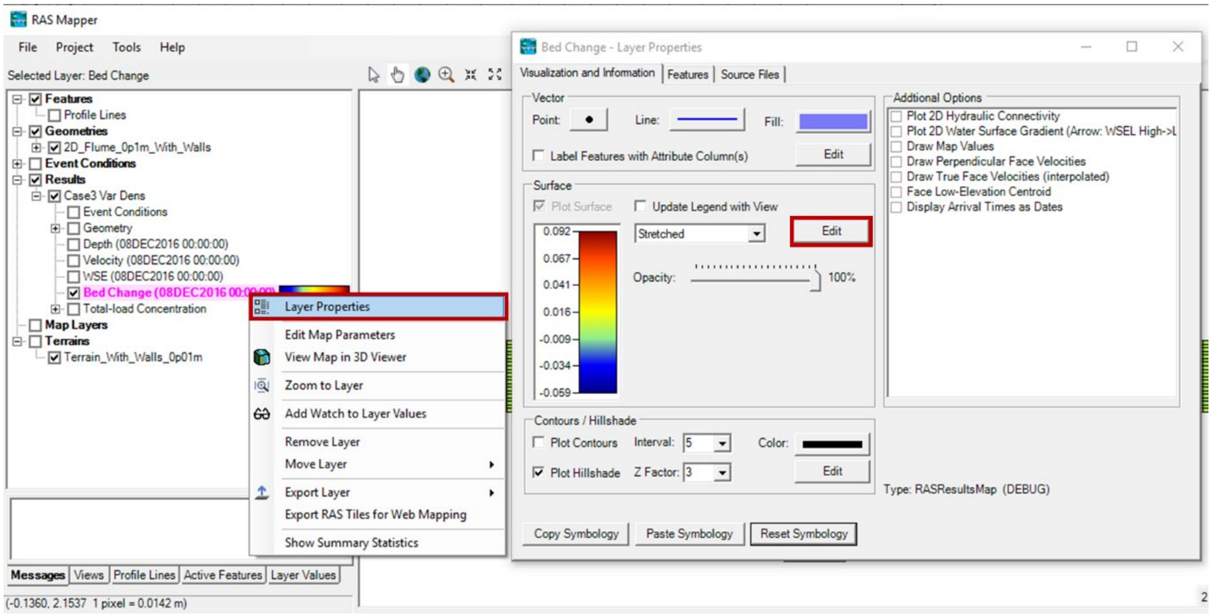


Figure 2-54. To edit the color ramp and display properties of the seidment maps, right click on the map and select **Layer Properties**. Then Click **Edit** under the **Surface** menu.

RAS Mapper includes a standard **Bed Change** color ramp designed to display this common sediment result map (see figure below). However, this display works best if it is symetrical, where white is "no/minor change" and aggredation and degredation get their own colors. To make bed change semetrical, turn of the **Use Dataset Min/Max** to make the **Min** and **Max** editable, and then set them both equal to whichever value is larger, making sure to keep the **Min** negative (e.g. if the **Max** in the example below is 0.091 and the **Min** is -0.073, set the **Min** to -0.091 to make the bed change display symetrical).

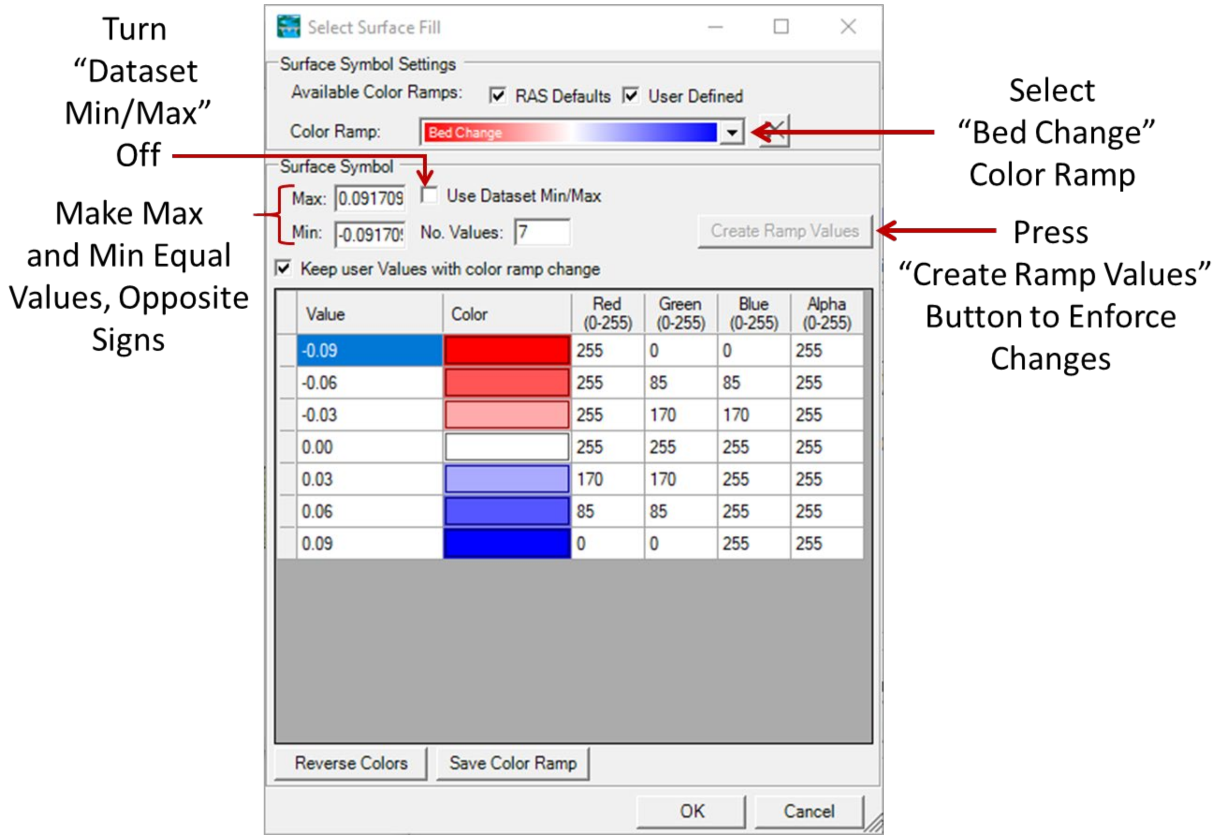
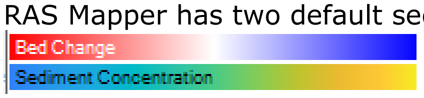


Figure 2-55. Setting the **Max** and **Min** to equal values (whichever abolute value is larger) with opposite signs, centers the **Bed Change** plot, making all depsoitin and erosion the same colors and the range of no change white.

RAS Mapper has two default sediment color maps: Bed Change and Concentration.



Modelers will develop preferred color ramps and viusaliztion approaches. RAS Mapper allows users to add customized color ramps and visualization parameters to the color ramp editor (see figure below). Edit the color ramp to optimize the visualization, then press **Save Color Ramp**. Give the customized color ramp a name, and it will show up at the bottom of the color ramp list for any result in this project.

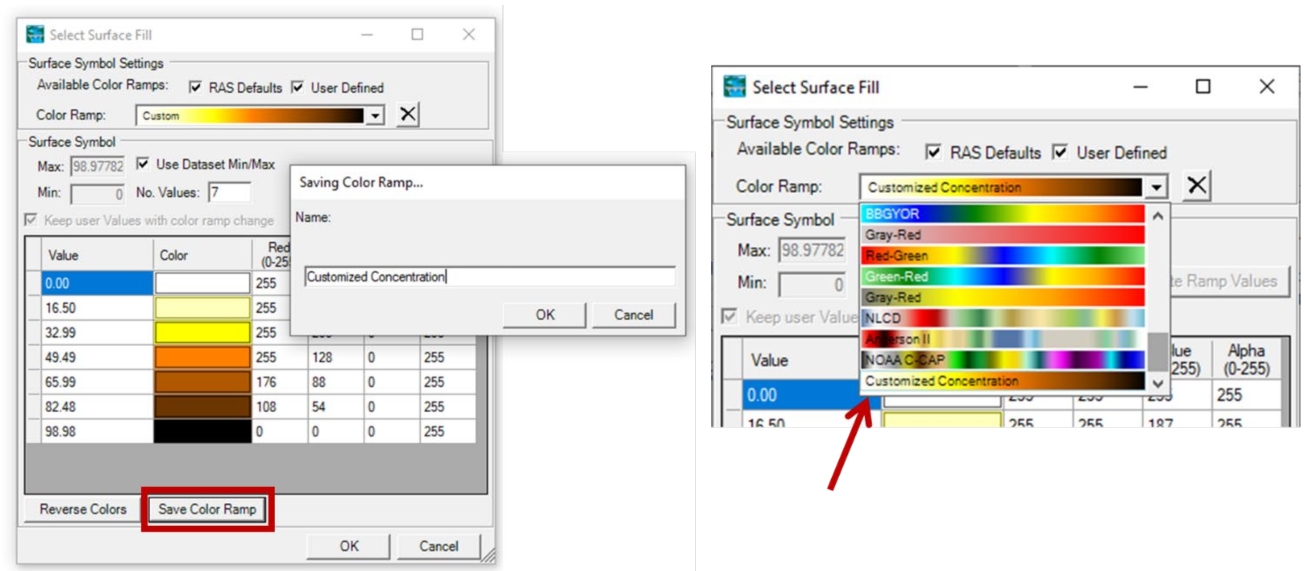
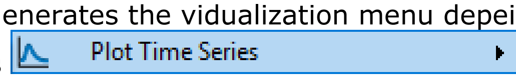


Figure 2-56. Save customized sediment color ramps that persist throughtou the project with the **Save Color Ramp** button.

2.3.1 Plotting 2D Sediment Time Series

Right click on a cell or cell face to visualize sediment time series within the model domain. Right clicking on a model cell or face generates the vidualization menu depeicted in the figure below. Select **Plot Time Series** 

. The **Plot Time Series** option expands into a sub-menu with that includes all of the Results maps (default and added) included in the active plan(s). Only the Results Maps selected (checked) in RAS Mapper are avialble, however. In the example below, WSE, Velocity, Depth, and Courant are not selected (checked) in RAS Mapper, so they are greyed out. But bot Bed Change and Total-Load Concentration are checked, so they are availbe. The example below slected **Cell Bed Change**, requesting the depicted time series at this cell.

If sediment results have multiple grain classes, (e.g. Total-load Concentration below) these variables have additional sub-menus where users can choose if they want to plot the Total result or the result from individual grain classes. Again, only the sub-class results selected in the main RAS Mapper pane will be available.

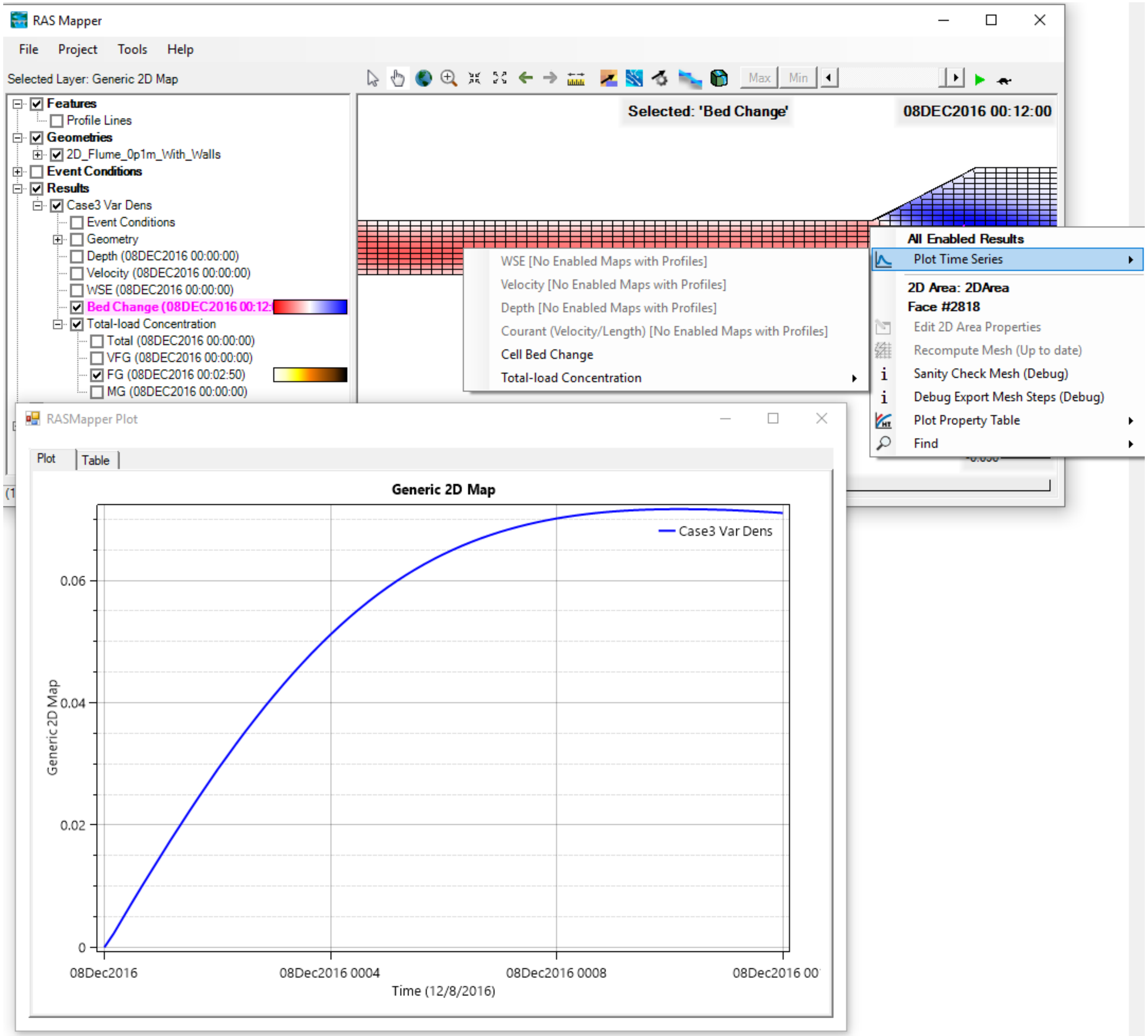


Figure 2-57. View a time series of a sediment (or hydraulic) result by selecting (chekcing) it in the RAS Mapper result tree and then right clicking on the cell. Select **Plot Time Series** and then the result map to launch the time series for that cell or cell face.

2.3.2 Plotting 2D Sediment Transects/Profile Lines

RAS Mapper can also display results for multiple cells along a transect. HEC-RAS callse transects of 2D results **Profile Lines**. To create a results transect Right Click on **Features** menu and select **Create a New Layer→Polyline Layer**. Name the Profile Line and press OK (see figure below).

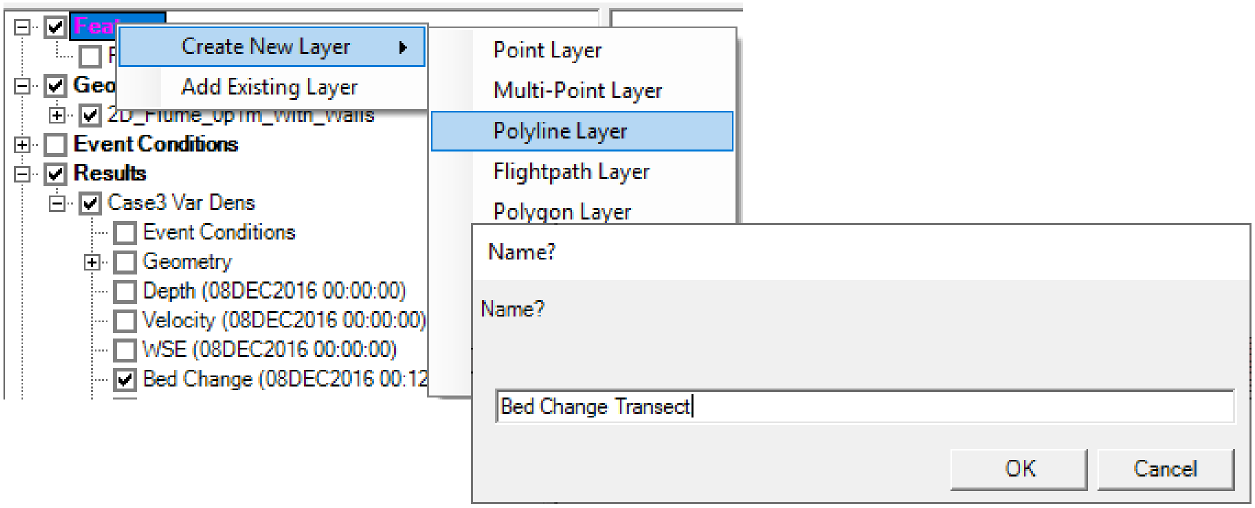
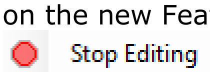


Figure 2-58. Right Click on the **Feature** menu to create a Polyline Layer. Give it a name.

This adds the transect to **Features** and activates tehe drawing tool. Draw the polyline that you would like to visualize results along. Dobule click when it is complete. Then right click on the new Feature (Bed Change Transect in the figure below) and select **Stop Editing**.



Click **Yes** when asked to save.

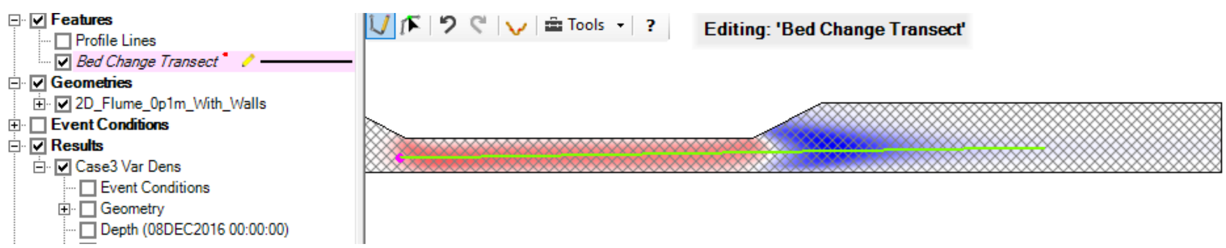


Figure 2-59. Draw the polyline layer along the 2D sediment results transect.

Now, right clicking on this feature, generates a menu similar to the menu RAS Mapper provides when right clicking a cell or cell face. Users can select a profile plot and animate it with time. A profile will plot a longitudinal transect of the seleted result for the displayed time step. As with all of the time series and profile plots in RAS Mapper, press the **Table** tab to retrieve the numerical results behind this plot.

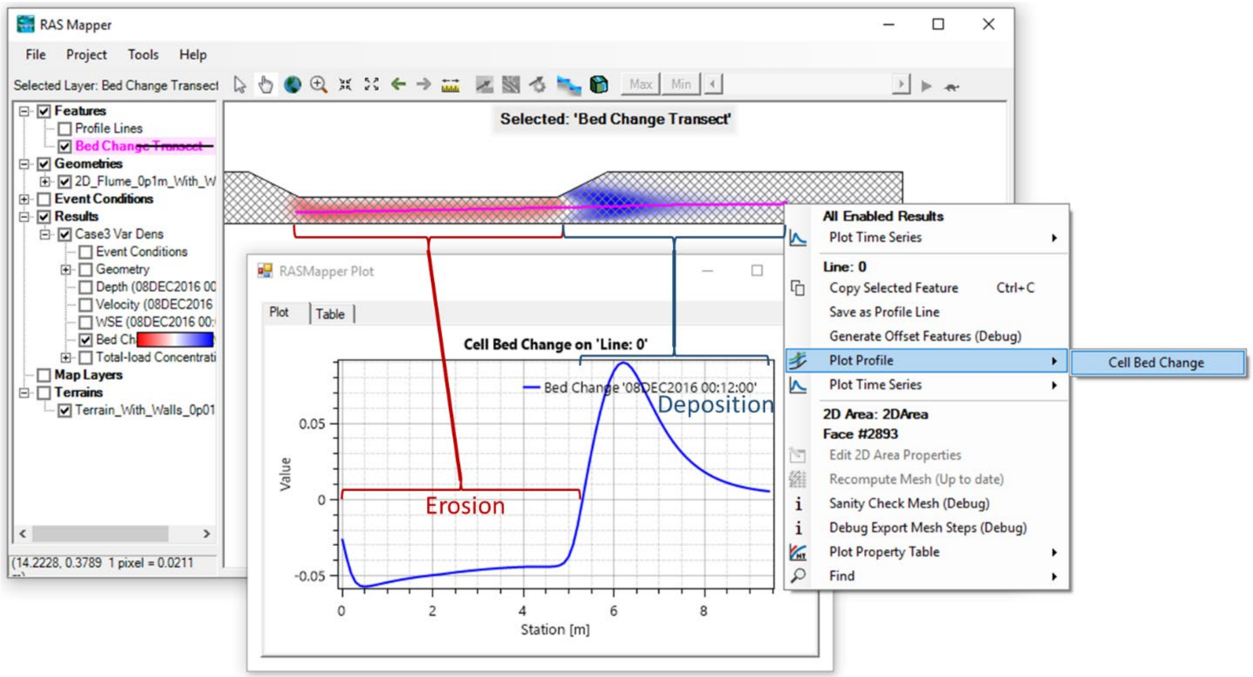


Figure 2-60. Plot a bed change transect with a polyline profile plot.

2.4 Sediment Computation Options and Tolerances

The sediment transport user-specified computational options, parameters, tolerances, and methods are set in the **Sediment Computation Options and Tolerances** editor. To open the editor, open the **Unsteady Flow Analysis** editor and select the **Options** menu and click on the menu item **Sediment Computation Options and Tolerances** (see figure below).

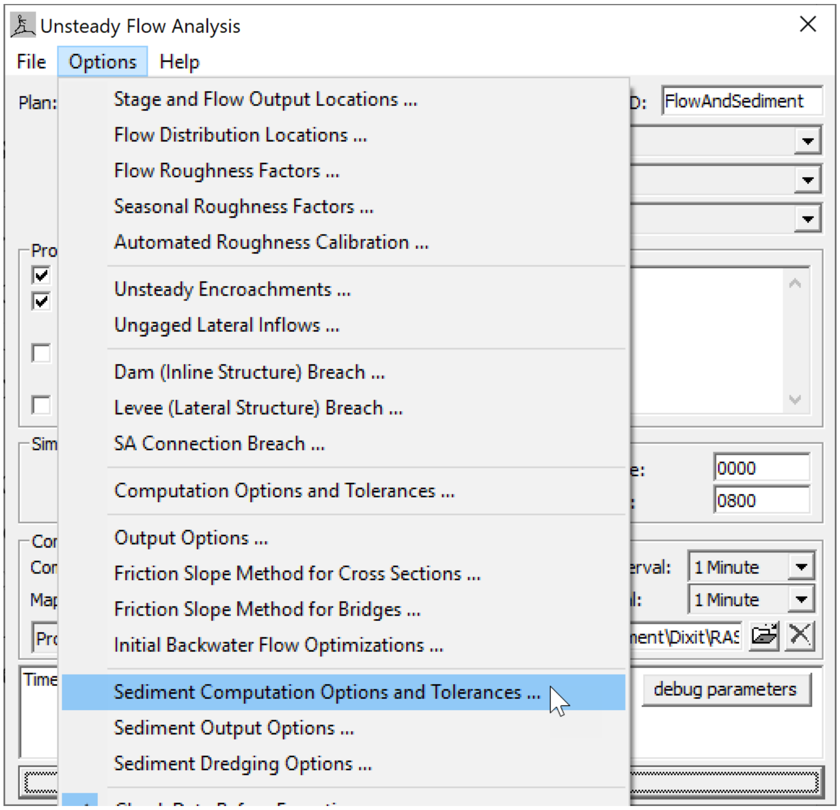


Figure 2-61. Bed Gradation editor with an example grain size distribution.

The **Sediment Computation Options and Tolerances** editor has two tabs: **General** and **2D Computational Options**. These tabs are described below.

2.4.1 Sediment Computation Options and Tollerances

General

The **General** tab of the **Sediment Computation Options and Tolerances** editor contains the 1D computational options but also includes some options which the 1D and 2D sediment models share (see figure below). The 2D sediment transport model uses the **Bed Roughness Predictor**, the **Computation Multiplier**and **Warmup Periods**.

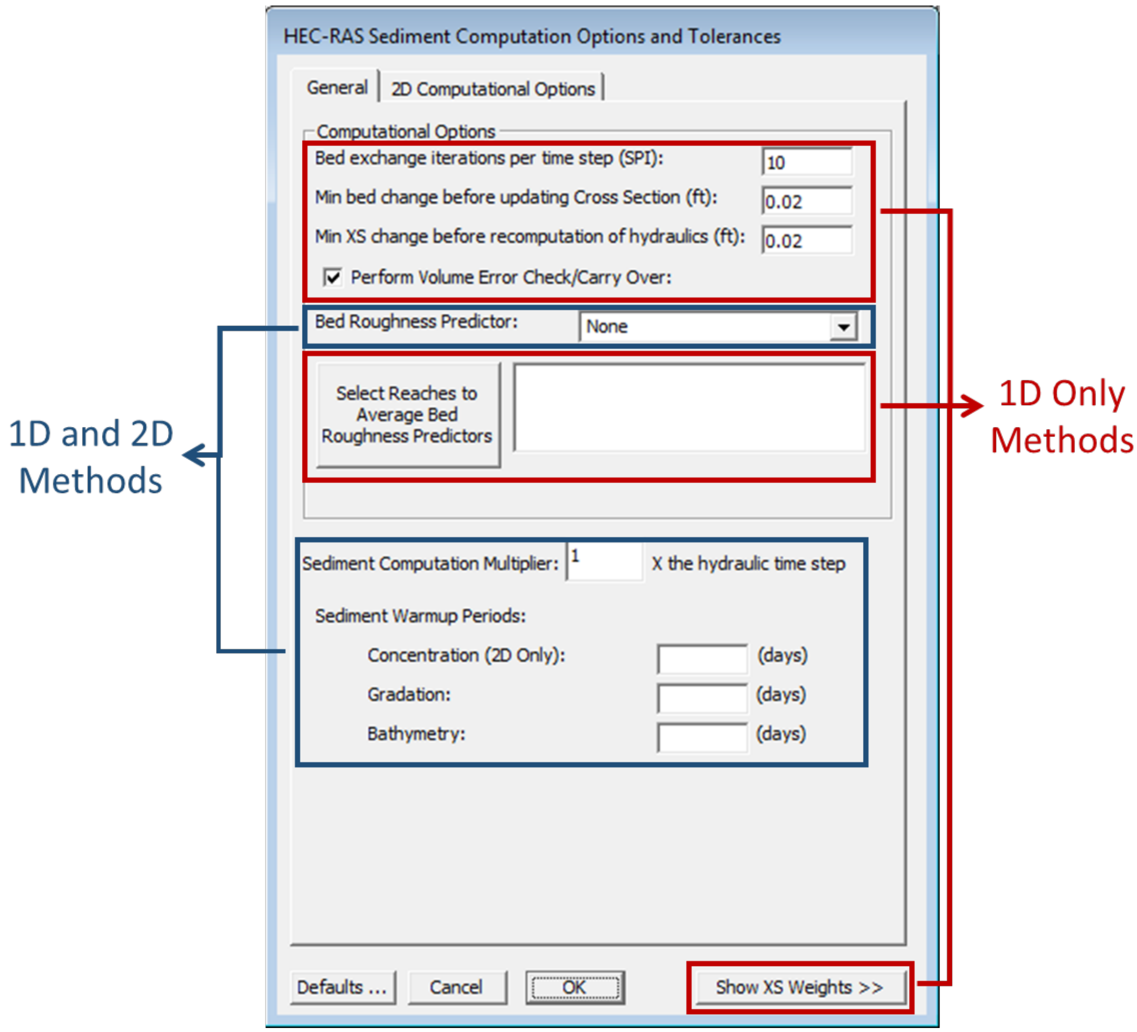


Figure 2-62. General tab of the Sediment Computation Options and Tolerances editor.

Bed Roughness Predictor

The **Bed Roughness Predictor** options include three methods:

1. Limerinos
2. Brownlie
3. Van Rijn

The bed roughness predictor computes bed roughness dynamically based on the hydrodynamics and bed materials. The sediment transport model and hydraulic models use the computed roughness, then update it based on the new hydraulics and bed materials. The 1D model allows users to define sub-reaches to apply the bed roughness predictor, but the 2D model will apply the selected algorithm to the all wet cells.

When using bed-roughness predictor it is recommended to also output the cell bed roughness's and evaluate the computed bed roughness to maker sure results are realistic.

Warmup Periods

Warmup periods are simulation time windows added before the start of the simulation (negative time) during which the boundary conditions are held constant and certain state variables are updated. The **Sediment Warmup Periods** are computed after the unsteady flow **Initial Conditions Time** and before the unsteady flow warmup period. During the **Initial Conditions Time**, the flow and stage boundary conditions are "ramped up" or increased from dry conditions to their initial value. During this period, each 2D area is running separately. The unsteady flow warmup period is used to reach an initial condition for hydraulics when running 1D and 2D flow simulations or with multiple coupled 2D areas. Since 2D sediment does not support coupling of sediment across 1D and 2D or multiple 2D areas, the unsteady flow warmup period should not be used with 2D sediment.

There are three **Sediment Warmup Periods** run in sequence: (1) Concentration, (2) Gradation, and (3) Bathymetry. The start of each warmup period activates a portion of the sediment computations as described in the table below.

Table 2-3. Sediment Warmup Period

Sediment Warmup Period	**Variables Updated**
Concentration	Total-load sediment concentration and all advection-diffusion related variables
Gradation	Grain class fractions, bed layer thickness, and bed variables such bulk densities
Bathymetry	Sediment and flow bed elevations at cells and faces as well as hydraulic property tables

The **Sediment Warmup Periods** are specified at the bottom of the **General** tab of the **Sediment Computation Options and Tolerances** window (see figure below). The **Sediment Warmup Periods** are optional and any field left empty is assigned a zero value.

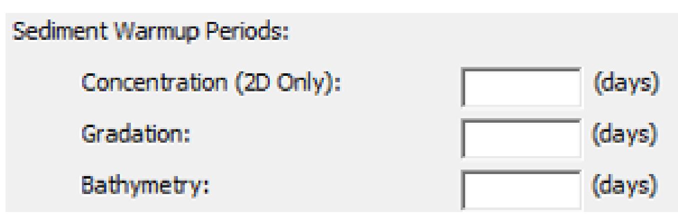


Figure 2-63. Specifying the warmup periods for 2D simulations.

During the **Concentration Warmup Period**, the 2D total-load advection-diffusion equation is solved for sediment concentrations while holding all boundary conditions, bed gradations, and bathymetry constant. The Concentration Warmup is only available in 2D sediment transport, and avoids the initial erosion associated with starting a model with clear water throughout the domain.

After the concentration warmup, the 2D model warms up the bed gradations. Starting with the cell concentrations at the end of the concentration warmup, HEC-RAS will run the unsteady, 2D, sediment model with constant flow, stage, and sediment boundary condtions (those associated with the first time step in the simulation window). During the gradation warmup, HEC-RAS will *not* adjust the bed, the elevation-volume curves for the cells, or the elevation-area curves of the cell faces. It will only ajust the bed gradations, allowing them to fine or (more often) coarsen in response to the flow field. The 2D sediment model will also begin to develop vertical gradational stratigraphy in this warmup period, even bed layers were not initially specified.

After the Gradation warmup, the 2D model will warmup the bathymetry. In this warmup period, the model will still hold they hydraulic and sediment boundary conditions constant, but will allow the bed elevations, and the elevation-volume/elevation-area curves to adjust in response to transport. This phase will tend to fill local depresions, scour local raised areas, plane out bed forms, highlight problems with the terrain, and, generally smooth the terrain.

2D Computational Options

The **2D Computational Options** tab of the **Sediment Computation Options and Tolerances** editor contains the computational options which are utilized for 2D sediment transport (see figure below). The editor has options and parameters related to the subgrid erosion and deposition calculation methods, the advection scheme used in the transport solver, the matrix solver, outer loop convergence tolerances,

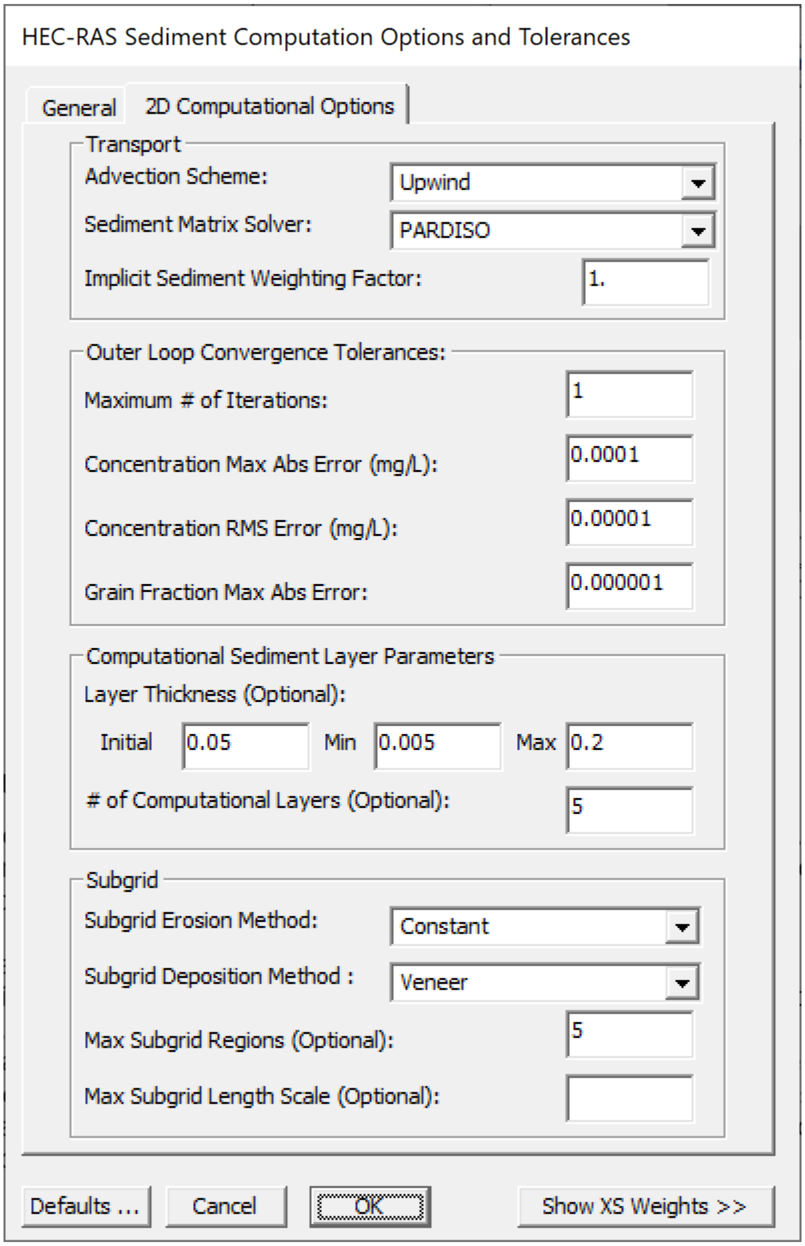


Figure 2-64. Specifying the warmup method for 2D simulations.

Subgrid Erosion and Deposition Methods

One of the key features of HEC-RAS 2D is the subgrid modeling. HEC-RAS 2D sediment has several methods for computing the subgrid erosion and deposition with different levels of complexity and computational requirements.

The erosion rate is computed as the erosion potential times the bed availability (grain fractions). Therefore, if the subgrid bed gradations vary, the subgrid erosion rates will also vary. However, the subgrid erosion potential may be calculated with one of four methods available (see table below).

Table 2-4. Summary of subcell erosion potential approaches.

Method	Depth-Weighting	Bed Properties	Hydraulics
Constant	None	Cell Wet-Average	Cell Wet-Average
Depth-Weighted	Yes	Cell Wet-Average	Cell Wet-Average
Variable Bed	None	Subcell	Cell Wet-Average
Full Subgrid	None	Subcell	Subcell

The **Constant** erosion method is the simplest and most computationally efficient. For every cell, a single erosion potential is computed using wet-area averaged hydraulics, and bed properties. The bed properties include erosion coefficients, roughness, and grain size distribution, etc. The **Depth-Weighted** erosion method also computes a single erosion potential for every cell but applies a depth-weighting to compute the subgrid erosion potentials. Therefore, the **Depth-Weighted** method uses averaged bed and hydraulics to compute a cell erosion potential, but which is then weighted using the water depths to compute the subgrid erosion potentials. Again, subgrid erosion rates always take into account the subgrid grain fractions (material availability). The **Depth-Weighted** method is only slightly more computationally expensive than the **Constant** method. The **Variable Bed** erosion method does not perform depth-weighting but computes subgrid erosion potentials utilizing the subgrid bed properties. The **Variable Bed** method utilizes average hydraulic variables for the wetted area of the cell. The **Full Subgrid** erosion method does not perform depth-weighting but computes subgrid erosion potentials utilizing the subgrid bed properties and hydraulics. The method requires estimating subgrid hydraulic variables such as current velocities, shear stresses, shear velocities, depths, etc. depending on the transport potential formula utilized. The **Full Subgrid** method is the most computationally expensive of all the methods and will generally lead to the largest variations in subgrid erosion compared to the other methods. All of the erosion methods assume that a constant adaptation coefficient within the cell.

HEC-RAS 2D sediment has three subgrid deposition methods (see table below). All the deposition methods assume that the sediment concentration and adaptation coefficient are constant within a cell. The first is the **Veneer** method. The **Veneer** method applies a spatially constant deposition rate over the wet portion of the cell. The **Veneer** method is the simplest and most computationally efficient of the methods. The **Veneer** deposition method is analogous to the **Veneer** method utilized in HEC-RAS 1D sediment transport. The **Depth-Weighted** deposition method is similar to the **Reservoir** method in HEC-RAS 1D sediment transport. The **Capacity-Weighted** deposition method is similar to the **Capacity-Weighted** erosion method.

Table 2-5. Summary of subcell deposition approaches.

Method	Depth-Weighting	Capacity-Weighting
Veneer (Constant)	None	None
Depth-Weighted	Yes	None

Capacity-Weighted	None	Yes

Advection Scheme

HEC-RAS 2D sediment transport has the option to choose between four advection schemes:

1. Upwind
2. Exponential
3. Minmod
4. Harmonic

The selected advection schemes are designed to off the use a wide range of options. The **Upwind** and **Exponential** schemes are first-order difference schemes (Patankar 1980). The schemes are linear and therefore have the benefit of not requiring additional outer loop iterations. In addition, difference schemes are relatively simple, and provide smooth bounded solutions. The **Exponential** scheme is based on the analytical solution of the steady 1D advection-diffusion equation (without sources and sinks) and is less diffusive than the **Upwind** scheme. However, when the horizontal mixing is turned off, the **Exponential** scheme reduces to the **Upwind** scheme.

The **Minmod** and **Harmonic** schemes are high-resolution Total Variance Diminishing (TVD) schemes (Harten 1983). High-resolution TVD schemes allow for second order or higher accuracy in smooth and first-order accuracy in sharply varying regions without producing spurious oscillations (bounded solutions). The TVD schemes are implemented here using a flux-limiter formulation and a deferred correction approach which requires outer loop iterations to converge. The **Minmod** scheme has good convergence characteristics but is the most diffusive of the two TVD schemes. The **Harmonic** scheme is less diffusive, produces good convergence characteristics in implicit schemes, and is equivalent to the Hybrid Linear/Parabolic Approximation (HLPA) scheme of Zhu (1992).

Matrix Solvers

HEC-RAS 2D Sediment Transport solves an implicit Advection-Diffusion (transport) equation for the fractional total-load concentrations. The discretization produces a linear system of equations which may be represented by a sparse-matrix problem. The sparse matrix solver is an important component of the computational options because a large portion of the computational time can be spent solving the sparse matrices for each grain class transport equation. HEC-RAS has three options for the matrix solver:

1. PARDISO
2. FGMRES-SOR
3. FGMRES-ILU0

The **PARDISO** solver is a high-performance, robust, memory efficient and easy to use solver for solving large sparse symmetric and non-symmetric linear systems of equations on shared memory and distributed-memory architectures. Here the Intel Math Kernel Libraries (MKL) **PARDISO** solver is utilized. The solver utilizes a combination of parallel left- and right-looking supernode pivoting techniques to improve its factorization process (Schenk et al. 2004; Schenk et al. 2011).

Iterative solvers require an initial guess to the solution. Iterative solvers generally require less memory for because unlike with direct solvers, the structure of the matrix does not change during the iteration process. In addition, iterative solvers utilize matrix-vector multiplications which can be efficiently parallelized. The main drawback of iterative solvers is that the rate of convergence depends greatly on the condition number of the coefficient matrix. For poorly conditioned matrices, the iterative solver may not converge at all. Therefore, the efficiency of iterative solvers greatly depends on the size and condition number of the coefficient matrix.

Iterative solvers may be classified into stationary and projection methods. In stationary methods the solution for each iteration is expressed as finding a stationary point for the iteration. The number of operations for iteration step for stationary methods is always the same. Stationary methods work well for small problems but generally converge slowly for large problems. Projection methods extract an approximate solution from a subspace. Generally, projection methods have better convergence properties than stationary methods but because each iteration is generally more computationally demanding than stationary methods, they tend to be more efficient for medium to large systems of equations. The main disadvantage of iterative solvers is their lack of robustness.

HEC-RAS 2D sediment has the option of two iterative solvers: **FGMRES-SOR** and **FGMRES-ILU0**. The first part FGMRES refers to the matrix solver while second parts SOR and ILU0 refer to the preconditioner utilized. FGMRES (Flexible Generalized Minimal RESidual) is a projection method which is applicable to coefficient matrices which are non-symmetric indefinite (Saad, 1993). The "flexible" variant of the Generalized Minimal RESidual method (GMRES) allows for the preconditioner to vary from iteration to iteration. The flexible variant requires more memory than the standard version, but the extra memory is worth the cost since any iterative method can be used as a preconditioner. For example, the SOR could be used as a preconditioner with different relaxation parameter values each time it is applied. The FGMRES (and GMRES) method becomes impractical for large number of iterations because memory and computational requirements increase linearly as the number iterations increases. To remediate this the algorithm is restarted after iterations with the last solution used as an initial guess to the new iterative solution. This procedure is repeated until convergence is achieved. The FGMRES solver with restart is often referred to as FGMRES(m) where m is the restart parameter. However, here the shorter name FGMRES is used for simplicity. If m is too small, the solver may converge too slowly are even fail completely. A value of m that is larger than necessary involves excessive work and memory storage. Typical restart values are between 5 and 20. Here m is set to 10 which works well for the most practical applications.

The Successive-Over-Relaxation (SOR) is a stationary iteration method based on the Gauss-Seidel (GS) method. When $\omega = 1$, the SOR method reduces to the Gauss-Seidel method. In addition, for $\omega < 1$, the method technically applies under-relaxation and not over-relaxation. However, for simplicity and convenience the method is referred to as SOR for all values of ω. Kahan (1958) showed that the SOR method is unstable for relaxation values outside of $0 < \omega < 2$. The optimal value of the relaxation factor is problem specific. The SOR method is guaranteed to converge if either (1) if $0 < \omega < 2$, and (2) the matrix is symmetric positive-definite, or strictly or irreducibly diagonally dominant. However, the method sometimes converges even if the second condition is not satisfied. For simplicity, the relaxation parameter is set to 1.3 here and cannot be adjusted by the user. The value of 1.3 has been found to work reasonably well for a wide range of problems. A simple parallel version of the SOR is utilized here which is referred to as the Asynchronous SOR (ASOR) which uses new values of unknowns in each iteration/updates as soon as they are computed in the same iteration (see Chazan and Miranker 1969; Leone and Mangasarian 1988). The ASOR is part of a class of iterative solvers known as chaotic relaxation methods. Since the order of relaxation is unconstrained, synchronization is avoided at all stages of the solution. However, the convergence behavior can be slightly different for different number of threads. The ASOR solver has been parallelized with OpenMP.

The SOR preconditioner is based on the SOR solver except that no convergence checking is done during the iteration process (DeLong 1997). This is done for simplicity and to avoid additional computations associated with the determining the convergence status. The SOR preconditioner is utilized for non-symmetric matrices. The SOR preconditioner matrix is given by

The ILU0 (Incomplete Lower Upper with Zero Infilling) is part of a large class of preconditioners which utilize incomplete factorizations of the coefficient matrix. The effectiveness of the preconditioner depends on how well the sparse matrix by factored into lower and upper sparse matrices. ILU0 is one of the most common types of incomplete factorizations. In this factorization, all non-zero values of the exact factorization which are located in zero value positions are discarded. The advantage of the ILU0 preconditioner is that it preserves the structure of the original matrix. Another advantage of ILU0 versus other similar factorizations is that it does not require specifying additional tolerances and settings.

Outer Loop Convergence Options

The outer loop refers to the loop in which the transport equations are coupled to the bed change and sorting equations whereas the inner loop is the iterative solver loop. The outer loop is also necessary for updating the deferred corrections from the high-resolution advection schemes. If a direct sparse matrix solver is utilized, there is no inner loop. The maximum number of outer loop iterations may be set by user (see figure below). The maximum number of outer loop iterations is a compromise between computational efficiency and accuracy. If the sediment model is iterating every time step and going to the maximum number of iterations, this is an indication, the either the time step is too big or the convergence tolerances have been set too small. Outer loop convergence is monitored by change in the sediment concentrations and active layer bed fractions between outer loop iterations. The convergence of the fractional total-load sediment concentrations is assessed by means of two tolerances. The first is the maximum value of the absolute differences (errors) in concentrations between outer loop iterations. The second is the root-mean-square of the differences (errors) between outer loop iterations. For the first iteration, the error is approximated by comparing the current concentrations with the previous time step values. The convergence of the active bed grain fractions is assessed by means of a maximum absolute error tolerance. This approach works well for both constant density and variable density simulations.

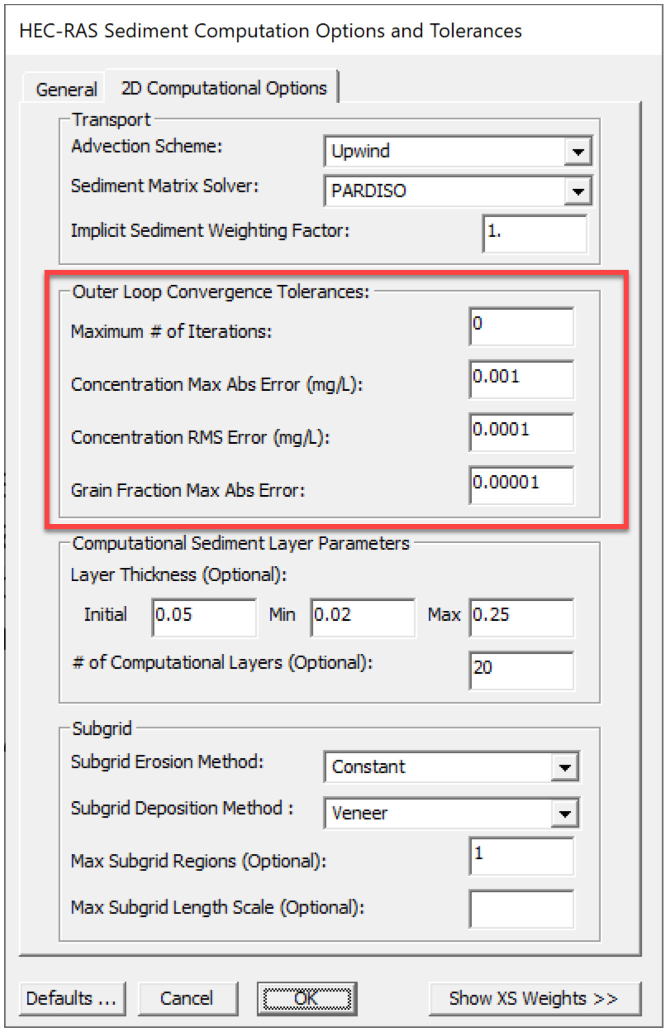


Figure 2-65. Outer loop Convergence Parameters.

Whenever, the sediment concentrations or active layer grain fractions do not converge or reach the maximum number of iterations, a message is printed to the log file. In addition, the convergence status is written to the HDF5 file at the Mapping Output Interval. This log information can be used to optimize the convergence parameters and computational time step.

When simulating **Non-erodible Surfaces**, the active layer grain fractions can vary significantly in a time step and even within a time step (outer-loop iterations). Therefore, it is expected that when simulating **Non-erodible Surfaces** with multiple-grain classes, at least one or two iterations will be needed for the active layer fractions to converge. In fact, even when simulating a single grain class, iterations are still required because for the sediment concentrations to convergence above **Non-erodible Surfaces** because the erosion rates are limited before solving concentrations using an expression which includes an estimate of the deposition rates from the previous iteration.

Computational Sediment Layer Parameters

There are two types of layers in HEC-RAS. The first type is the bed layers which are used to specify the bed gradations and the second is the computational bed layers which are used in the solution of the bed sorting and layering. Specifying initial sediment bed layers is optional. If the user does not specify initial bed layers, a vertically uniform bed composition is assumed, and computational bed layers are created based on the user-specified initial bed layer thickness (see figure below).

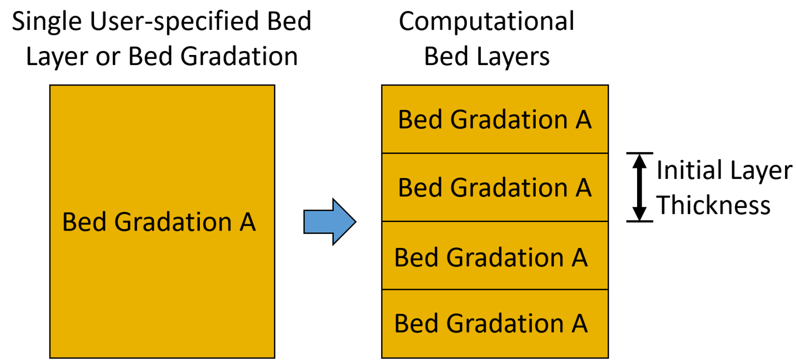


Figure 2-66. Calculation of computational bed layer thickness from a single user-specified initial bed layer or bed gradation.

If the user specifies initial bed layers, these are subdivided (discretized) such that the initial bed layer thickness is equal to or less than then the user-specified initial bed layer thickness (see figure below).

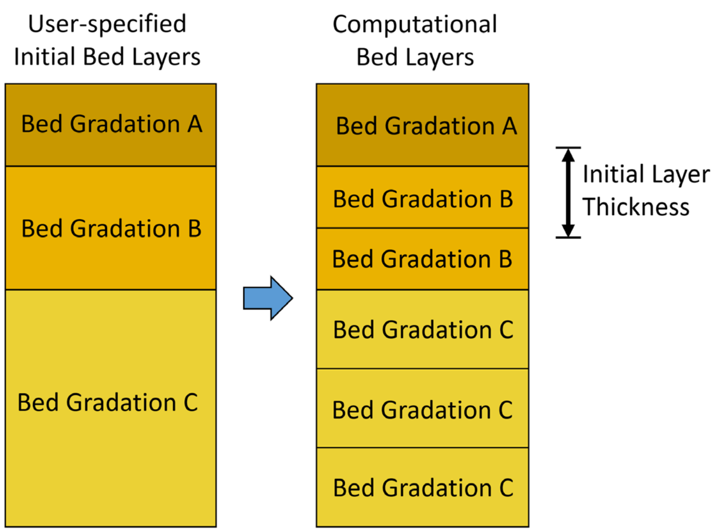


Figure 2-67. Calculation of computational bed layer thickness and composition from user-specified initial bed layers.

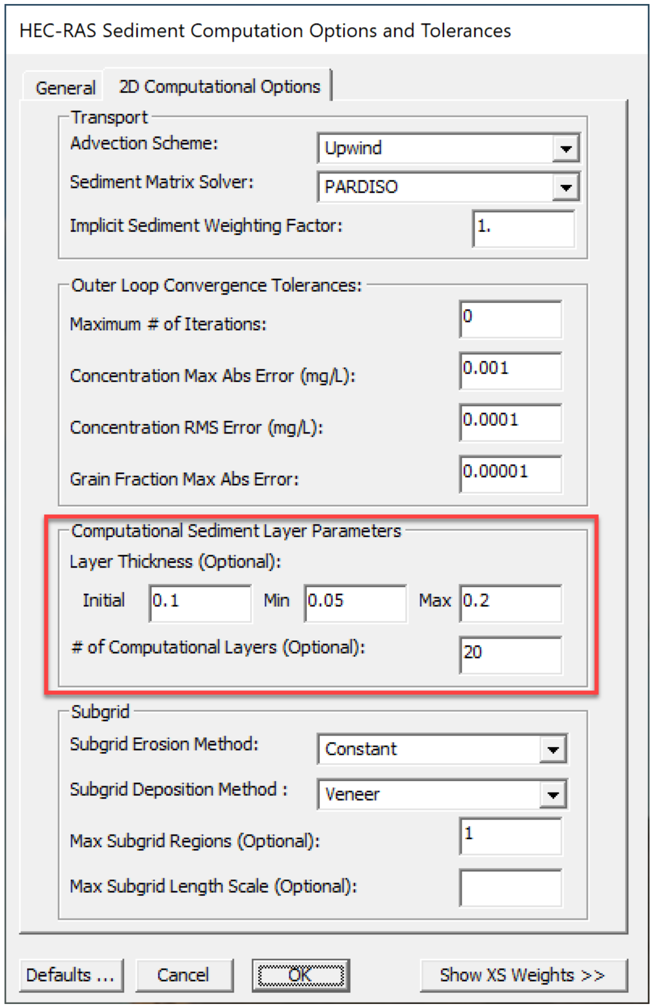


Figure 2-68. Computational Sediment Layer Parameters section in the HEC-RAS Sediment Computation Options and Tolerances editor.

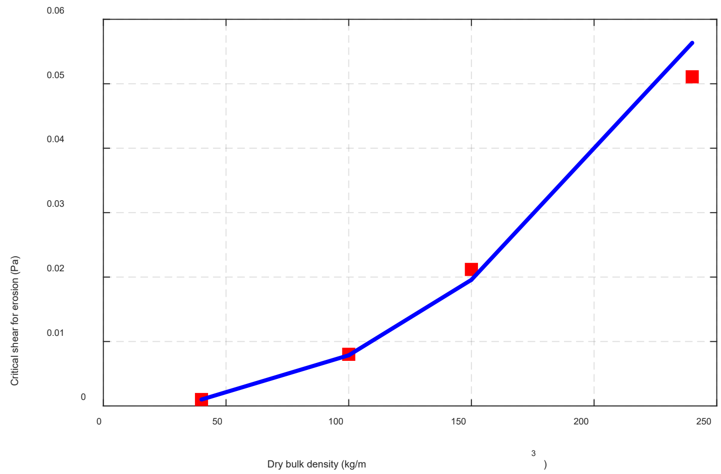


Figure 2-69. Example of a power-law parameterization of the critical shear for erosion as a function of the dry bulk density.

2.5 Sediment Output Options

The sediment output options are entered in the apply named **Sediment Output Options** editor which can be accessed from the **Option | Sediment Output Options...** menu in the **Unsteady Flow Analysis** editor (see figure below).

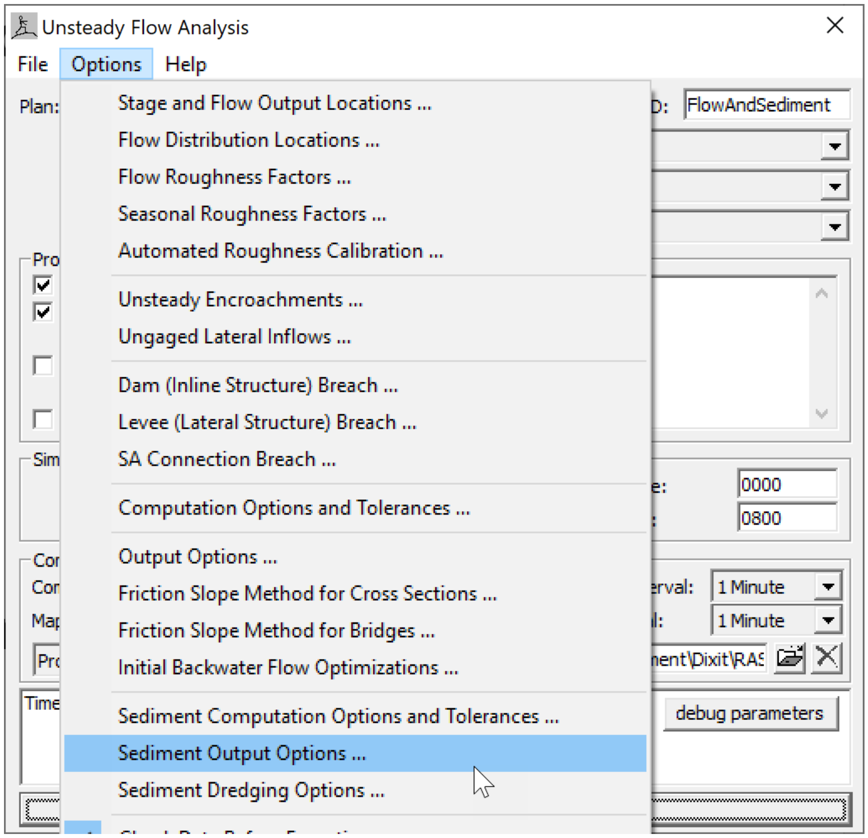


Figure 2-70. Opening the Sediment Output Options editor from the Unsteady Flow Analysis editor.

The **Sediment Output Options** editor allows the user to specify which variables to output and at what frequency.

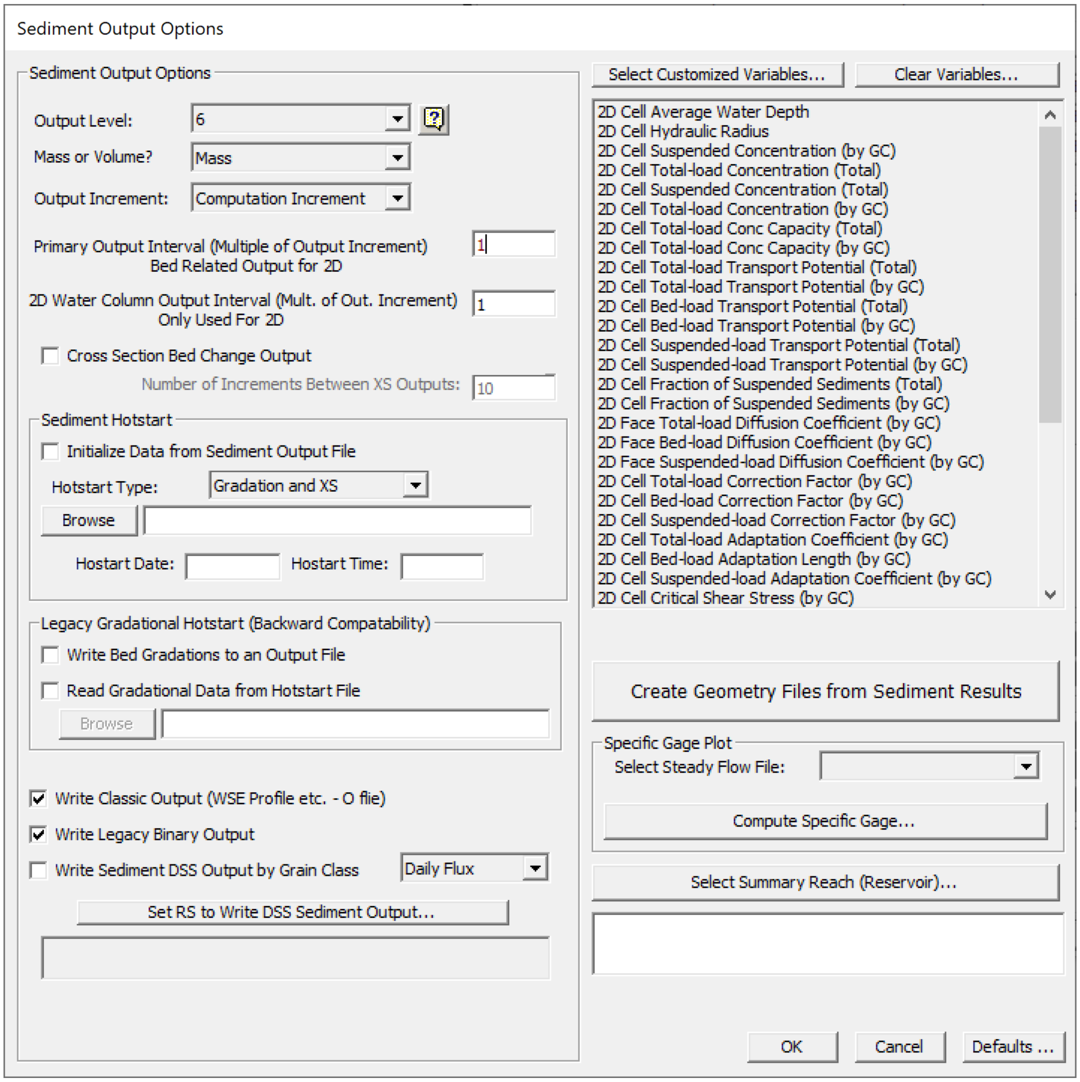


Figure 2-71. Sediment Output Options editor.

2.5.1 Output Level

The **Output Level** allows the user to control how much logging information is written to the **Computation Log File** as well as select a predefined list of output variables. The **Output Level** is set within the **Sediment Output Options** editor which is accessed by clicking on the **Options | Sediment Output Options** menu within the **Unsteady Flow Analysis** editor (see figure below).

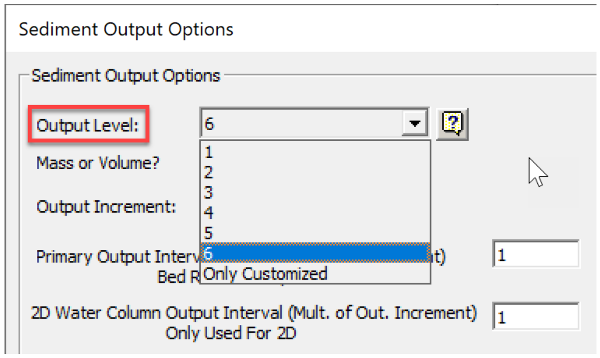


Figure 2-72. Opening the User Defined Grain Classes editor from the Sediment Data editor.

Table 2-6. Output sediment variables as function of the Output Level.

Output Level	**Sediment Output Variable**	**Units**
≥1	Cell average bed change	ft or m
≥1	Cell total total-load concentration	mg/L
≥2	Cell average bed elevation	ft or m
≥2	Cell total total-load concentration capacity (i.e. equilibrium total-load concentration).	mg/L
≥3	Cell fractional total-load concentrations (for each grain class)	mg/L
≥4	Cell fractional total-load concentration capacities (i.e. fractional equilibrium total-load concentrations)	mg/L
≥5	Cell total fraction of suspended sediments (not by grain class)	-
≥5	Cell total total-load transport potential	lb/ft/s or kg/m/s
≥6	Cell fractional fraction of suspended sediments (for each grain class)	-
≥6	Cell total bed shear stress	lb/ft^2 or Pa
≥6	Cell grain bed shear stress	lb/ft^2 or Pa
≥6	Cell critical shear stress for each grain class	lb/ft^2 or Pa
≥6	Cell fall velocity for each grain class	ft/s or m/s
≥6	Cell 16th percentile diameter (d_{16})	mm

≥6	Cell 50th percentile diameter (d_{50})	mm
≥6	Cell 90th percentile diameter (d_{90})	mm

2.5.2 Output Interval Multiples

Sediment transport output is classified into two groups referred to as **Output Blocks**: (1) **Sediment Transport** and (2) **Sediment Bed**. The main reason for this classification is to be able to easily control the output interval of variables which vary at similar time scales. Generally, "transport variables" which are usually within the water column (e.g. concentrations, transport rates, etc.) vary at time scales similar to the hydraulics, while sediment variables on the bed (e.g. bed elevations and gradations) vary at longer time scales. Allowing the user to specify different output intervals for these two output groups helps reduce the size of the HDF5 Output File by allowing the user to specify a larger output interval for variables which change slowly, compared to the hydraulics. The variables which correspond to the **Sediment Bed** are the bed roughness's, bed elevations, bed changes, bed change rate, bed slopes, bed layer fractions, bed layer thicknesses, bed layer percentile diameters, bed layer dry densities. All other variables correspond to the **Sediment Transport** group. The precise Output Block for each output variable is noted in the captions of Tables 2-6 through 2-14.

2.5.3 Customized Sediment Output Variables

There is a large number of variables that the user can select to output. The optional output variables are selected within the **Sediment Output Options** editor which is accessed from the **Options | Sediment Output Options...** menu from the **Unsteady Flow Analysis** editor. The following Tables 2-6 through 2-14 list all of the optional output variables related to 2D sediment transport and their units.

Table 2-7. Output hydraulic variables. These variables correspond to the Sediment Transport Output Block.

Output Variable	**Units**
Shear Stress	Pa or lb/ft^2
Shear Velocity	m/s or ft/s
Velocity	m/s or ft/s
2D Cell Hydraulic Depth	m or ft
2D Cell Hydraulic Radius	m or ft
2D Subcell Velocity	m/s or ft/s
2D Subface Hydraulic Radius	m or ft

Table 2-8. Output sediment concentrations. These variables correspond to the Sediment Transport Output Block.

Output Variable	**Units**
2D Cell Total-load Concentration (Total)	mg/L
2D Cell Total-load Concentration (by GC)	mg/L
2D Cell Suspended Concentration (Total)	mg/L
2D Cell Suspended Concentration (by GC)	mg/L
2D Cell Bed-load Concentration (Total)	mg/L
2D Cell Bed-load Concentration (by GC)	mg/L
2D Cell Total-load Conc Capacity (Total)	mg/L
2D Cell Total-load Conc Capacity (by GC)	mg/L
2D Cell Suspended Conc Capacity (Total)	mg/L
2D Cell Suspended Conc Capacity (by GC)	mg/L

Table 2-9. Output sediment transport potentials. These variables correspond to the Sediment Transport Output Block.

Output Variable	**Units**
2D Cell Total-load Transport Potential (Total)	kg/m/s or lb/ft/s
2D Cell Total-load Transport Potential (by GC)	kg/m/s or lb/ft/s
2D Cell Bed-load Transport Potential (Total)	kg/m/s or lb/ft/s
2D Cell Bed-load Transport Potential (by GC)	kg/m/s or lb/ft/s
2D Cell Suspended-load Transport Potential (Total)	kg/m/s or lb/ft/s
2D Cell Suspended-load Transport Potential (by GC)	kg/m/s or lb/ft/s

Table 2-10. Output sediment transport variables. These variables correspond to the Sediment Transport Output Block.

Output Variable	**Units**
2D Cell Fraction of Suspended Sediments (Total)	-
2D Cell Fraction of Suspended Sediments (by GC)	-
2D Face Total-load Diffusion Coefficient (by GC)	m^2/s or ft^2/s

2D Face Bed-load Diffusion Coefficient (by GC)	m^2/s or ft^2/s
2D Face Suspended-load Diffusion Coefficient (by GC)	m^2/s or ft^2/s
2D Cell Total-load Correction Factor (by GC)	-
2D Cell Bed-load Correction Factor (by GC)	-
2D Cell Suspended-load Correction Factor (by GC)	-
2D Cell Total-load Adaptation Length (by GC)	m or ft
2D Cell Total-load Adaptation Coefficient (by GC)	-
2D Cell Bed-load Adaptation Length (by GC)	m or ft
2D Cell Suspended-load Adaptation Coefficient (by GC)	-
2D Cell Erosion Rates (by GC)	$kg/m^2/s$ or $lb/ft^2/s$
2D Cell Deposition Rates (by GC)	$kg/m^2/s$ or $lb/ft^2/s$

Table 2-11. Output incipient motion variables. These variables correspond to the Sediment Transport Output Block.

Output Variable	**Units**
2D Cell Critical Shear Stress (by GC)	Pa or lb/ft^2
2D Cell Hiding and Exposure Correction Factor (by GC)	-

Table 2-12. Output sediment settling variables. These variables correspond to the Sediment Transport Output Block.

Output Variable	**Units**
2D Cell Settling Velocity (Total)	m/s or ft/s
2D Cell Settling Velocity (by GC)	m/s or ft/s

It is noted that the units of density in the **US Customary Unit System** are represented as lb/ft^3. Here lb represent pounds mass and are obtained by multiplying $slugs/ft^3$ by a standard gravity of 31.174 ft/s^2.

Table 2-13. Output sediment active layer variables. These variables correspond to the Sediment Bed group (Output Block).

Output Variable	Units
2D Cell Fractions Active	-
2D Cell Layer Thickness Active	m or ft
2D Cell Dry Density Active	kg/m^3 or lb/ft^3
2D Cell d10 Active	mm
2D Cell d16 Active	mm
2D Cell d35 Active	mm
2D Cell d50 Active	mm
2D Cell d65 Active	mm
2D Cell d84 Active	mm
2D Cell d90 Active	mm

Table 2-14. Output Sediment bed Composition and layering variables. These variables correspond to the Sediment Bed Output Block.

Output Variable	Units
2D Layer Fractions	-
2D Layer Thickness	m or ft
2D Layer Dry Density	kg/m^3 or lb/ft^3

Table 2-15. Output bed roughness variables. These variables correspond to the Sediment Bed Output Block.

Output Variable	Units
2D Cell Manning Total	$s/m^{1/3}$
2D Cell Manning Grain	
2D Cell Manning Bedform	
2D Cell Manning Transport	

Table 2-16. Output bathymetry variables. These variables correspond to the Sediment Bed Output Block.

Output Variable	Units
2D Cell Bed Elevation	m or ft
2D Cell Bed Change	m or ft
2D Cell Bed Change Rate	m/s or ft/s
2D Face Bed Elevation	m or ft
2D Face Bed Change	m or ft
2D Face Bed Change Rate	m/s or ft/s
2D Subcell Bed Elevation	m or ft
2D Subcell Bed Change	m or ft
2D Subface Bed Elevation	m or ft
2D Subface Bed Change	m or ft

2.5.4 Sediment Hotstart

Currently, the sediment hotstart feature is not supported by the beta release of 2D sediment transport in HEC-RAS. This feature will be fully supported in the first official release of 2D sediment transport. Currently, hotstart files (a.k.a. restart files) cannot be used when using 2D sediment transport.

2.6 Viewing Results

2.6.1 Exploring the HDF5 File

The HEC-RAS **HDF5 Output File** may be explored by reading the file with a computer language (e.g. MATLAB or Python) or by opening it with an external HDF5 utility such as HDFView (https://www.hdfgroup.org/downloads/hdfview/) or Panoply (https://www.giss.nasa.gov/tools/panoply/). The HEC-RAS output is grouped in the HDF5 file into **Output Blocks**. There are several output blocks including **Base Output**, **Computation Block**, **DSS Hydrograph Output**, **DSS Profile Output**, among others. HEC-RAS 2D sediment output is separated into two Output Blocks: **Sediment Transport** and **Sediment Bed**. The path of the **Output Blocks** within the HDF5 file is /Results/Unsteady/Output/Output Blocks/. The name of each output dataset follows a specific convention as <Location> <Variable Name> for variables which are not specific to each grain class and <Location> <Variable Name> – <Grain Class Name> for variables which are output for each grain class. For all the output variables, the rows indicate the output times and the columns indicate the variation location (i.e. cell, face, subcell, or subface).

2.6.2 Log Output

Monitoring the convergence status of a model is important but often difficult due the complexity of the sediment transport models. The sediment log output may be grouped similar to the HDF5 spatial output as: (1) **Sediment Transport** (sediment concentrations), (2) **Sediment Bed** (grain class fractions and dry densities in the active layer). In addition, the logging output is written out to two different places: (1) the **Computation Log File** (*.bco*), and (2) the **HDF5 Output File** (*.p*.hdf).

The amount of information which is written to the **Computation Log File** depends on the sediment **Output Level** (see Section 2.4 Sediment Output Options) and the convergence status. The log output in the **Computation Log File** is output only when a convergence tolerance is exceeded for **Output Levels** less than 5. If the output level is 5 or 6, a log record is written at a constant computation time step interval. For an **Output Level** of 5, the log record only contains convergence information for the last outer-loop iteration. For an **Output Level** of 6 the log record contains convergence information for all iterations.

The log output in the **HDF5 Output File** is written to the same location as the **Sediment Transport** and the **Sediment Bed** output blocks and is therefore written at the corresponding output intervals. The output interval for the **Sediment Transport** and the **Sediment Bed** output blocks can be controlled by the user by specifying a multiple of the **Mapping Output Interval** (see Section 2.4 Sediment Output Options for details). The log output is written as floating point datasets instead of compound datasets or other forms for computational speeds.

The log output for **Sediment Transport** is written in the **HDF5 Output File** under

Dataset Name: Log Sediment Transport
Dataset Path: /Results/Unsteady/Output/Output Blocks/Sediment Transport/Unsteady Time Series/2D Flows Areas/<2D Flow Area Name>/

where <2D Flow Area Name> is the name of each 2D flow area.

Table 2-17. Sediment Transport Log Output. Note: HDF5 columns begin at 0.

Column	Log Output Variable	Units
0	Overall convergence status flag	-
1	Transport convergence status flag	-
2	Number of outer-loop iterations	-
3	Maximum total total-load concentration	mg/L
4	Cell location of maximum total total-load concentration	-
5	Maximum fractional total-load concentration	mg/L
6	Cell location of maximum fractional total-load concentration	-
7	Grain class corresponding to maximum fractional total-load concentration	-

8	Concentration maximum absolute correction for all grain classes	mg/L
9	Cell location of maximum absolute concentration correction for all grain classes	-
10	Grain class corresponding to maximum absolute concentration correction for all grain classes	-
11	Percent of active grid	%
12	Minimum total inner loop iterations (only for iterative matrix solvers)	-
13	Grain class corresponding to minimum inner loop iterations (only for iterative matrix solvers)	-
14	Maximum total inner loop iterations (only for iterative matrix solvers)	-
15	Grain class corresponding to maximum inner loop iterations (only for iterative matrix solvers)	-
16	Maximum root-mean-squared residual of inner-loop iterations (only for iterative matrix solvers)	-
17	Grain class corresponding to maximum root-mean-squared residual of inner-loop iterations (only for iterative matrix solvers)	-

Currently when the model diverges, it stops the simulation. In future versions, diverged time steps will be repeated with subcycles in order to try to obtain a converged solution. Usually divergence indicates a NaN (not a number for bed change, bed fractions, or sediment concentrations). However, it could also mean an internal divergence tolerance was exceeded. Future versions of the model will include more information on how the model diverged.

Similarly, the logging output for the **Sediment Bed** is written in the **HDF5 Output File** under

> Dataset Name: Log Sediment Bed
> Dataset Path: /Results/Unsteady/Output/Output Blocks/Sediment Bed/Unsteady Time Series/2D Flows Areas/<2D Flow Area Name>/

where again <2D Flow Area Name> is the name of each 2D flow area.

The convergence status flags indicate different model states (see Table 2-17). A status is computed each outer iteration for the sediment transport and bed calculations. The overall convergence status takes into account transport and bed sorting.

Table 2-18. Convergence Status Values

Status Value	Status Name	Description
-1	Diverged	The solution has diverged. Divergence is determined with a variety of tolerances and checks for many variables.
1	Iterating	Either the convergence tolerances or minimum number of iterations have not been satisfied.
0	Converged	Both the convergence tolerances and minimum number of iterations have been satisfied.
2	Continue	Either the convergence has stalled, or the maximum number of iterations has been reached. The solution will continue to the next time step.

Table 2-19. Sediment Bed Log Output. Note: HDF5 begin start at 0.

Column	Log Output Variable	Units
0	Overall status flag	-
1	Sediment bed status flag	-
2	Number of outer-loop iterations	-
3	Maximum absolute value of active layer fraction correction (difference between outer-loop iteration values)	%
4	Cell location of maximum absolute value of active layer fraction correction	-
5	Subarea corresponding to maximum absolute value of active layer fraction correction	-
6	Grain class corresponding to maximum absolute value of active layer fraction correction	-
7	Number of avalanching iterations	-
8	Number of avalanches at last iteration	-
9	Maximum bed change due to avalanching	ft or m
10	Cell location of maximum bed change to due avalanching	-

Chapter 3

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