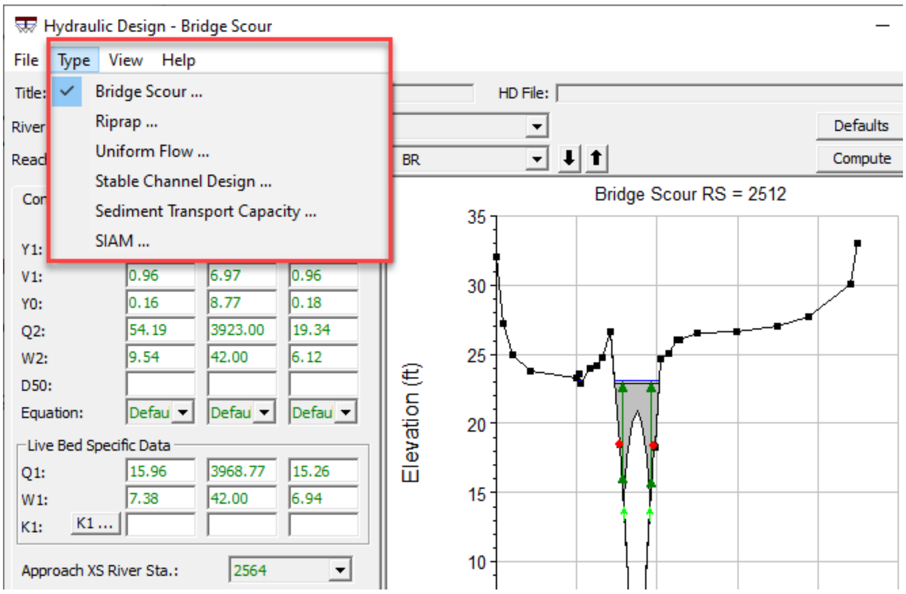
11 HYDRAULIC DESIGN (HD) CALCULATORS

HEC-RAS includes a suite of hydraulic and sediment transport calculators called the **Hydraulic Design** tools. These tools are HEC-RAS post-processors that use results from 1D steady and/or unsteady hydraulic computations to perform common, classic, or simplified analyses for hydraulic design or sediment transport problems.

This suite of tools is actively expanding, including a new Riprap Calculator in version 6.1, with more planned for upcoming versions.

To use one of the **Hydraulic Design Calculators** press the HD button , or select the **Run** → **Hydraulic Design Functions** menu from the main HEC-RAS editor. The HD editor automatically opens to the **Bridge Scour** tool. To select any of the other HD calculators, select the **Type** menu and choose one of the other options.



The Hydraulic Design tools currently include the following six hydraulic and sediment transport calculators:

Icon	Analysis	Description
	Bridge Scour	Applies the US Federal Highway Administration's bridge scour equations and algorithms from HEC-18 to a steady flow hydraulics profile
	Riprap	Computes a stable rock size for bank protection using the USACE guidance in EM 1110-2-1601 and applies a suite of general and bend scour equations to help design toe protection.
	Uniform Flow	A normal depth calculator, that allows users to apply manning's equation to compute a hydraulic geometry without a full HEC-RAS model.

Icon	Analysis	Description
	Stable Channel Design	A suite of tools (including tractive force, Lane, and Copeland methods) that compute the hydraulic geometry that is in transport equilibrium with the flow and sediment in a channel, or visa versa.
$\frac{\partial G_s}{\partial t}$	Sediment Transport Capacity	Simplified calculator that computes sediment transport capacity for a steady flow profile - with a suite of sediment transport equations - ignoring supply, flux, or feedback that make a sediment transport model both more useful, and more difficult.
	SIAM	The Sediment Impact Analysis Methods is a sediment budget tool that uses steady flow results from HEC-RAS, transport functions, and user specifications of watershed and point-source loads to screen sediment impacts alternatives on a watershed scale.
	Sediment Rating Curve Analysis Tool	Imports sediment load, concentration, and load-gradation data and leads analysts through common statistical and conceptual analyses to help them fit an appropriate rating curve through the data cloud.

Computing Scour at Bridges

The computation of scour at bridges within HEC-RAS is based upon the methods outlined in Hydraulic Engineering Circular No. 18 (FHWA, 2001). Before performing a scour analysis with the HEC-RAS software, the engineer should thoroughly review the procedures outlined in the Hydraulic Engineering Circular No. 18 (HEC 18) report. This chapter presents the data input required for computing contraction scour and local scour at piers and abutments.
For information on the bridge scour equations, please see Chapter 10 of the HEC-RAS Hydraulic Reference Manual.

IMPORTANT NOTE: The HEC-RAS software is based on the 2001 version of the FHWA HEC No. 18 manual. This manual has been modified since that time. However, the HEC-RAS software has not been modified to keep up with the changes that FHWA has made to the Bridge Scour document. The bridge scour routines have been left in HEC-RAS in order to reproduce previous studies that used this software and that version of the HEC No. 18 document.

General Modeling Guidelines

In order to perform a bridge scour analysis, the user must first develop a hydraulic model of the river reach containing the bridge to be analyzed. This model should include several cross sections downstream from the bridge, such that any user defined downstream boundary condition does not affect the hydraulic results inside and just upstream of the bridge. The model should also include several cross sections upstream of the bridge, in order to evaluate the long term effects of the bridge on the water surface profile upstream.

The hydraulic modeling of the bridge should be based on the procedures outlined in Chapter 5 of the Hydraulic Reference Manual. If observed data are available, the model should be calibrated to the

fullest extent possible. Once the hydraulic model has been calibrated (if observed data are available), the modeler can enter the design events to be used for the scour analysis. In general, the design event for a scour analysis is usually the 100 year (1 percent chance) event. In addition to this event, it is recommended that a 500 year (0.2 percent chance) event also be used in order to evaluate the bridge foundation under a super-flood condition.
The next step is to turn on the flow distribution option in the HEC-RAS software. This option allows for additional output showing the distribution of flow for multiple subdivisions of the left and right overbanks, as well as the main channel. The output of the flow distribution option includes the following items for each flow slice: percentage of flow; flow area; wetted perimeter; conveyance; hydraulic depth; and average velocity. The user can control the number of slices in each flow element (left overbank, main channel, and right overbank), up to a maximum of 45 total slices. The flow distribution output is controlled from the **Options** menu of the **Steady Flow Analysis** window (see Chapter 7, Simulation Options).

The user must request the flow distribution output for the cross sections inside the bridge, the cross section just upstream of the bridge, and the approach section (cross section upstream of the bridge at a distance such that the flow lines are parallel and the flow has not yet begun to contract due to the bridge constriction). Flow distribution output can be requested at additional cross sections, but these are the only cross sections that will be used in the bridge scour computations. The flow distribution option must be turned on in order to get more detailed estimates of the depth and velocity at various locations within the cross section. Once the user has turned this option on, the profile computations must be performed again in order for the flow distribution output to be computed and included in the output file.

After performing the water surface profile calculations for the design events, and computing the flow distribution output, the bridge scour can then be evaluated. The total scour at a highway crossing is comprised of three components: long-term aggradation and degradation; contraction scour; and local scour at piers and abutments. The scour computations in the HEC-RAS software allow the user to compute contraction scour and local scour at piers and abutments. The current version of the HEC-RAS software does not allow the user to evaluate long-term aggradation and degradation. Long term aggradation and degradation should be evaluated before performing the bridge scour analysis. Procedures for performing this type of analyses are outlined in the HEC No. 18 report.

Entering Bridge Scour Data

The bridge scour computations are performed by opening the **Hydraulic Design Functions** window and selecting the **Scour at Bridges** function. Once this option is selected the program will automatically go to the output file and get the computed output for the approach section, the section just upstream of the bridge, and the sections inside of the bridge. The Hydraulic Design window for Scour at Bridges will appear as shown in Figure 11-1.

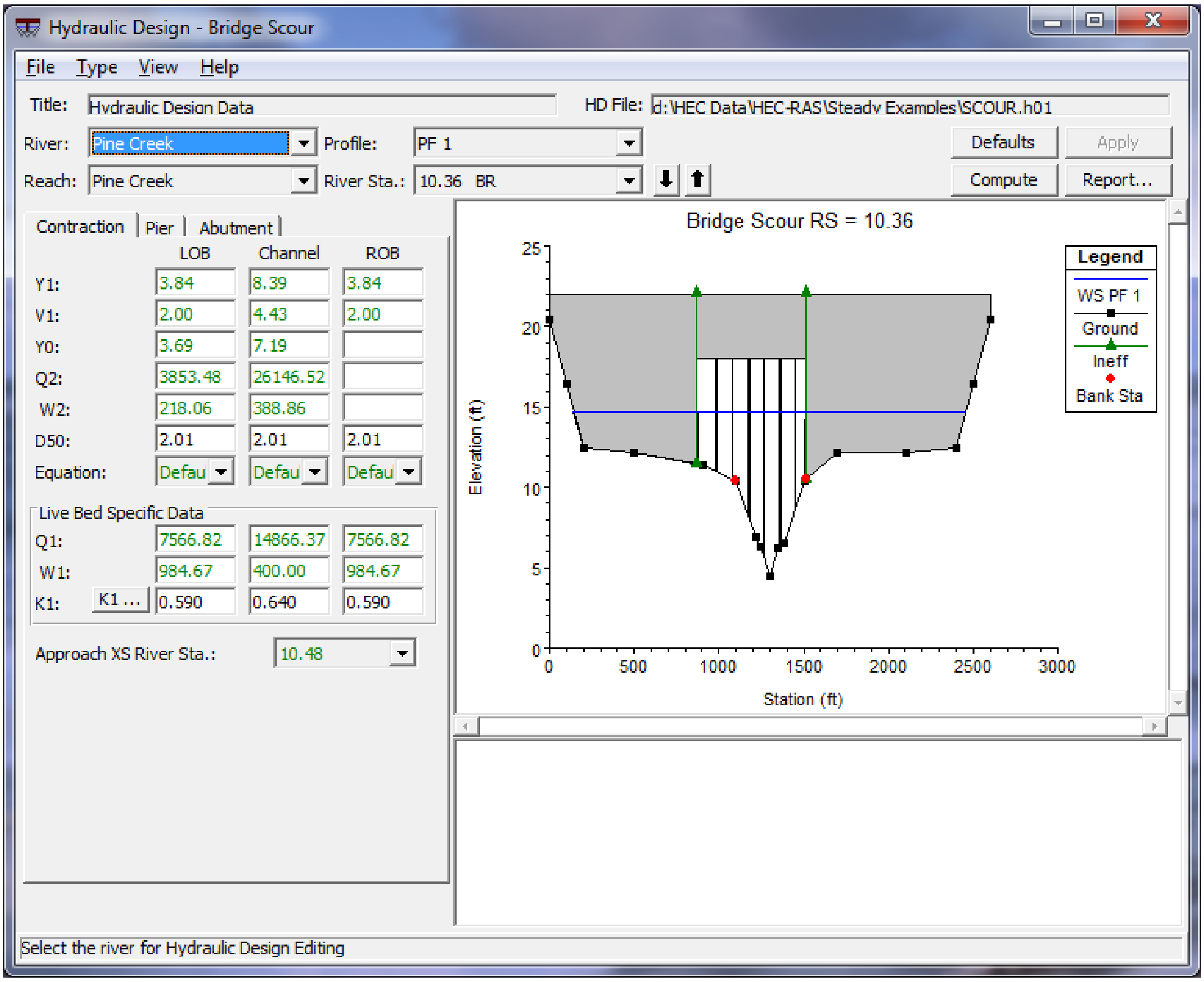


Figure 11 1. Hydraulic Design Window for Scour at Bridges

As shown in Figure 11-1, the Scour at Bridges window contains the input data, a graphic, and a window for summary results. Input data tabs are available for contraction scour, pier scour, and abutment scour. The user is required to enter only a minimal amount of input and the computations can be performed. If the user does not agree with any of the data that the program has selected from the output file, the user can override it by entering their own values. This provides maximum flexibility in using the software.

Entering Contraction Scour Data

Contraction scour can be computed in HEC-RAS by either Laursen's clear-water (Laursen, 1963) or live-bed (Laursen, 1960) contraction scour equations. Figure 11-2 shows all of the data for the contraction scour computations. All of the variables except K1 and D50 are obtained automatically from the HEC-RAS output file. The user can change any variable to whatever value they think is appropriate. To compute contraction scour, the user is only required to enter the D50 (mean size fraction of the bed material) and a water temperature to compute the K1 factor.

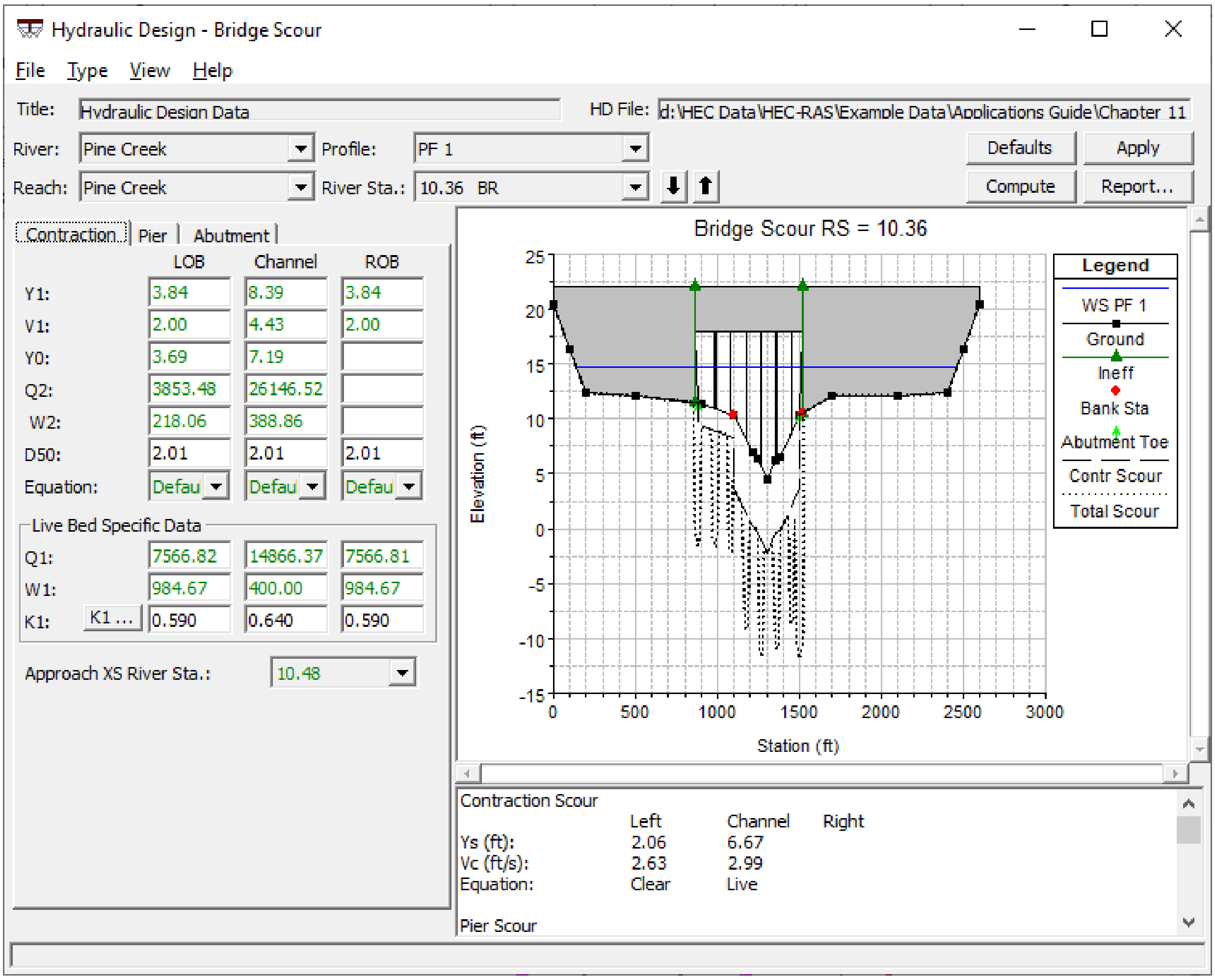


Figure 11 2. Example Contraction Scour Calculation

Each of the variables that are used in the computation of contraction scour are defined below, as well as a description of where each variable is obtained from the output file.

Y1: The average depth (hydraulic depth) in the left overbank, main channel, and the right overbank, at the approach cross-section.

V1: The average velocity of flow in the left overbank, main channel, and right overbank, at the approach section.

Y0: The average depth in the left overbank, main channel, and right overbank, at the contracted section. The contracted section is taken as the cross section inside the bridge at the upstream end of the bridge (section BU).

Q2: The flow in the left overbank, main channel, and right overbank, at the contracted section (section BU).

W2: The top width of the active flow area (not including ineffective flow area), taken at the contracted section (section BU).

D50: The bed material particle size of which 50% are smaller, for the left overbank, main channel, and the right overbank. These particle sizes must be entered in millimeters by the user.

Equation: The user has the option to allow the program to decide whether to use the live-bed or clear-water contraction scour equations, or to select a specific equation. If the user selects the **Default** option (program selects which equation is most appropriate), the program must compute Vc, the critical velocity that will transport bed material finer than D50. If the average velocity at the approach cross section is greater than Vc, the program uses the live-bed contraction scour equation. Otherwise, the clear-water contraction scour equation will be used.

Q1: The flow in the left overbank, main channel, and right overbank at the approach cross-section.

W1: The top width of the active flow area (not including ineffective flow area), taken at the approach cross section.

K1: An exponent for the live-bed contraction scour equation that accounts for the mode of bed material transport. The program can compute a value for K1 or the user can enter one. To have the program compute a value, the K1 button must be pressed. Figure 11-3 shows the window that comes up when the K1 button is pressed. Once a water temperature is entered, and the user presses the OK button, the K1 factor will be displayed on the main contraction scour window. K1 is a function of the energy slope (S1) at the approach section, the shear velocity (V*) at the approach section, water temperature, and the fall velocity (w) of the D50 bed material.

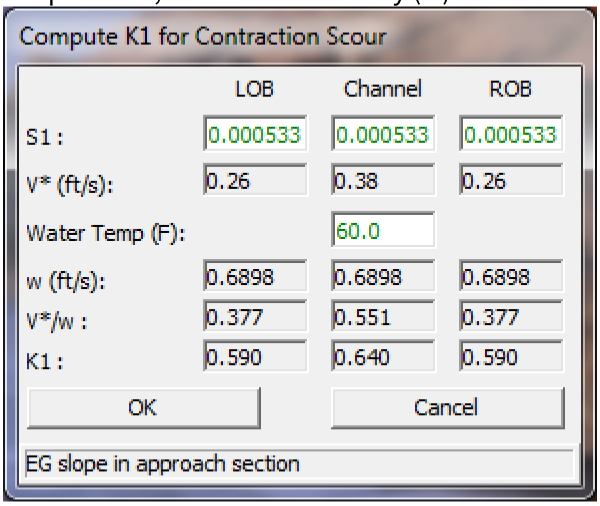


Figure 11 3. Computation of the K1 Factor

Approach XS River Sta.: The river station of what is being used as the approach cross section. The approach cross section should be located at a point upstream of the bridge just before the flow begins to contract do to the constriction of the bridge opening. The program assumes that the second cross section upstream of the bridge is the approach cross section. If this is not the case, the user can select a different river station to be used as the approach cross section.

As shown in Figure 11-2, the computation of contraction scour is performed separately for the left overbank, main channel, and right overbank. For this example, since there is no right overbank flow inside of the bridge, there is no contraction scour for the right overbank. The summary results show that the computed contraction scour, Ys, was 2.06 feet for the left overbank, and 6.67 feet for the main channel. Also note that the graphic was updated to show how far the bed would be scoured due to the contraction scour.

Entering Pier Scour Data

Pier scour can be computed by either the Colorado State University (CSU) equation (Richardson, et al, 1990) or the Froehlich (1988) equation (the Froehlich equation is not included in the HEC No.18 report). The CSU equation is the default. As shown in Figure 11-4, the user is only required to enter the pier nose shape (K1), the angle of attack for flow hitting the piers, the condition of the bed (K3), and a D95 size fraction for the bed material. All other values are automatically obtained from the HEC-RAS output file.

As shown in Figure 11 4, the user has the option to use the maximum velocity and depth in the main channel, or the local velocity and depth at each pier for the calculation of the pier scour. In general, the maximum velocity and depth are used in order to account for the potential of the main channel thalweg to migrate back and forth within the bridge opening. The migration of the main channel thalweg could cause the maximum potential scour to occur at any one of the bridge piers.

Each of the variables that are used in the computation of pier scour are defined below, as well as a description of where each variable is obtained from the output file.

Maximum V1 Y1: If the user selects this option, the program will find the maximum velocity and depth located in the cross section just upstream and outside of the bridge. The program uses the flow distribution output to obtain these values. The maximum V1 and Y1 will then be used for all of the piers.

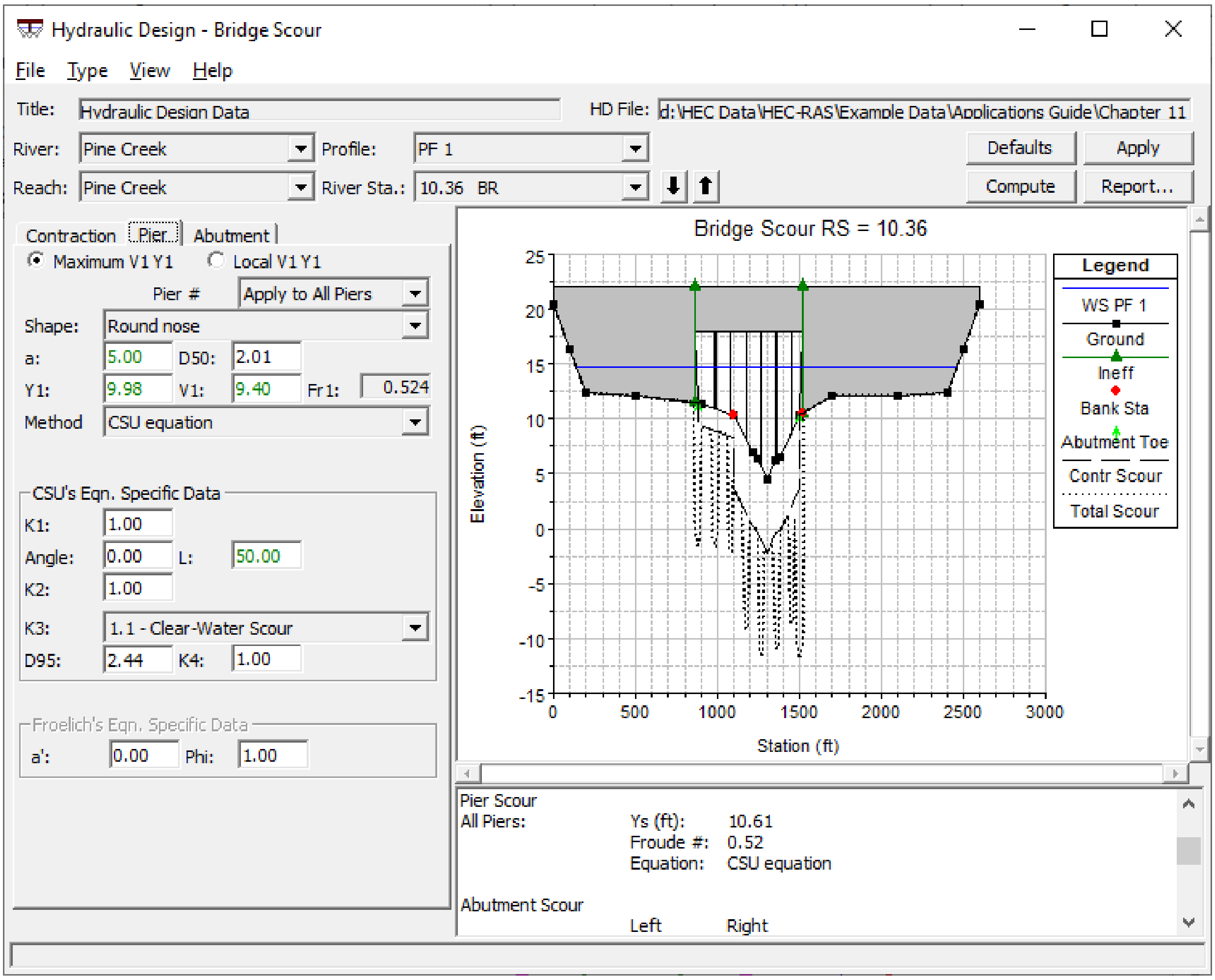


Figure 11 4. Example Pier Scour Computation

Local V1 Y1: If the user selects this option, the program will find the velocity (V1) and depth (Y1) at the cross section just upstream and outside of the bridge that corresponds to the centerline stationing of each of the piers.

Method: The method option allows the user to choose between the CSU equation and the Froehlich equation for the computation of local scour at bridge piers. The CSU equation is the default method.

Pier #: This selection box controls how the data can be entered. When the option "**Apply to All Piers**" is selected, any of the pier data entered by the user will be applied to all of the piers. The user does not have to enter all of the data in this mode, only the portion of the data that should be applied to all of the piers. Optionally, the user can select a specific pier from this selection box. When a specific pier is selected, any data that has already been entered, or is applicable to that pier, will show up in each of the data fields. The user can then enter any missing information for that pier, or change any data that was already set.

Shape: This selection box is used to establish the pier nose (upstream end) shape. The user can select between square nose, round nose, circular cylinder, group of cylinders, or sharp nose (triangular) pier shapes. When the user selects a shape, the K1 factor for the CSU equation and the

Phi factor for the Froehlich equation are automatically set. The user can set the pier nose shape for all piers, or a different shape can be entered for each pier.

a: This field is used to enter the width of the pier. The program automatically puts a value in this field based on the bridge input data. The user can change the value.

D50: Median diameter of the bed material of which 50 percent are smaller. This value is automatically filled in for each pier, based on what was entered for the left overbank, main channel, and right overbank, under the contraction scour data. The user can change the value for all piers or any individual pier. This value must be entered in millimeters.

Y1: This field is used to display the depth of water just upstream of each pier. The value is taken from the flow distribution output at the cross section just upstream and outside of the bridge. If the user has selected to use the maximum Y1 and V1 for the pier scour calculations, then this field will show the maximum depth of water in the cross section for each pier. The user can change this value directly for each or all piers.

V1: This field is used to display the average velocity just upstream of each individual pier. The value is taken from the flow distribution output at the cross section just upstream and outside of the bridge. If the user has selected to use the maximum Y1 and V1 for the pier scour calculations, then this field will show the maximum velocity of water in the cross section for all piers. The user can change this value directly for each or all piers.

Angle: This field is used to enter the angle of attack of the flow approaching the pier. If the flow direction upstream of the pier is perpendicular to the pier nose, then the angle would be entered as zero. If the flow is approaching the pier nose at an angle, then that angle should be entered as a positive value in degrees. When an angle is entered, the program automatically sets a value for the K2 coefficient. When the angle is > 5 degrees, K1 is set to 1.0.

L: This field represents the length of the pier through the bridge. The field is automatically set by the program to equal the width of the bridge. The user can change the length for all piers or each individual pier. This length is used in determining the magnitude of the K2 factor.

K1: Correction factor for pier nose shape, used in the CSU equation. This factor is automatically set when the user selects a pier nose shape. The user can override the selected value and enter their own value.

K2: Correction factor for angle of attack of the flow on the pier, used in the CSU equation. This factor is automatically calculated once the user enters the pier width (a), the pier length (L), and the angle of attack (angle).

K3: Correction factor for bed condition, used in the CSU equation. The user can select from: clear-water scour; plane bed and antidune flow; small dunes; medium dunes; and large dunes.

D95: The median size of the bed material of which 95 percent is finer. The D95 size fraction is used in the computation of the K4 factor, and must be entered in millimeters directly by the user.

K4: The K4 factor is used to decrease scour depths in order to account for armoring of the scour hole. This factor is only applied when the D50 of the bed material is greater than 0.006 feet (0.2 mm) and the D95 is greater than 0.06 feet (2.0 mm). This factor is automatically calculated by the program, and is a function of D50; D95; a; and the depth of water just upstream of the pier. The K4 factor is used in the CSU equation.

a: The projected pier width with respect to the direction of the flow. This factor should be calculated by the user and is based on the pier width, shape, angle, and length. This factor is specific to Froehlich's equation.

Phi: Correction factor for pier nose shape, used in the Froehlich equation. This factor is automatically set when the user selects a pier nose shape. The user can override the selected value and enter their own value.
For the example shown in Figure 11 4 the CSU equation was used, resulting in a computed pier scour of 10.61 feet at each pier (shown under summary results in Figure 11 4). Also shown in Figure 11 4 is an updated graphic with both contraction and pier scour shown.

Entering Abutment Scour Data

Abutment scour can be computed by either the HIRE equation (Richardson, 1990) or Froehlich's equation (Froehlich, 1989). The input data and results for abutment scour computations are shown in Figure 11-5.

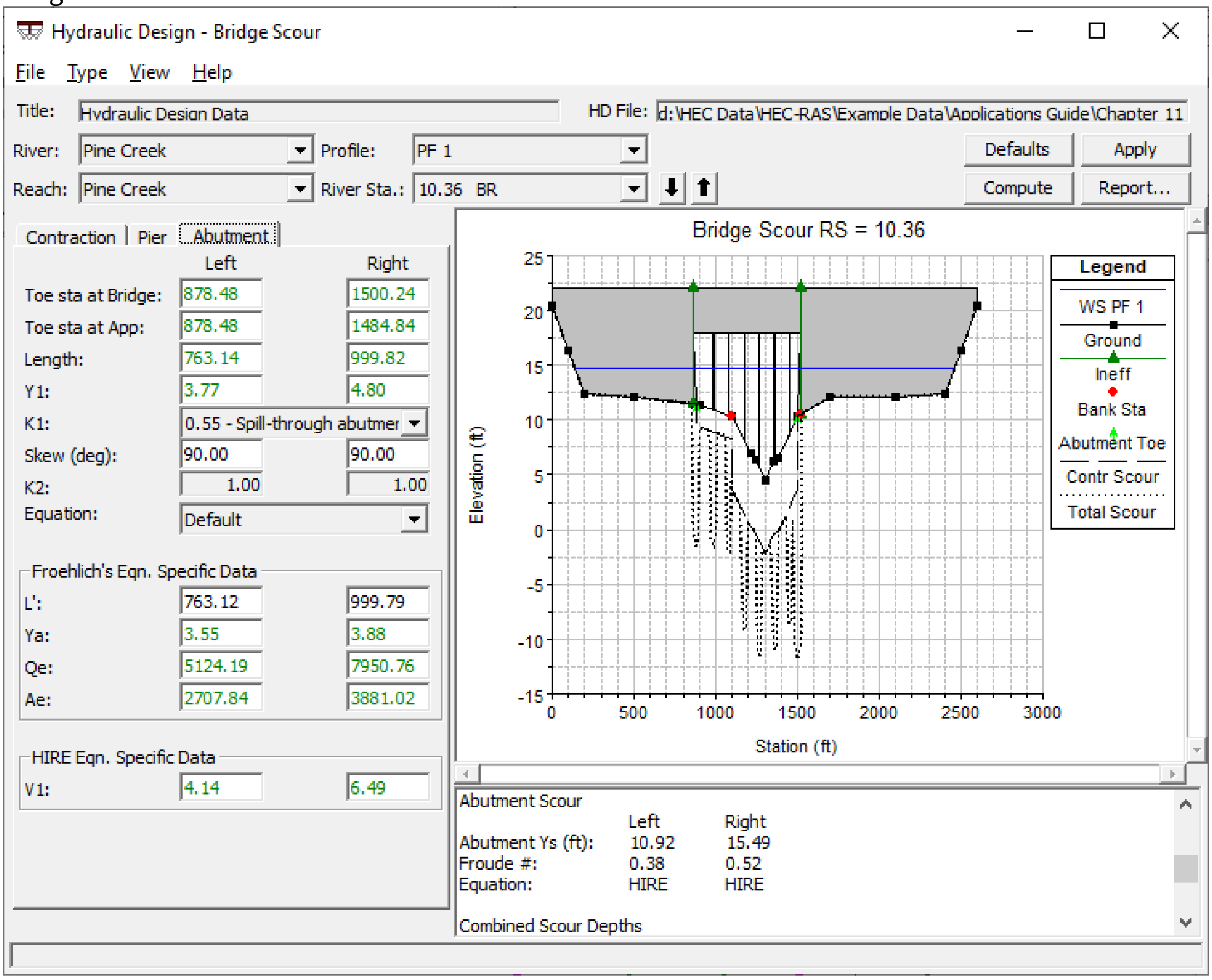


Figure 11 5. Example Abutment Scour Computations

As shown in Figure 11-5, abutment scour is computed separately for the left and right abutment. The user is only required to enter the abutment type (spill-through, vertical, vertical with wing walls). The program automatically selects values for all of the other variables based on the hydraulic output and

default settings. However, the user can change any variable. The location of the toe of the abutment is based on where the roadway embankment intersects the natural ground. This stationing is very important because the hydraulic variables used in the abutment scour computations will be obtained from the flow distribution output at this cross section stationing. If the user does not like the stationing that the model picks, they can override it by entering their own value.
Each of the variables that are used in the computation of abutment scour are defined below, as well as a description of where each variable is obtained from the output file.
Toe Sta at Bridge: This field is used to define the stationing in the upstream bridge cross section (section BU), where the toe of the abutment intersects the natural ground. The program automatically selects a value for this stationing at the point where the road embankment and/or abutment data intersects the natural ground cross-section data. The location for the abutment toe stationing can be changed directly in this field.

Toe Sta at App.: This field is used to define the stationing in the approach cross section (section 4), based on projecting the abutment toe station onto the approach cross section. The location for this stationing can be changed directly in this field.

Length: Length of the abutment and road embankment that is obstructing the flow. The program automatically computes this value for both the left and right embankments. The left embankment length is computed as the stationing of the left abutment toe (projected up to the approach cross section) minus the station of the left extent of the active water surface in the approach cross section. The right embankment length is computed as the stationing of the right extent of the active water surface minus the stationing of the toe of the right abutment (projected up to the approach cross section), at the approach cross section. These lengths can be changed directly.

Y1: This value is the computed depth of water at the station of the toe of the embankment, at the cross section just upstream of the bridge. The value is computed by the program as the elevation of the water surface minus the elevation of the ground at the abutment toe stationing. This value can also be changed by the user. This value is used in the HIRE equation.

K1: This value represents a correction factor accounting for abutment shape. The user can choose among: vertical abutments; vertical with wing walls; and spill-through abutments.

Skew: This field is used to enter the angle of attack of the flow against the abutment. A value of 90 degrees should be entered for abutments that are perpendicular to the flow (normal situation). A value less than 90 degrees should be entered if the abutment is pointing in the downstream direction. A value greater than 90 degrees should be entered if the abutments are pointing in the upstream direction. The skew angle is used in computing the K2 factor.

K2: Correction factor for angle of attack of the flow on the abutments. This factor is automatically computed by the program. As the skew angle becomes greater than 90 degrees, this factor increases from a value of one. As the skew angle becomes less than 90 degrees, this value becomes less than one.

Equation: This field allows the user to select a specific equation (either the HIRE or Froehlich equation), or select the default mode. When the default mode is selected, the program will choose the equation that is the most applicable to the situation. The selection is based on computing a factor of the embankment length divided by the approach depth. If this factor is greater than 25, the program will automatically use the HIRE equation. If the factor is equal to or less than 25, the program will automatically use the Froehlich equation.

L': The length of the abutment (embankment) projected normal to the flow (projected up to the approach cross section). This value is automatically computed by the program once the user enters an abutment length and a skew angle. This value can be changed by the user.

Ya: The average depth of flow (hydraulic depth) that is blocked by the embankment at the approach cross section. This value is computed by projecting the stationing of the abutment toe's up to the approach cross section. From the flow distribution output, the program calculates the area and top width left of the left abutment toe and right of the right abutment toe. Ya is then computed as the area divided by the top width. This value can be changed by the user directly.

Qe: The flow obstructed by the abutment and embankment at the approach cross section. This value is computed by projecting the stationing of the abutment toes onto the approach cross-section. From the flow distribution output, the program calculates the percentage of flow left of the left abutment toe and right of the right abutment toe. These percentages are multiplied by the total flow to obtain the discharge blocked by each embankment. These values can be changed by the user directly.

Ae: The flow area that is obstructed by the abutment and embankment at the approach cross section. This value is computed by projecting the stationing of the abutment toes onto the approach cross-section. From the flow distribution output, the program calculates the area left of the left abutment toe and right of the right abutment toe. These values can be changed by the user directly.

V1: The velocity at the toe of the abutment, taken from the cross section just upstream and outside of the bridge. This velocity is obtained by finding the velocity in the flow distribution output at the corresponding cross section stationing of the abutment toe. These values can be changed by the user directly.
In addition to the abutment input data, once the compute button is pressed, the bridge scour graphic is updated to include the abutment scour and the summary results window displays the computed abutment results. For the example shown in Figure 11-5, the program selected the HIRE equation and computed 10.92 feet of local scour for the left abutment and 15.49 feet of local scour for the right abutment.

Computing Total Bridge Scour

The total scour is a combination of the contraction scour and the individual pier and abutment scour at each location. Table 12.1 shows a summary of the computed results, including the total scour.
Table 12.1
Summary of Scour Computations
<u>Contraction Scour</u>
Left O.B. Main Channel Right O.B.
Ys =2.06 ft (0.63 m)6.67 ft (2.03 m)0.00 ft (0.0 m)
Eqn =Clear-Water Live-Bed
<u>Pier Scour</u>
Piers 1-6 Ys = 10.61 ft (3.23 m)
Eqn. =CSU equation
<u>Abutment Scour</u>
Left Right
Ys =10.92 ft (3.33 m)15.49 ft (4.72 m)
Eqn =HIRE equation HIRE equation
<u>Total Scour</u>

Left Abutment =12.98 ft (3.96 m)
Right abutment =22.16 ft (6.76 m)
Piers 1-2 (left O.B.)=12.67 ft (3.86 m)
Piers 3-6 (main ch.)=17.28 ft (5.27 m)

Once all three types of scour data are entered, and the compute button is pressed, the bridge scour graphic is updated to reflect the total computed scour. Shown in Figure 11-6 is the graphic of the final results (the graphic has been zoomed in to see more detail). The graphic and the tabular results can be sent directly to the default printer, or they can be sent to the Windows Clipboard in order to be pasted into a report. A detailed report can be generated, which shows all of the input data, computations, and final results.

The bridge scour input data can be saved by selecting Save Hydraulic Design Data As from the File menu of the Hydraulic Design Function window. The user is only required to enter a title for the data. The computed bridge scour results are never saved to the hard disk. The computations can be performed in a fraction of a second by simply pressing the compute button. Therefore, when the Hydraulic Design Function window is closed, and later re-opened, the user must press the compute button to get the results.

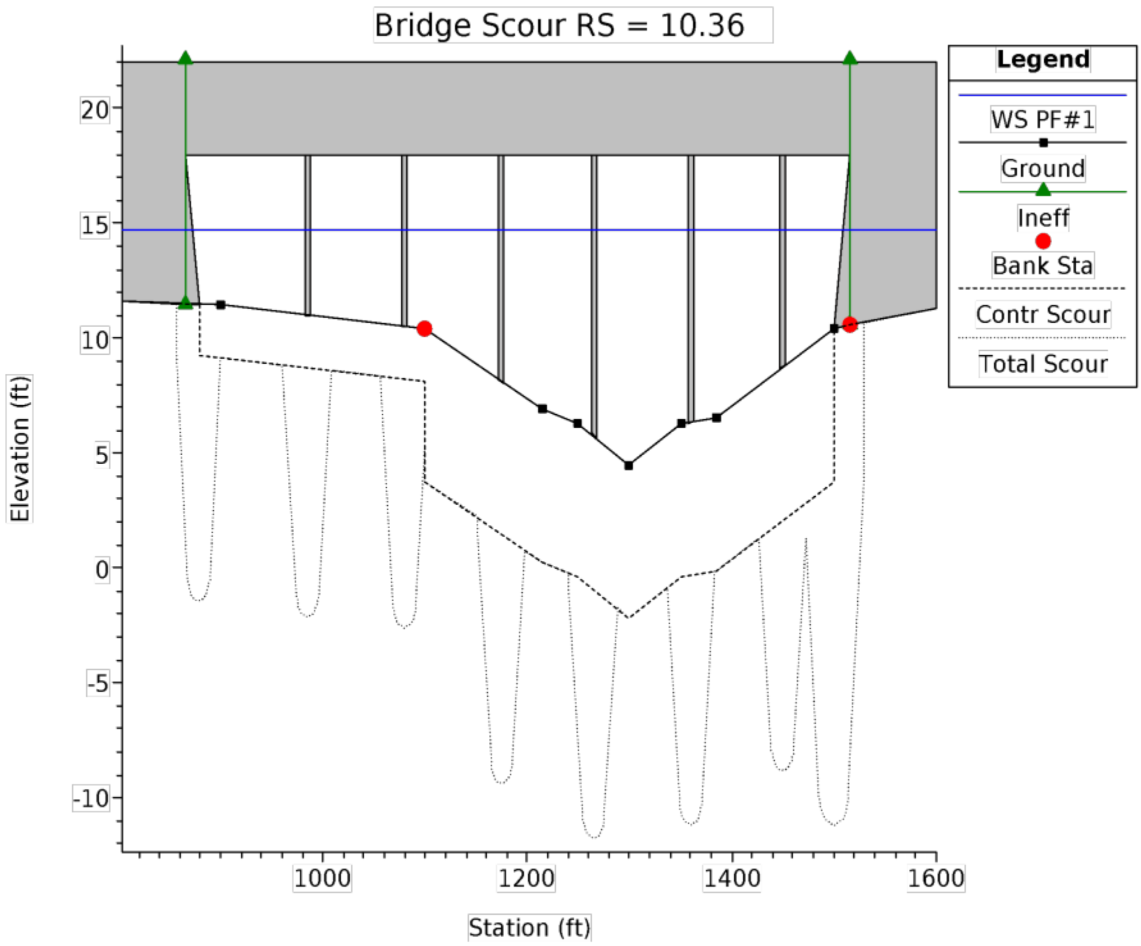


Figure 11 6. Total Scour Depicted in Graphical Form

Riprap and Scour Calculator

HEC added the Riprap and Scour calculator to HEC-RAS version 6.1. This tool computes riprap size and gradation and the potential toe scour that the design must account for. An introductory video and the files used in that video are included below.

Sorry, the widget is not supported in this export.
But you can reach it using the following URL:

https://www.youtube.com/watch?v=M3AVtQIpcAo

Sorry, the widget is not supported in this export.
But you can reach it using the following URL:

http://youtube.com/watch?v=USqcACyNpGw

RiprapExample.zip

Introduction and Conceptual Approach

The Hydraulic Design, Riprap and Scour Calculator has two components that track the two main tasks associated with bank-protection design.

1. Size the Rock and Select an Available Gradation
2. Compute the Potential Scour to Determine the Depth of Toe Protection

HEC developed these calculators together because these computations are often used in tandem to determine the size of rock required and the volume of launchable stone required to protect the toe.

Riprap Calculator:

Size Rock and

Select Gradation

Step 1	Run HEC-RAS Steady Flow Hydraulics (or compute flow depth and width externally).
Step 2	Identify Upstream "Reference" or "Crossing" Cross Section
Step 3	Compute Radius of Curvature and Enter Data
Step 4	Compute d_{30} of Stable Rock Gradation
Step 5	Select Appropriate Riprap Gradation and Compute Thickness

Scour Calculator:

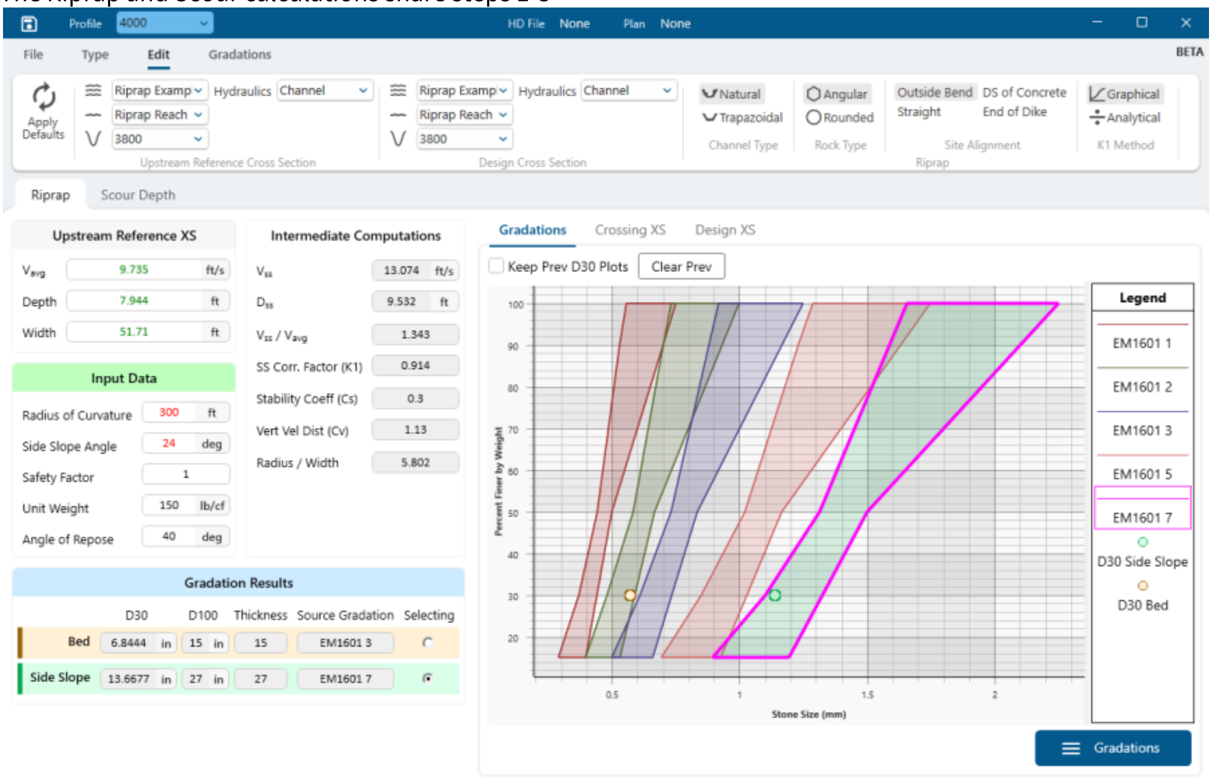
Compute Key Depth

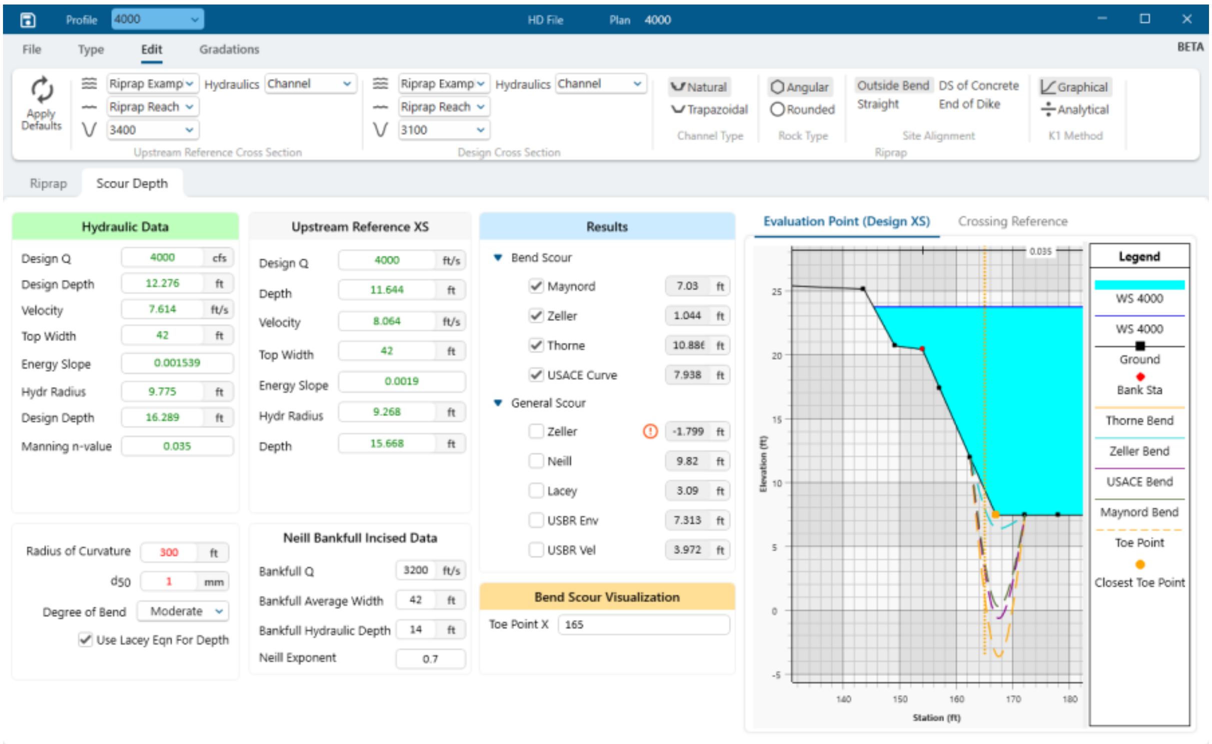
or Launchable Volume

Step 1*	Run HEC-RAS Steady Flow Hydraulics (or compute hydraulic parameters externally).
Step 2*	Identify Upstream "Reference" or "Crossing" Cross Section

Step 3*	Compute Radius of Curvature and Enter Data
Step 4	Select Appropriate Equations
Step 5	Compute Ensemble Scour Depths
Step 6	Visualize Results: Select a Toe Station to Plot Bend Scour
Step 7	Select a Reasonable Scour Depth Based on Calculations, Regional Geology, and Engineering Judgement
Step 8	Use Selected Scour Depth to Compute Volume of Launchable Rock or Depth of Stone Key

- The Riprap and Scour calculations share steps 1-3





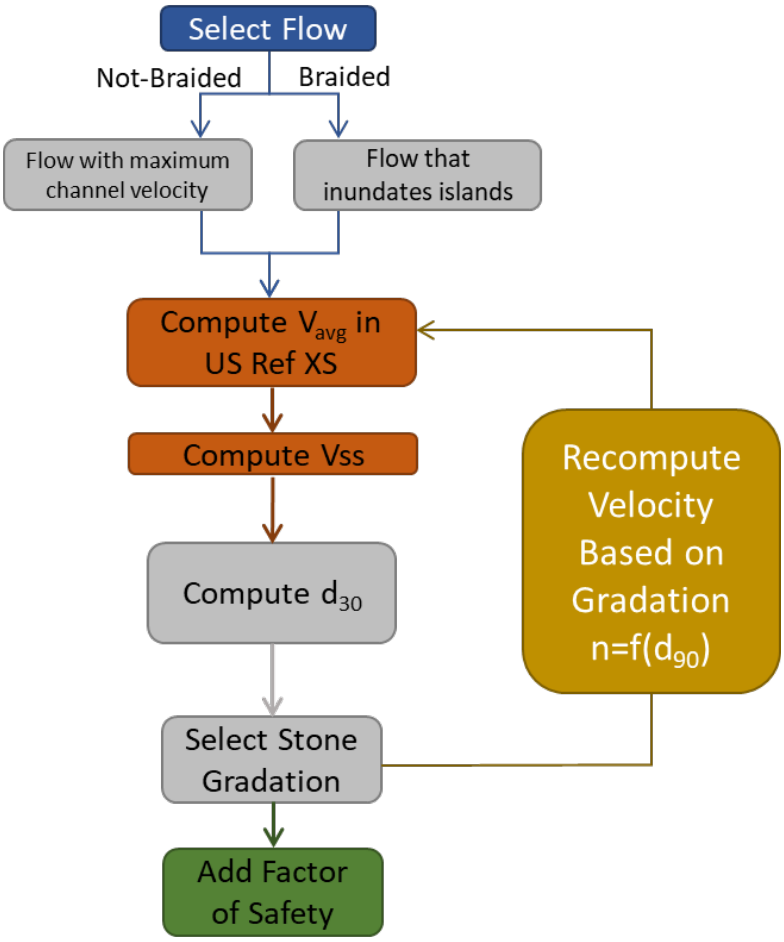
Riprap Calculator: Sizing Rock Gradation

The Riprap Calculator in the current version of HEC-RAS follows the approach described in the USACE Engineering Manual EM 1110-2-1601: Hydraulic Design of Flood Control Channels (USACE, 1994). The design approach is outlined in Chapter 3 of EM 1601 and is based on the work of Dr. Stephen Maynord.

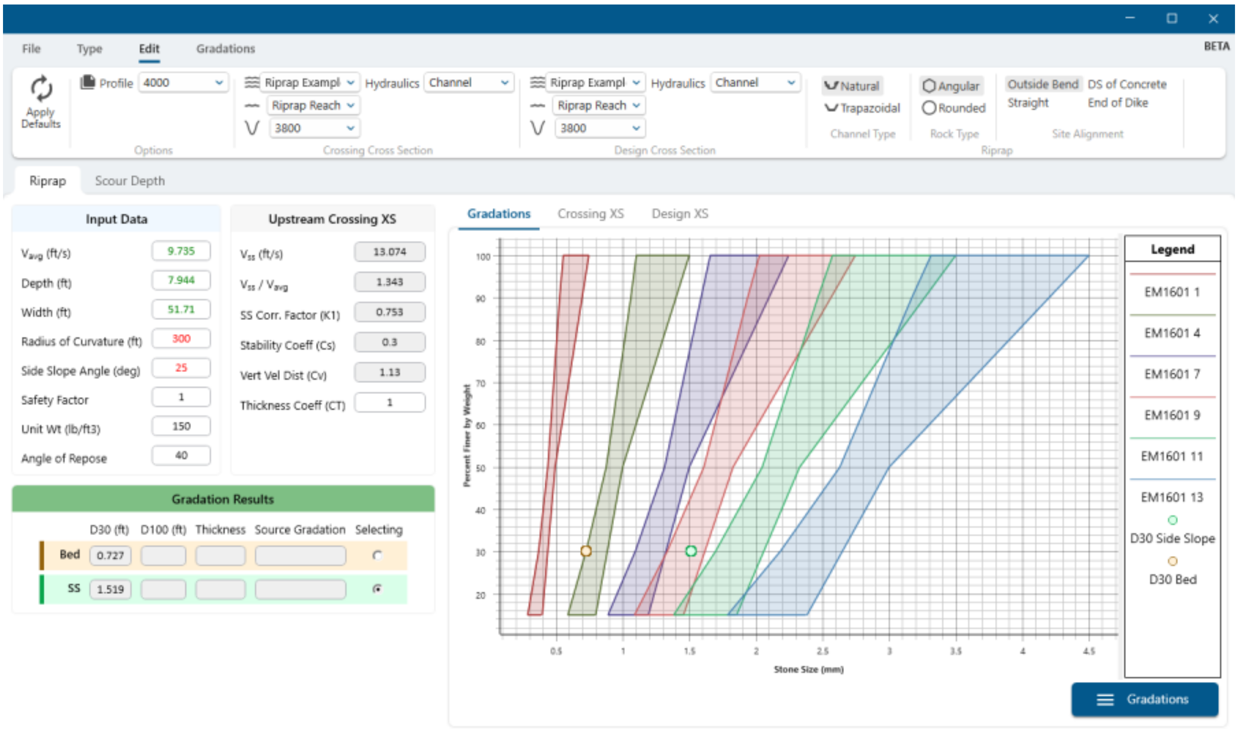
See also, Maynord (1992) "Riprap Resistance Tests From a Large Test Channel"
and
Maynord S., Ruff, J., and Abt, S. (1989) Riprap Design, ASCE Journal of Hydraulics..

The recommended approach is based on a series of experiments conducted at the Engineering Research and Development Center (ERDC, formerly Waterways Experimentation Station – WES) Riprap Test Facility, which measured rock stability in a series of bends in a mesoscale flume (pictured below).

The general workflow of the USACE riprap design approach is illustrated in the figure below:



Future versions of HEC-RAS will include other Riprap sizing methods.



Limitations

The EM 1601 design guidance applies to riprap design for open channels not immediately downstream of stilling basins or other highly turbulent areas (for stilling basin riprap, use HDC 712-1, EM 1601 Plates 29 and 30).
Transitions in size or shape may also require riprap protection. The procedures in this calculator are applicable to gradual transitions where flow remains tranquil. In areas where flow changes from tranquil to rapid and then back to tranquil, riprap sizing methods applicable to hydraulic structures (HDC 712-1) should be used. In expanding transitions, flow can concentrate on one side of the expansion and design velocities should be increased. For installations immediately downstream of concrete channels, a vertical velocity distribution coefficient of 1.25 (an option in the calculator) should be used due to the difference in velocity profile over the two surfaces.
Both the EM 1601 riprap computation and HEC-RAS model application are suitable for shallow slopes with gradually varied flow. As the Froude number approaches 1.0 (critical depth), the user should strongly consider alternative methods. For steep slopes ranging from 2 to 20 percent where unit discharge is low, EM 1601 presents a separate design process that is not included in the riprap calculator. A typical application is a rock-lined chute (EM 1601 section 3.7 (e)).

Step 1: Calculate Hydraulics and Select Profile

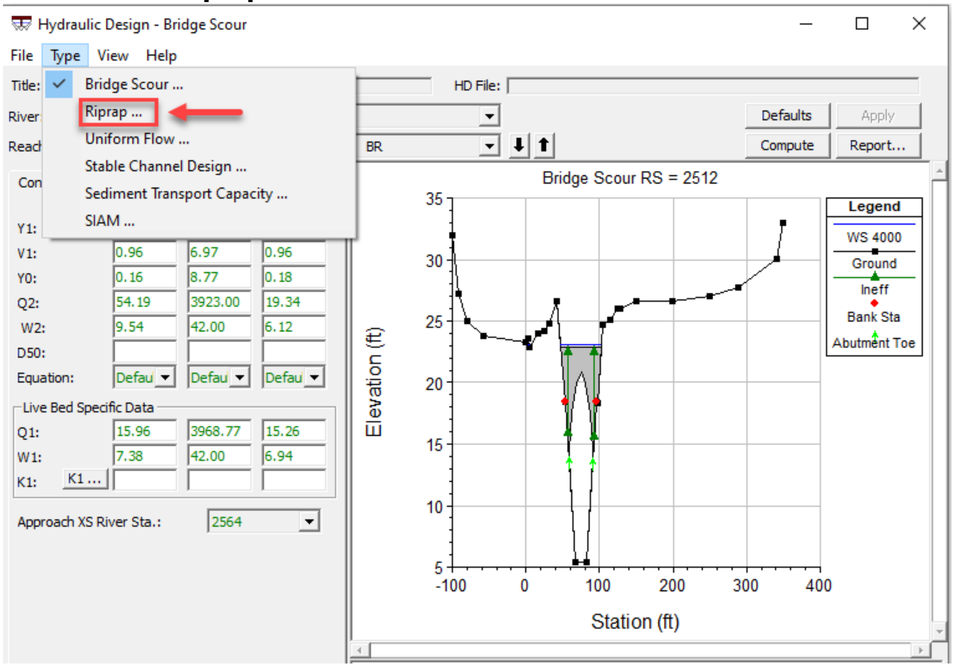
Compute Hydraulics

HEC included the Riprap calculator into HEC-RAS because many engineers sizing riprap use HEC-RAS to compute hydraulic parameters required for riprap design. The Riprap Calculator opens the output associated with the active steady flow plan. Therefore, the user must select the appropriate plan and run the simulation before launching the Riprap Calculator.

Open the Riprap Calculator from the Hydraulic Design Menu

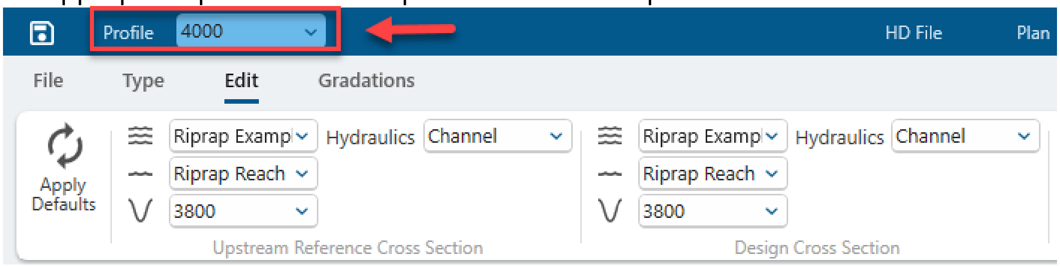
The Riprap Calculator is part of the Hydraulic Design tools. The Hydraulic Design suite is a collection of calculators, tools, and post processors that apply river mechanics and river engineering analyses to HEC-RAS results.

To Launch the Hydraulic Design Editor, select the HD icon from the Main HEC-RAS menu  or select the *Run → Hydraulic Design Functions…* menu.
From the Hydraulic Design editor, Select **Type** to get a list of the different HD calculators and tools, and select the **Riprap and Scour Calculator** from that list.



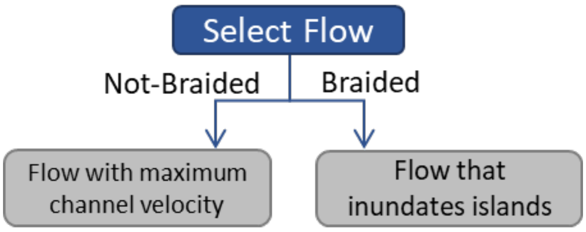
> **Note: Use a Calibrated Hydraulic Model for These Calculations**
>
> Riprap and scour calculations will only be as good as the hydraulic calculations that they are based on. Additionally, because these calculators not only utilized depth, but also velocity, they will be sensitive to hydraulic roughness, ineffective flow areas, and other hydraulic parameters, even though the user does not enter these directly into the calculators. The hydraulic model should be calibrated at or near the design flow before the hydraulics are used to compute riprap and scour. If you have an unsteady flow run, determine the flow rate that results in the design condition, then develop a steady flow file and steady plan file for that flow condition.

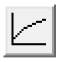
Finally, select the appropriate steady flow profile for the rock size analysis. The Riprap calculator can only compute rock size for one steady flow profile at a time. If your plan has multiple profiles select the appropriate profile in the dropdown box at the top of the calculator.

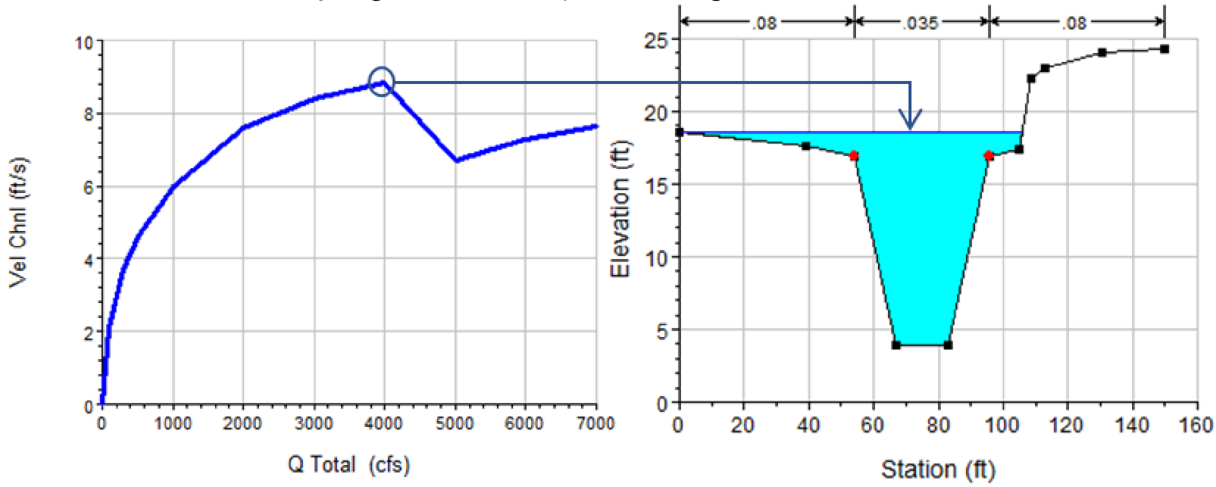


Select Design Flow

The USACE riprap sizing approach uses a different design flow for braided and unbraided systems. The first step of the riprap analysis workflow is reproduced below:

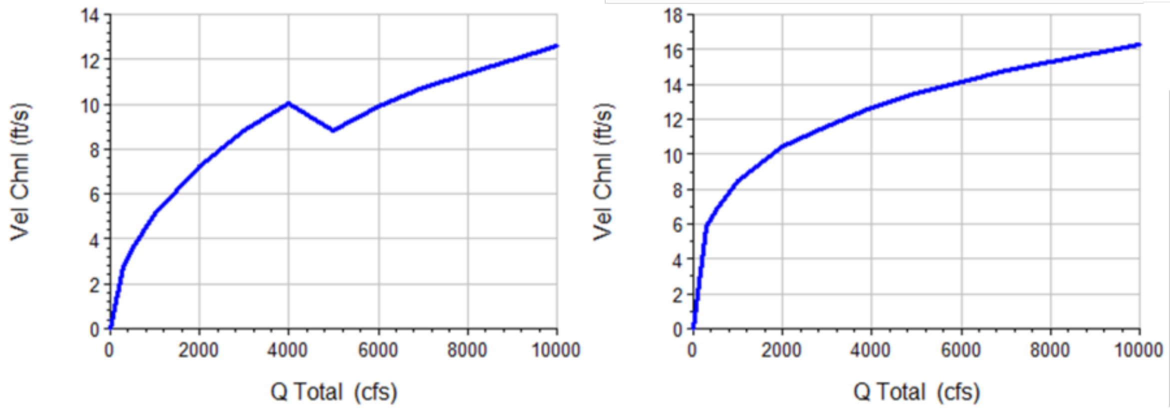


If the channel is not braided, the design discharge (Q_d) should be the flow that generates the maximum channel velocity. This is often bank-full flow. But it is important to test larger, less frequent flows as well. You can use the Hydraulic **Rating Curve** Tool  in HEC-RAS to evaluate the maximum channel velocity. Right click on the plot to change the "Y Variable" to **Vel Chan**:



However, flow-velocity relationships do not always have a clear maximum like the example above.

Velocity often increases with flow, with no convenient or obvious maximum or critical condition.



In these cases, the project team must select a design flow based on risk and uncertainty principles and cost-benefit analyses. Evaluating several flows, including the channel forming discharge, bankfull flow, 1.5-2 year event, and important design floods (e.g. 10%, 2%, and/or 1% Annual Exceedance Probability) can help the project delivery team evaluate the rock size and costs associated with different risk levels.

If the channel is braided, EM 1110-2-1601 recommends selecting the minimum flow that inundates the bars in the channel for riprap design. EM 1110-2-1601 provides additional considerations for application on braided channels with impinging flow in section 3.7 (5).

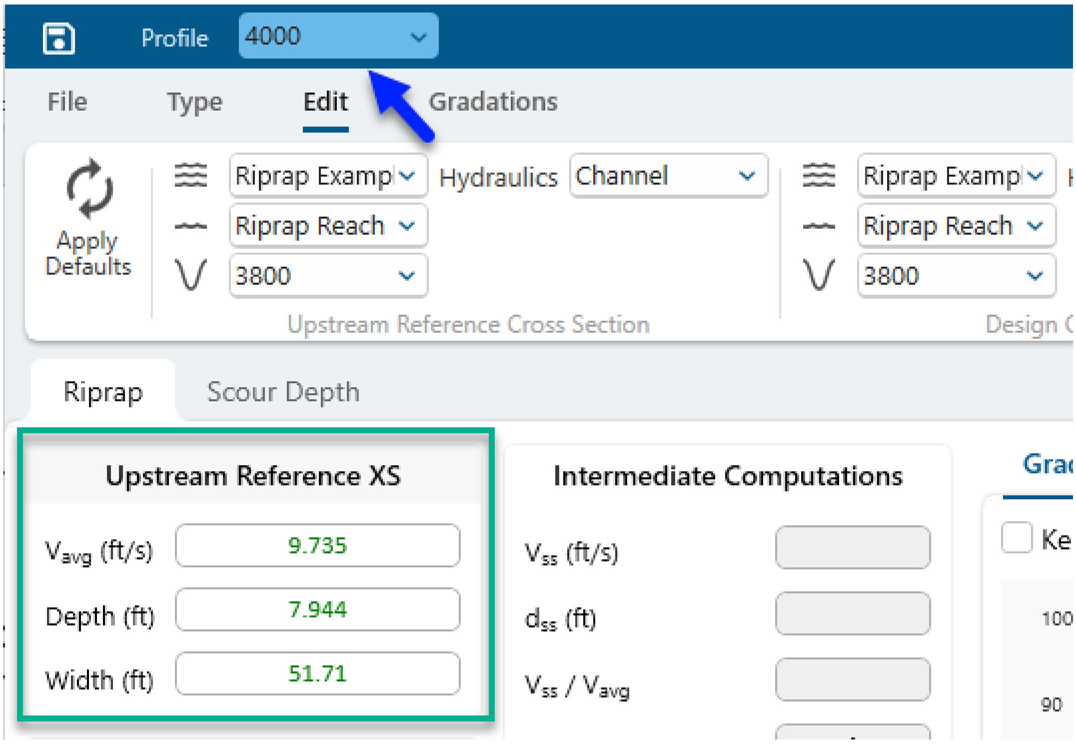
Warning: Be Careful Using Models Developed Flood Risk Analysis

Many HEC-RAS projects are developed for flood risk management or flood insurance mapping applications. The riprap design flow is often closer to the bankfull condition. Riprap and scour protection features often require a new HEC-RAS geometry with hydraulic model parameters selected for reasonable estimates of project design velocity in the Riprap Calculator. Considerations include seasonal roughness variation, expansion and contraction coefficients, ineffective flow area, blocked obstructions, looped rating curve effects, and other HEC-RAS model parameters.

Modeling Note:

The critical hydraulic condition governing riprap sizing may not coincide with the peak flow rate. In some cases lower flow rates during a rising limb of a flood hydrograph will generate in higher velocities than peak flow conditions where storage areas have filled and submerged backwater conditions may have developed.

Once you have identified the design flow, run steady flow hydraulics with that flow (or flows) and select the profile associated with each flow in the Riprap Calculator (blue arrow in figure below).

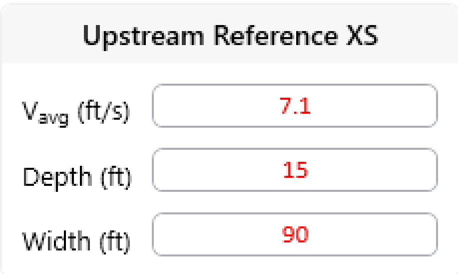


The Riprap Calculator will automatically populate the average velocity, depth, and width associated with the **Upstream Reference Cross Section**, and **XS Hydraulics** (channel or full cross section) selected.

Overriding HEC-RAS Results

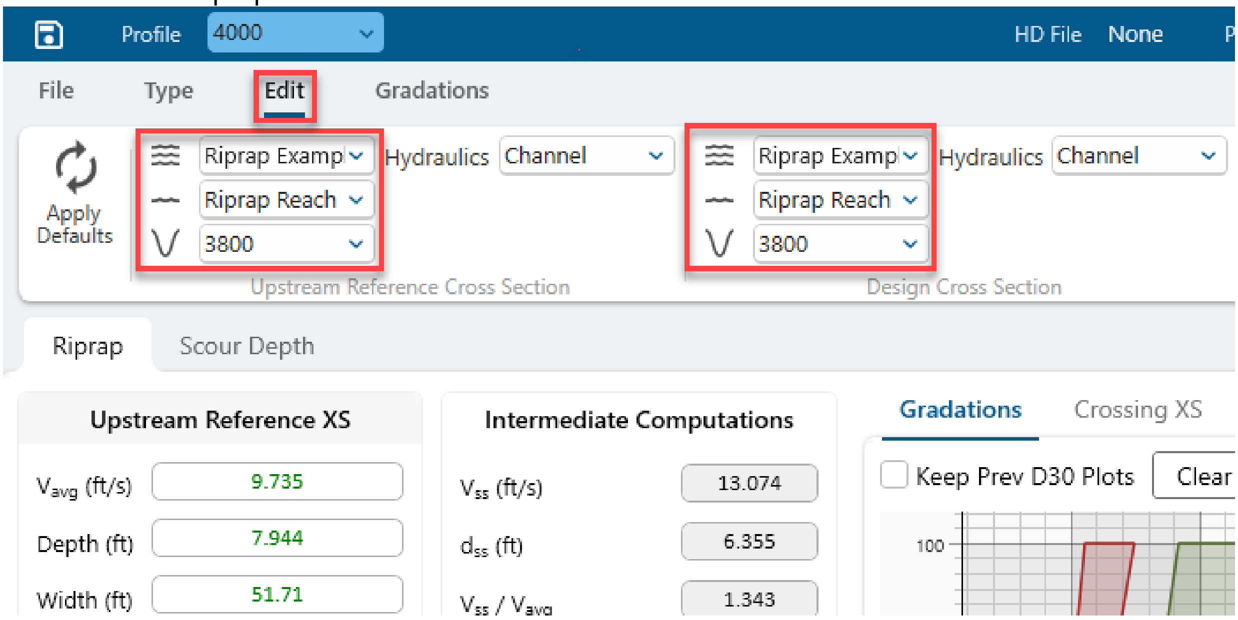
The riprap calculator only uses three hydraulic parameters from HEC-RAS, making the tool easy to use with or without a steady flow simulation. To use the calculator without HEC-RAS results, open the HD editor without a simulated plan.

Alternatively the user can overwrite HEC-RAS results. In the HD editors, if a user replaces a hydraulic parameter that the tool generally reads from HEC-RAS output, the calculations update based on the change. But the Riprap and Scour Calculator will update the value from green to red, to indicate that the value has changed.



Step 2: Identify Design and Upstream Reference XSs

Choose the River, Reach, and River Station of the design and reference cross sections in the **Edit** tab above the main riprap calculator.



Select the Design Cross Sections

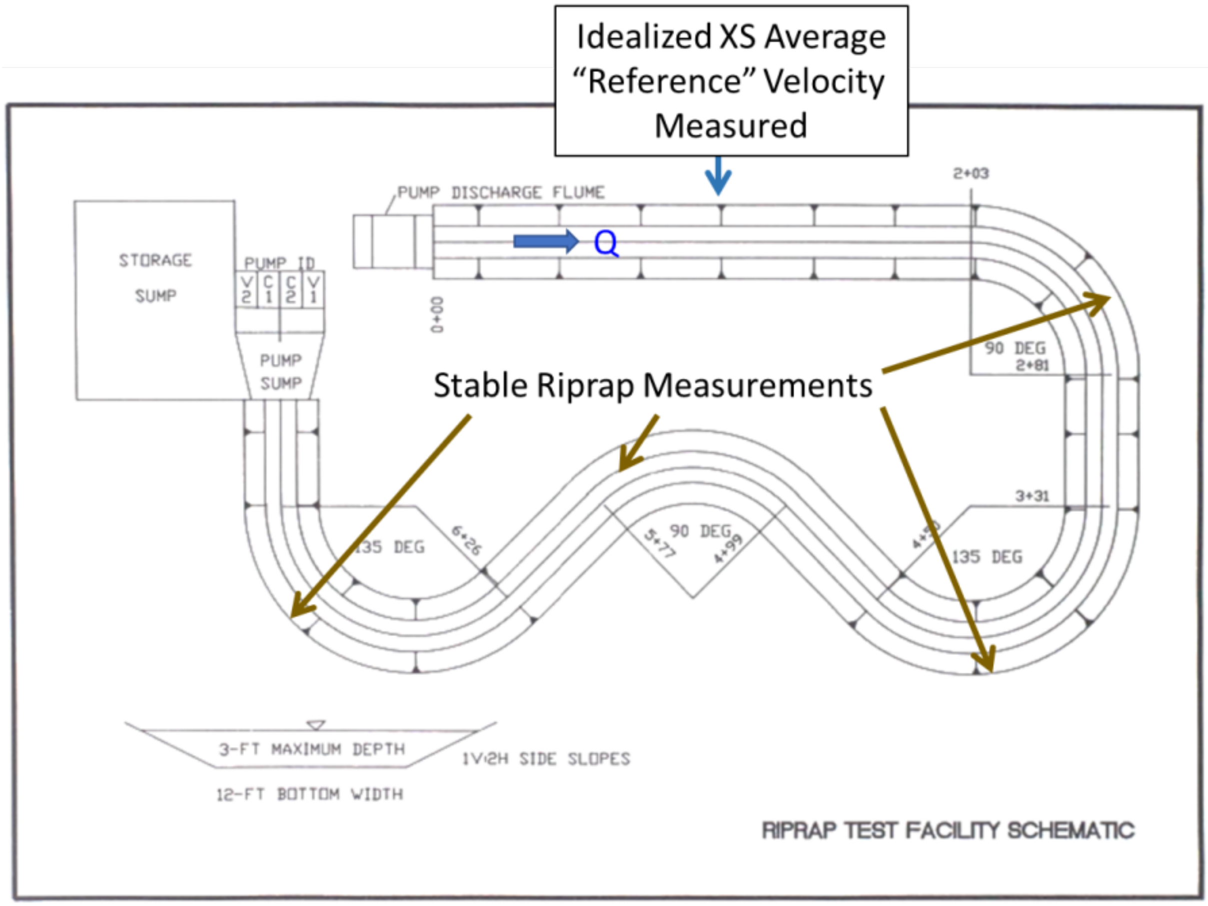
The Design Cross Section should be the cross section that will exert the highest hydraulic forces on the bank. This will be the critical condition for rock mobility, and will determine rock size.
The critical cross section location is generally on the outside and downstream end of a bend.

Note:

The USACE riprap calculation is *only* based on the reference cross section. It does not use the design cross section anywhere in the calculations. But you still must identify a design cross section to compute the radius of curvature and it is just good design and engineering practice to identify the worst-case design location. The Scour Calculator does use the design cross section in its calculations.

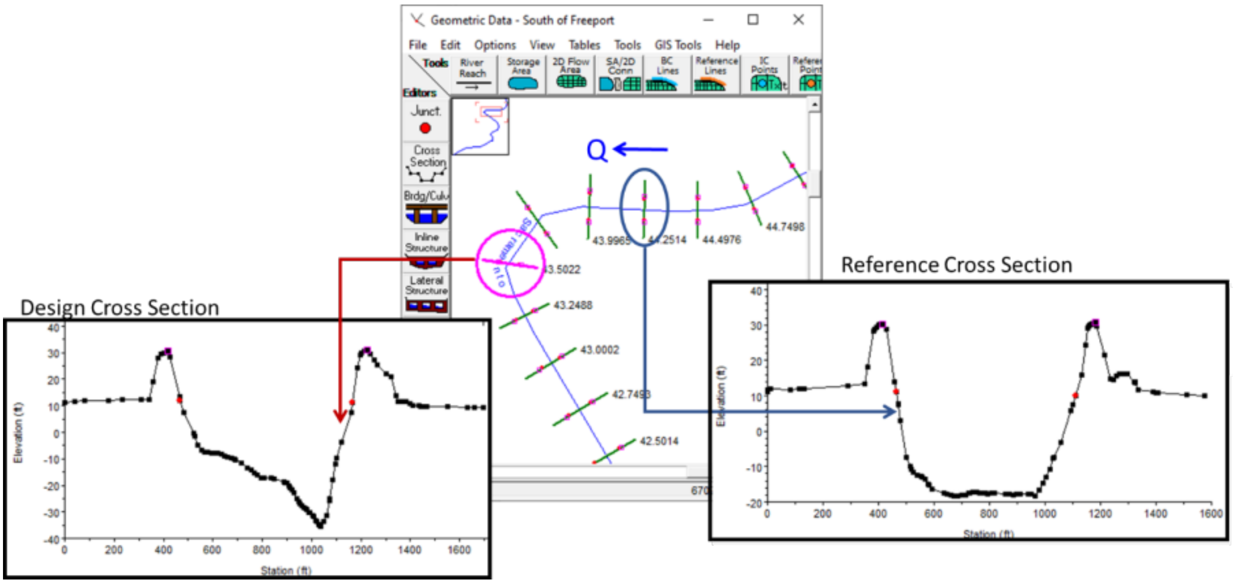
Select the Reference Cross Sections

The USACE Riprap equation is based idealized 1D measurements. A schematic of the ERDC Riprap test facility - used to develop these equations - is included below. The stable rock size in the bends was not correlated to local velocities, or even the average velocity in the bend, but in a straight, symmetrical, idealized reach upstream of the bends.

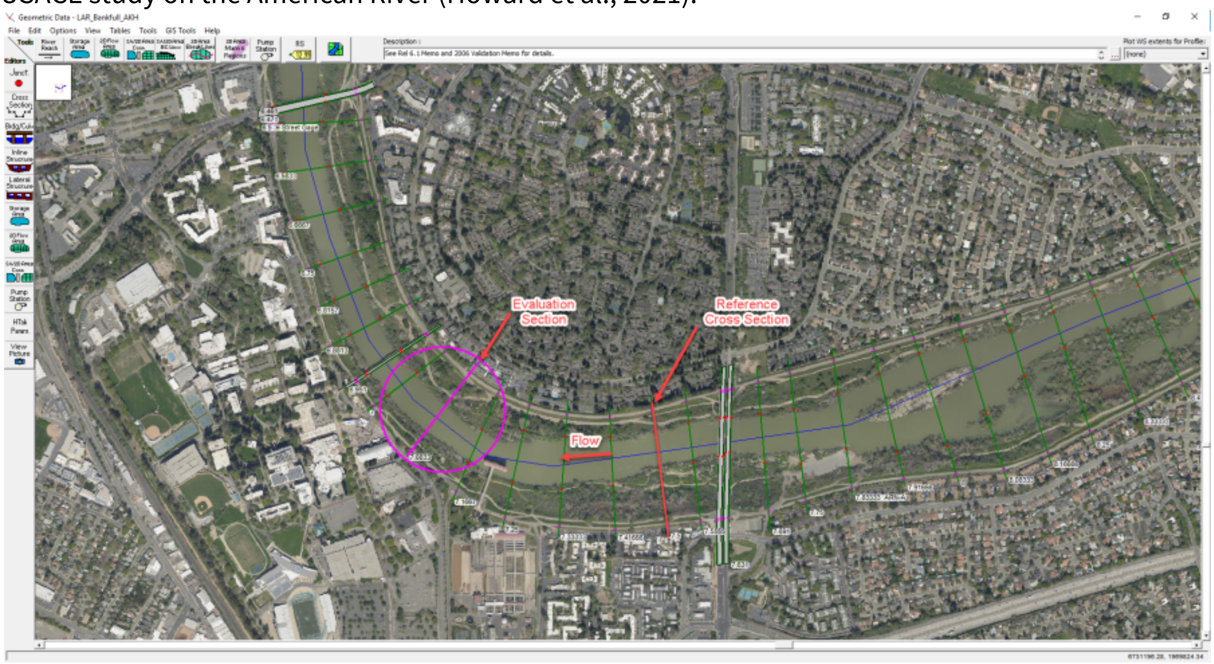


To respect the assumptions of the analysis and transfer these mesoscale laboratory data to field applications, we must not only use 1D cross-section average velocities, but 1D velocities in a relatively symmetrical, idealized reach upstream of the bend.

The figure below identifies an idealized design and reference cross section. The design cross section is highly asymmetrical, with a deep pool on the outside of the bend. This cross section shape is the result of helical flow and multi-dimensional processes. An average XS velocity from this cross section is not appropriate for the empirical equations used in this calculator. The "crossing" or "run" cross section upstream has a more symmetrical geometry. One-dimensional, cross section averaged, velocities at this cross section are a better approximation of system velocities and the analysis assumptions.

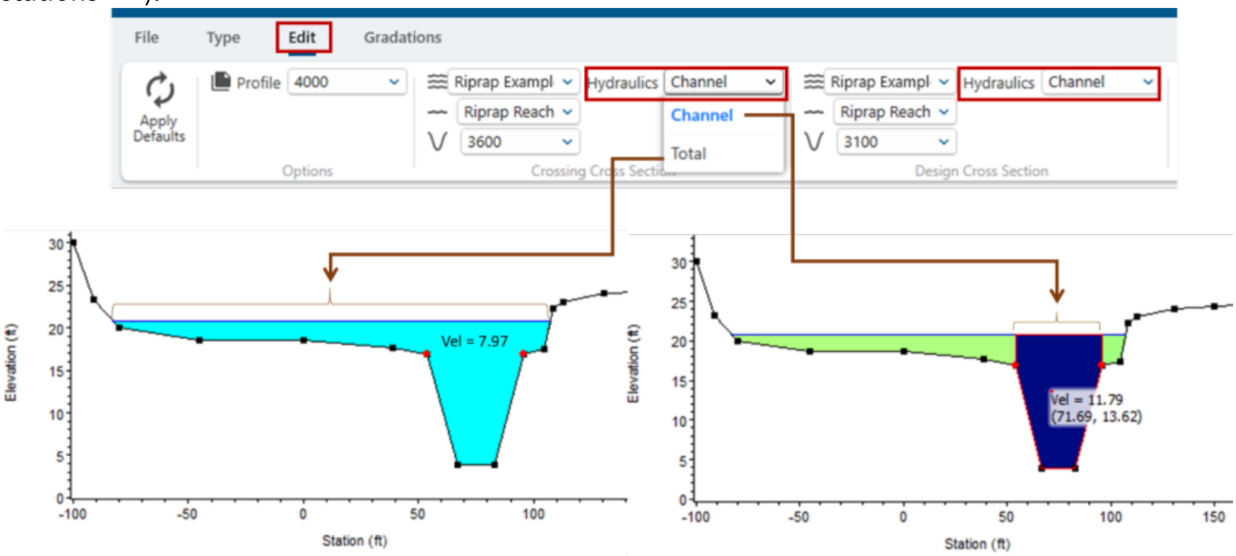


The next figure shows the selected design ("evaluation") and reference cross sections for an actual USACE study on the American River (Howard et al., 2021).



Hydraulic Averaging Assumption

HEC-RAS can provide two average velocities for the Design and Reference Cross Sections. The model can average velocity over the entire cross section (including channel and flood plains/overbanks) or it can report an average velocity for the channel alone (the region of the model between the bank stations 🔴).



> **Modeling Note:**
>
> It is important that bank stations are defined appropriately for the riprap design flow. Bank stations that have been set based on the low-flow channel may need to be revised to reflect the effective main channel for the design condition.

The riprap experiments used the entire cross section, but only used idealized, trapezoidal channels. They did not consider or measure results from compound channels. Therefore, qualitative engineering judgement is often required to apply these results to natural, compound channels. The channel velocity will usually be more appropriate for this analysis and is the default.

Results will be sensitive to the reference cross section selected, so Sensitivity Analysis are recommended (see section on the persistent d_{30} tool).

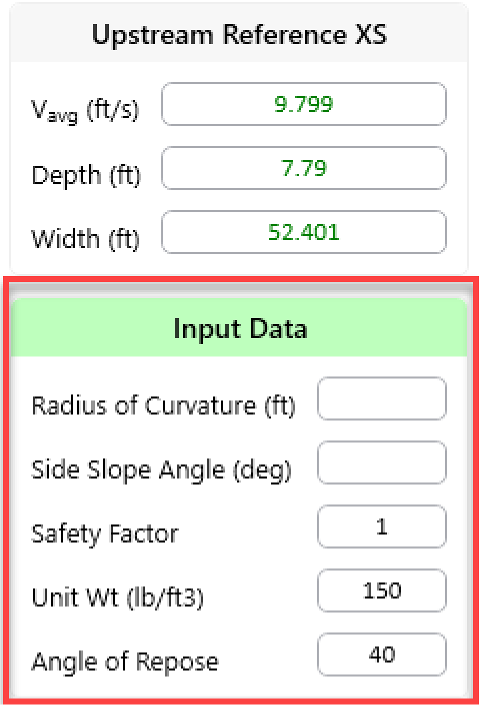
The Riprap and Scour Calculator use the same design and reference cross section. These are global options that affect both tabs.

Summary of Hydraulic Modeling Considerations for Riprap Analysis

1. The typical USACE project design approach is to select the critical velocity / stone size from the reference and design cross sections for an entire reach and use that for rock size, gradation, and construction plans. Most USACE projects will use only one or two riprap gradations for the entire project to be economical from the quarry and for constructability
2. The user often will create a geometry with modified parameters (ineffective flow, roughness, expansion / contraction coefficients) to compute the best estimate velocity for use with the calculator.
3. Converting unsteady flow models to steady flow for application with the Riprap calculator will often require revised model calibration.
4. Run a full range of frequency profiles to select the most critical design condition with informed user choices for risk tolerance.

Step 3a: Define Manual Input Variables

The Riprap Calculator requires five additional measurements and parameters that do not come directly from HEC-RAS results. Three of those parameters populate with default values, two require user input:



Radius of Curvature (R)

Both the riprap and scour equations are based on a dimensionless ratio of the radius of curvature to the channel width (R/W) which is a relative measure of bend severity. HEC-RAS will compute the width of the selected cross section. The numerical width is the wetted top-width between the channel banks (or the distance between the channel banks if the entire channel is inundated).

You must compute and enter a Radius of Curvature which quantifies the severity of a bend.

An example of the Jones Creek Bend on the Brazos River in Fort Bend County, Texas is included below. A circle was fit to the bend in Google Earth, which reported the radius. This bend has a radius of curvature of 1,155 ft and a channel width of 410 ft for an R/W ratio of 2.8. The riprap and bend scour calculations are all very sensitive to the R/W ratio. Therefore, identifying the appropriate radius of curvature, and carefully distinguishing the curvature scales of compound bends (see next section) will affect results.

Modeling Note: Radius of Curvature Extent

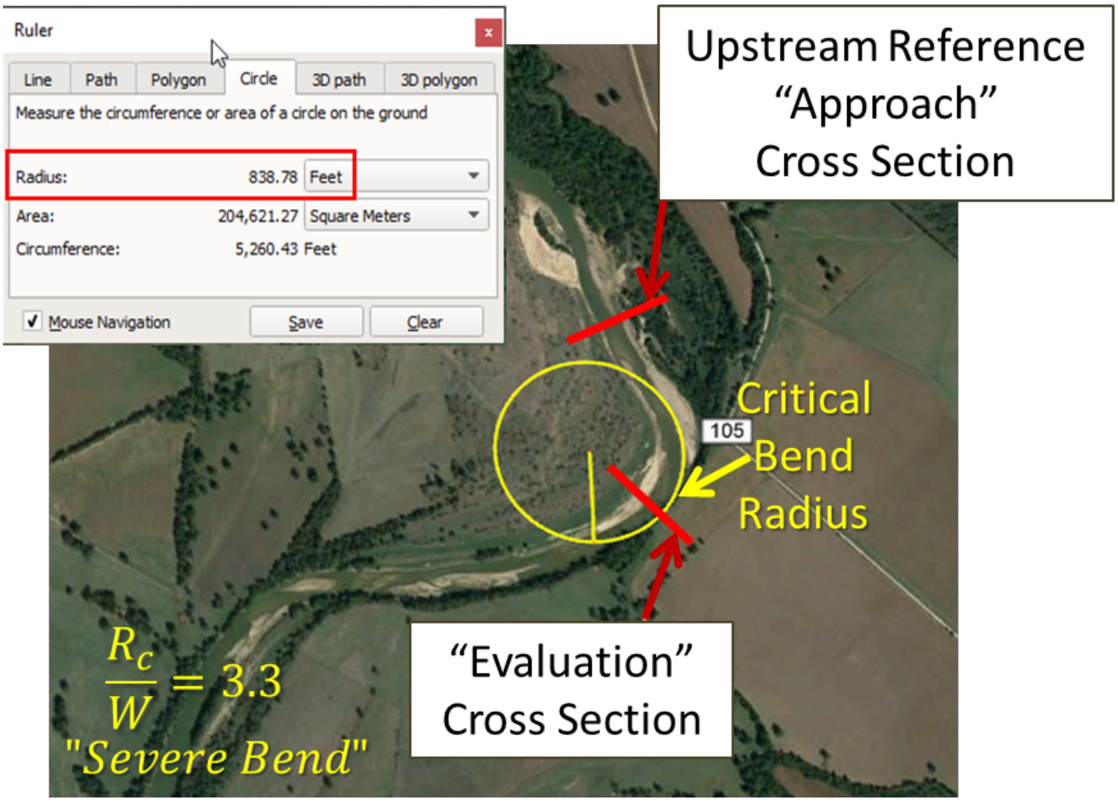
Different agencies and manuals of practice measure the radius of curvature differently. Some extend the circle that measures this radius to the edge of the bank. Others extend it to the centerline of the river. This variability in practice is part of the uncertainty in these calculations.

Computing the Radius of Curvature

You can compute the radius of curvature in a GIS, but Google Earth also has all the tools you will need to measure this input. The Radius of Curvature computation has three steps:

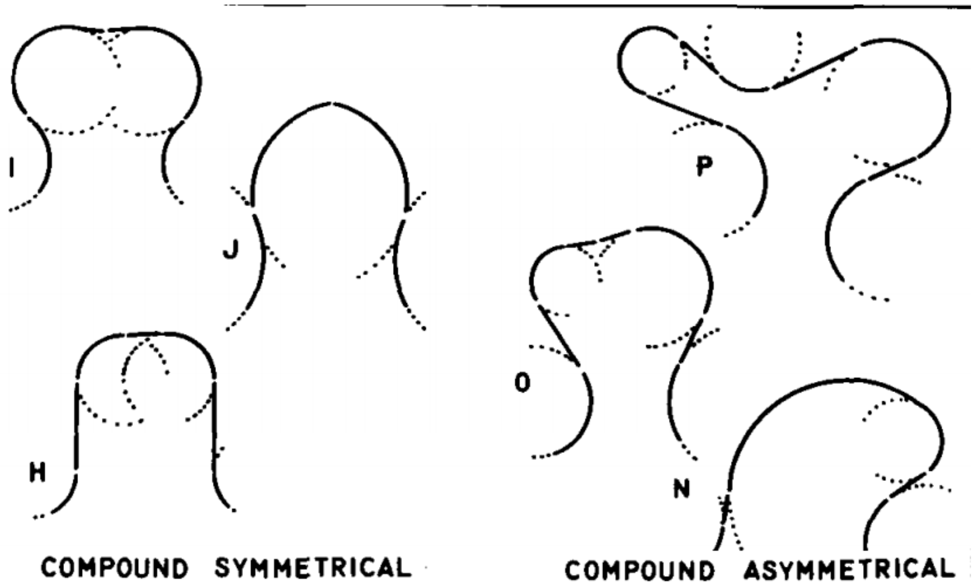
- Delineate the critical bankline, which is usually on the outside of the downstream third of the bend.
- Fit a circle to the critical section of the bend where the bend scour equation will be applied.
- Compute the radius of that circle.

The following figure illustrates an example radius of curvature calculation.

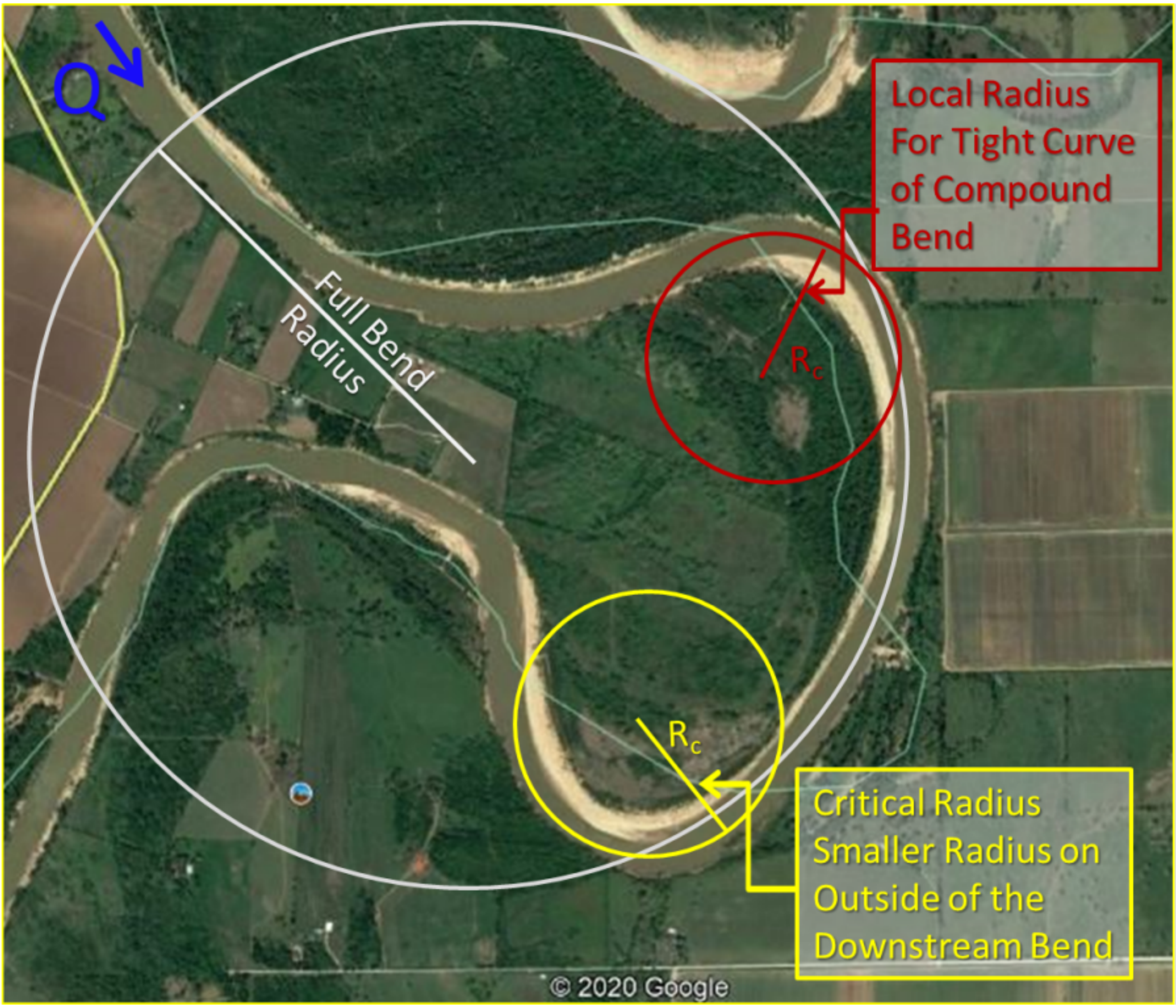


Compound Bends

Some bends do not have simple geometries, making it difficult to fit one, idealized circle to the bend. Bends that curve on multiple scales are called "compound bends." Brice (1974) Brice, J. (1974) "Evolution of Meander Loops" *Geological Society of America Bulletin,* 85, 581-586. illustrated and classified several examples of compound bends in the figure below:



The following figure includes an example of a compound section, which includes river bends at multiple scales (David May, personal communication). It is important to select the bend radius (and scour) at the critical location on a compound bend and the critical (usually the smallest), associated radius of curvature.



Radii of curvature appropriate for bend scour analysis on different locations along a compound bend. The section most susceptible to scour is often the downstream, outside bank of a tight sub-meander (the critical radius in the image).
It can be useful to compute stable rock size and scour at several locations within a compound bend to identify the critical location.

For more radius of curvature guidance and examples, see the detailed discussion in the National Cooperative Highway Research Program (2004) Handbook for Predicting Stream Meander Migration and Supporting Software.

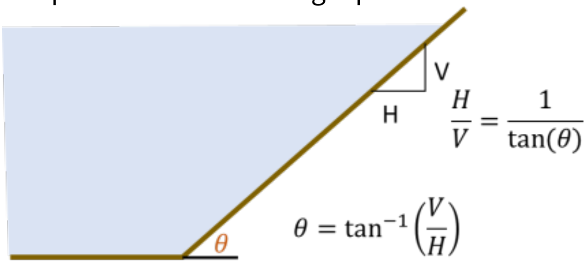
Side Slope (θ)

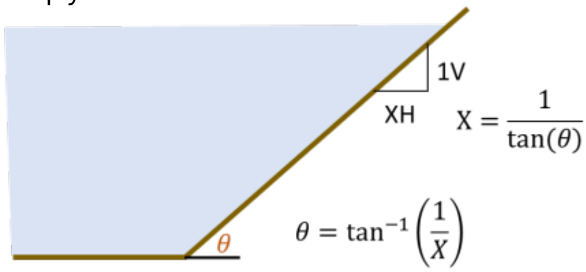
There are three common and interchangeable ways to define the side slope angle in engineering and architecture. HEC-RAS usually uses the ratio of horizonal distance to vertical rise (H:V) or the inverse.

The Riprap Calculator requires the bank side slope in degrees. Equations for converting V:H or % slope measurements to degrees (and back again) are included in the next section.

Converting Side Slope (Degrees, V:H, Percent)

Engineering and architecture use three interchangeable methods to quantify slope: degrees, V:H, and percent. The following equations and table will help you convert between them.





Degrees	V:H	Percent
0.6°	1 : 95.49	1.0%
1°	1 : 57.29	1.7%
1.15°	1 : 50	2%
1.19°	1 : 48	2.08%
2.86°	1 : 20	5%
4.76°	1 : 12	8.3%
5.71°	1:10	10%
7.13°	1 : 8	12.5%
10°	1 : 5.67	17.6%
14.04°	1:5	20%
14.04°	1 : 4	25%
15°	1 : 3.73	26.8%
18.43°	1:3	33.3%
26.57°	1 : 2	50%
30°	1 : 1.73	57.7%
33.69°	1:1.5	67.7%
45°	1 : 1	100%
60°	1 : 0.6	173.2%
90°	1 : 0	inf.

Safety Factor (FS)

HEC-RAS sets the safety factor to 1, by default. This provides the unfiltered results of the equation, and allows the user to make their own choice about the risk tolerance built into the Factor of Safety.

However, USACE Guidance (EM 1110-2-1601) recommends setting the **Factor of Safety to 1.1**.

The riprap calculator will multiply the calculated d30 by the factor of safety (so FS=1.14 will increase the d30 by 14%), increasing the W30 by approximately 50%. EM 1110-2-1601 includes several considerations that should lead a project team to increase the Factor of Safety.

Unit Weight

HEC-RAS uses the unit weight to convert riprap diameter to dry placement weight, using the equation:

$$Rock\ Weight = \frac{\pi * Unit\ Weight * Diameter^3}{6}$$

This is only used if the user requests results and gradations in terms of weight, instead of rock size (which is a common convention in riprap design).

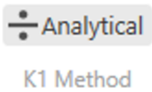
Modeling Note: Spherical Particles

The weight-diameter conversion assumes spherical particles. The volume is approximately half of an equivalent cube with edges matching the diameter. Some methods suggest using a ratio of 75%-85% of the equivalent volume of a cube, which would increase the weight or a stable particle diameter. Applying the assumption of angular riprap in the calculations does not affect the weight-diameter relationship.

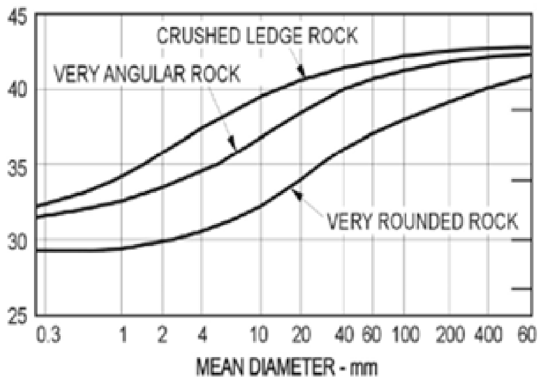
Angle of Repose (ϕ)

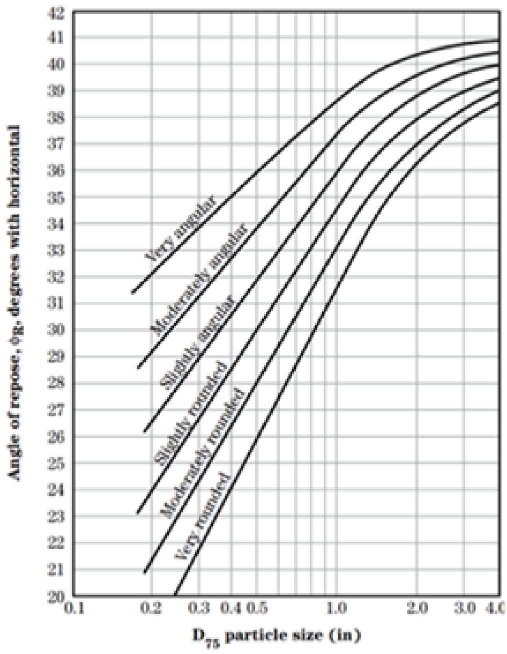
The angle of repose is the angle of the maximum slope an aggerate develops before it starts to move. It is a function of the size, compaction, and angularity of the material. Riprap tends to vary between 35 and 45 degrees. HEC-RAS populates a default of 40^{o}.

$$K_1 = \sqrt{1 - \frac{\sin^2 \theta}{\sin^2 \emptyset}}$$



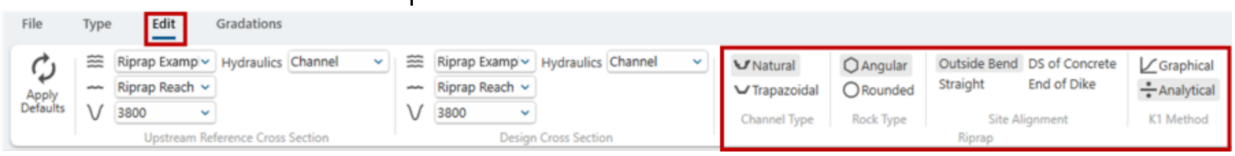
The riprap calculation only uses the angle of repose in the analytical calculation of K1.



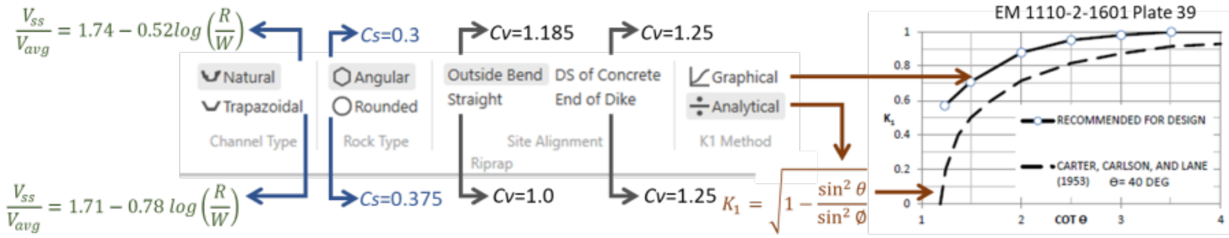


Step 3b: Select Riprap Coefficient Parameters

The riprap equation has several empirical coefficients or coefficient equations that the riprap calculator selects based on user options in the **Edit** ribbon:



These options translate into the following equation coefficients, equations, and parameters in the d_{30} calculation described in the Step 4:



These parameters and equations will be discussed in more detail in the next section on the d_{30} calculations, but are briefly described below:

Channel Type:
Choose **Natural** for a non-engineered channel with native materials in the bed and banks and some bank vegetation. Chose **Trapezoidal** for an engineered channel. The riprap calculator will choose the equation to compute the side slope velocity based on this selection. The calculator will generally compute higher side slope velocities for trapezoidal channels for all observed bends (as long as R/W>1).

Rock Type: The **Stability Coefficient** (C_S) was the original coefficient in the riprap equation. This is a linear coefficient in the equation, and is 0.3 for rounded rock (e.g. natural river stone and cobbles) and 0.375 for angular rock (e.g. riprap).

> **Warning**
>
> Community partners, project biologists, and landscape architects will often advocate for rounded river rock instead of angular, crushed riprap because it is aesthetically appealing. It is important to carefully account for rock type in the stability analysis. According to this equation, rounded rock must be 25% larger and 100% heavier (weight increases to the cube power of diameter) to provide comparable protection.

Site Alignment: The riprap calculator will also require a larger d_{30} if the site alignment deviates from a straight channel. This option selects the **Vertical Velocity Distribution Coefficient** (C_V) in the riprap equation, which is 1 for straight channels and 1.25 for locations where the channel transitions
Images?
from an engineered section to an un-protected section (downstream of a concrete lining or the end of a dike. At the outside of the bend, it computes the *Cv* coefficient based on the logarithm of the R/W ratio:

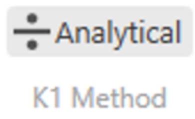
$$C_v = 1.283 - 0.2\log\left(\frac{R}{W}\right)$$

This value falls between 1 and 1.22 for 2<R/W<25. If R/W>25 the equation computes C_V less than 1, but the Riprap Calculator enforces a minimum value of C_V=1.

K1 Method: The riprap equation incudes a **Side Slope Correction Factor** (K_1). This factor is in the denominator of the Maynord equation and is a function of a trigonometric function of the side slope angle (θ), making the rock size directly related side slope (e.g. steeper slopes require larger rock).

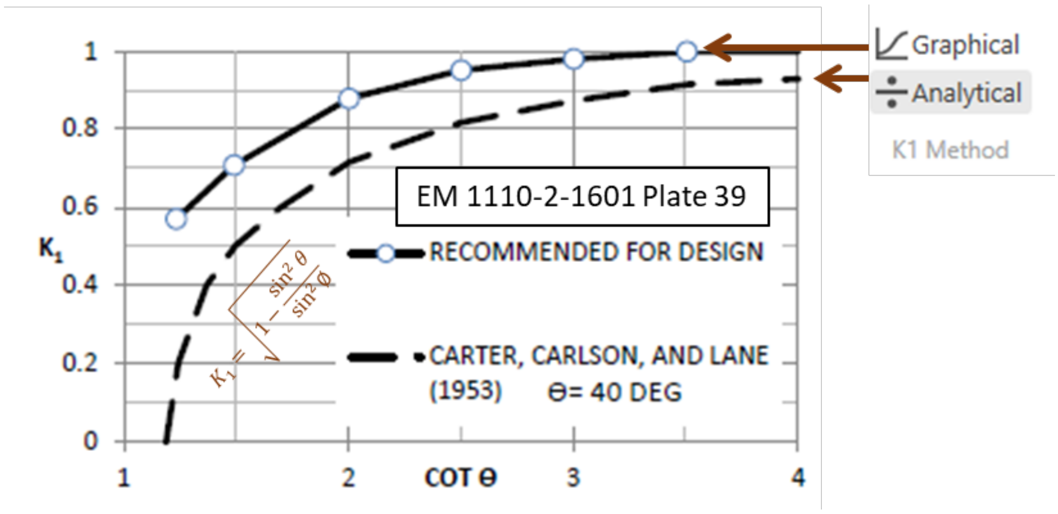
Early approaches used a relationship between the side slope angle and the angle of repose from Carter, Carleson, and Lane (1953):

$$K_1 = \sqrt{1 - \frac{\sin^2 \theta}{\sin^2 \emptyset}}$$



This is the "Analytical Approach" in the Riprap Calculator.

But the USACE Manual of Practice (EM 1110-2-1601) follows Maynord (1988), who found this relationship too conservative, and unhelpfully dependent on the angle of repose – which is uncertain. Therefore, the USACE recommended approach selects K_1 based on a recommended curve from Plate 39 in EM 1110-2-1601:



This is the "**Graphical Approach**" in the Riprap Calculator, which is the default.

Note:

Increasing the side slope has a direct, gravitational, impact on side slope rock size. But the K_1 factor is also included in the bed size equation. This effect is less direct.

Note: Slope Angle Approaching Angle of Repose

In some riprap sizing methods, as the side slope approaches the angle of repose, the required rock size approaches infinity because the rock is at the critical conditions for incipient motion.

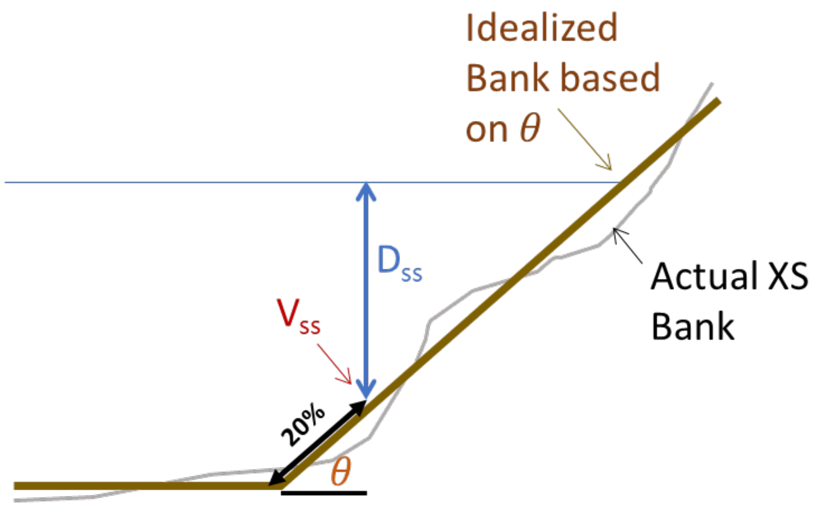
Step 4: Compute the d30 of the Stable Rock Size

The Riprap Calculator uses the Maynord equation to compute riprap size. The Maynord equation computes the 30th percentile rock size that should remain stable at the design velocity on the channel bed and on the side slope. Because of the gravitational component, the stable rock size on the side slope will be larger than the bed.

Computing Side Slope Velocity (V_{ss}) and Depth (D_{ss})

The Riprap Calculator uses the average channel velocity (V) and the hydraulic depth (D) from the upstream reference cross section to compute the riprap size on the channel bed. Then it computes modified side slope velocities (V_{ss}) and depth (D_{ss}) from V and D to compute the stable d30 on the side slopes.

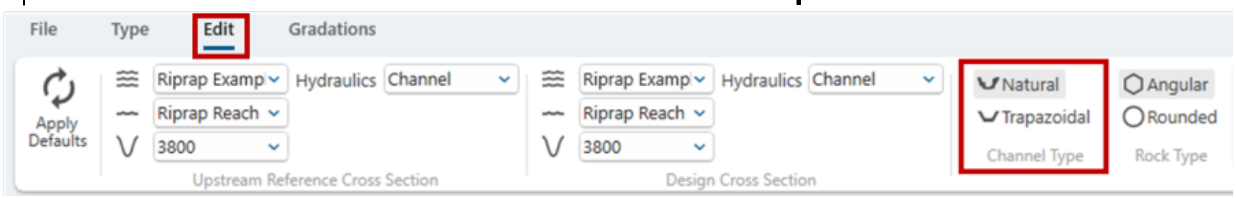
The Maynord equation computes the side slope velocity and depth based on a point located 20% of the length up the slope from the toe along an idealized wetted bank (based on the user entered side slope).



The riprap calculator computes D_{ss} with simple trigonometry (see next section).

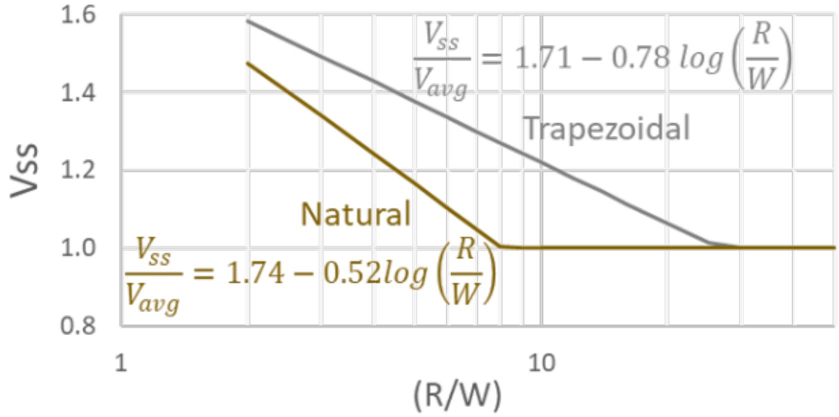
V_{ss} Calculation

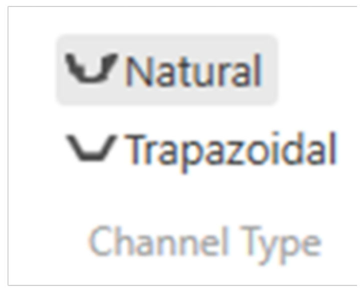
Computing the velocity at this critical side slope location (V_{ss}), from the 1D, channel-averaged velocity is not intuitive. EM 1110-2-1601 includes two empirical equations, based on measurements at this side slope location, from the Riprap Test Facility. The riprap calculator determines which equation to use based on whether the user selects **Natural** or **Trapezoidal** channel:



The Riprap Calculator uses the following relationships to compute the ratio of the side slope velocity to the average channel velocity (V_{ss}/V_{avg}). Because the side slope velocity (V_{ss}) is assumed to be at the outside of the bend, the side slope velocity should be greater than or equal to the average velocity ($V_{ss} \geq V_{avg}$). Therefore, when the logarithmic V_{ss}/V_{avg} relationships drop below 1, the Riprap

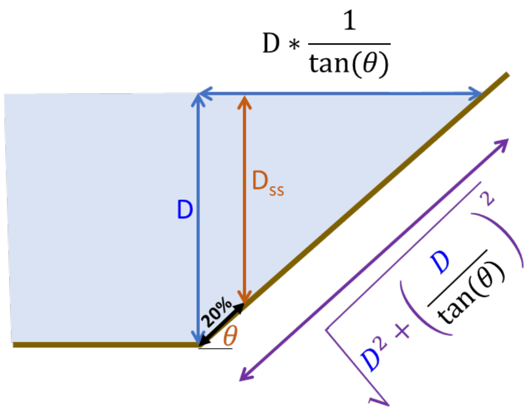
Calculator sets V_{ss}=V_{avg}.





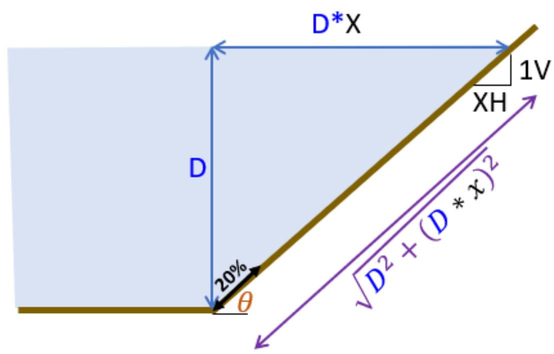
D_{ss} Calculation

The Riprap Calculator computes the depth 20% up the idealized side slope with simple trigonometry based on the side slope angle and the depth in the main channel:



$$\boxed{D_{ss} = D - 0.2\sqrt{D^2 + \left(\frac{D}{\tan(\theta)}\right)^2} * \sin(\theta)}$$

This equation can also be formulated in terms of a V:H



slope:

$$\boxed{D_{ss} = D - 0.2\sqrt{D^2 + (D * x)^2} * \sin(\theta)}$$

The Maynord Equation

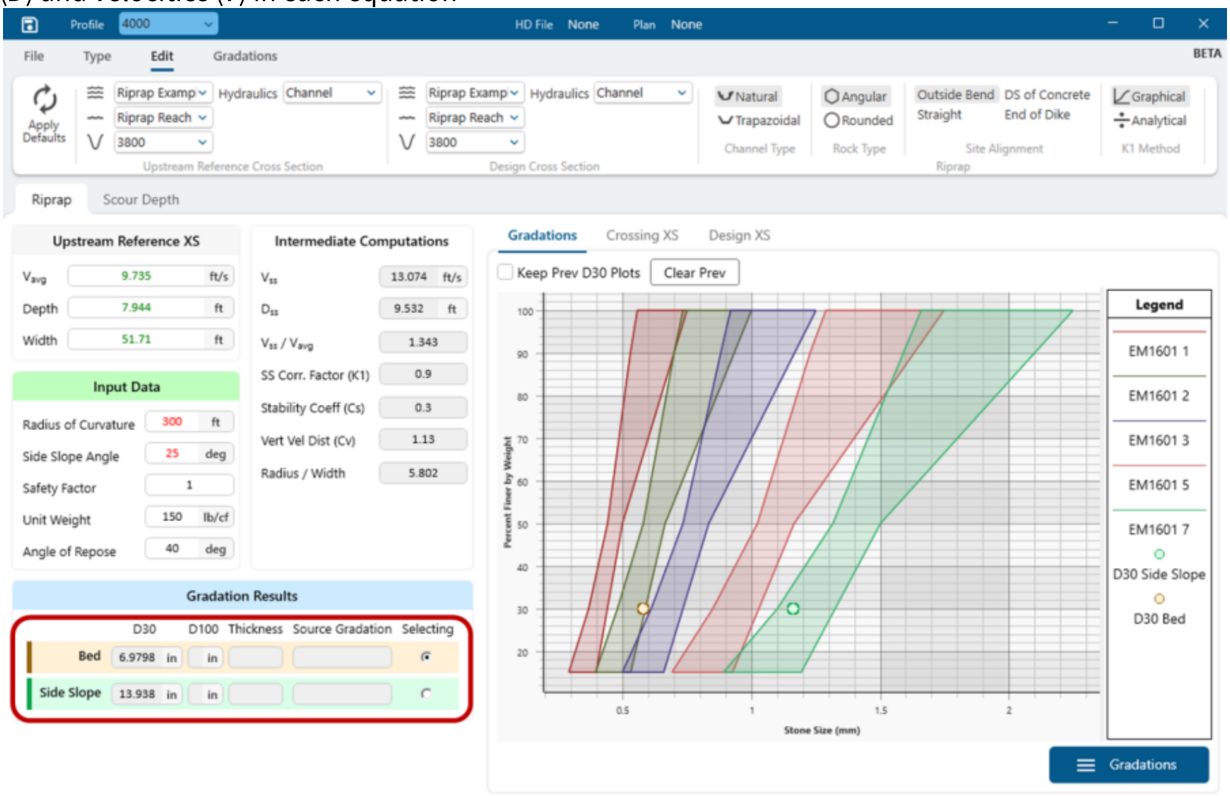
USACE guidance uses the Maynord equation to compute the minimum riprap size. This equation computes the 30th percentile grain size of the recommended rock gradation. The Maynord equation is:

$$d_{30} = SF \cdot C_s C_v D \left[\sqrt{\frac{\gamma_w}{\gamma_s - \gamma_w}} \frac{V}{\sqrt{K_1 g D}} \right]^{2.5}$$

Where:

SF = Safety Factor (USACE recommended = 1.1)
C_s = Stability coefficient for incipient failure (0.3-0.375)
C_v = Vertical velocity distribution coefficient (≥1.0)
D = Depth (either D_{avg} for bed or D_{ss} for side slope) (ft, m)
V = Velocity (either V_{avg} for bed or V_{ss} for side slope) (ft/s, m/s)
g_w = Unit Weight of Water (lb/ft^3, kg/m^3)
g_s = Unit Weight of solids (lb/ft^3, kg/m^3)
g = Gravitational constant (ft/s^2, m/s^2)
d_{30} = 30th percentile of recommended riprap gradation (computed in ft, reported in in, mm)

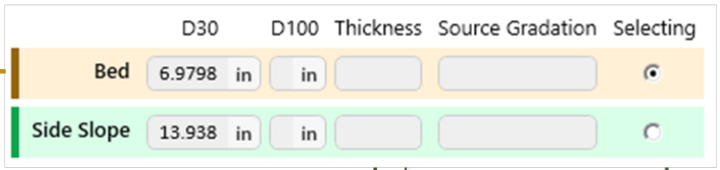
The Riprap Calculator applies this equation in the bed and banks, applying the appropriate depths (D) and velocities (V) in each equation



The calculator uses the hydraulic depth (*Depth*) and the average velocity (V_{avg}) to compute the

$d_{30(Bed)}$ in the bed. It uses the side slope velocity (V_{ss}) and side slope (D_{ss}) depth (computed 20% up the bank slope) for the side slope $d_{30(SS)}$.

$$d_{30(Bed)} = SF \cdot C_s C_v D_{Avg} \left[\sqrt{\frac{\gamma_w}{\gamma_s - \gamma_w}} \frac{V_{Avg}}{\sqrt{K_1 g D_{Avg}}} \right]^{2.5}$$



$$d_{30(SS)} = SF \cdot C_s C_v D_{SS} \left[\sqrt{\frac{\gamma_w}{\gamma_s - \gamma_w}} \frac{V_{SS}}{\sqrt{K_1 g D_{SS}}} \right]$$

Note:

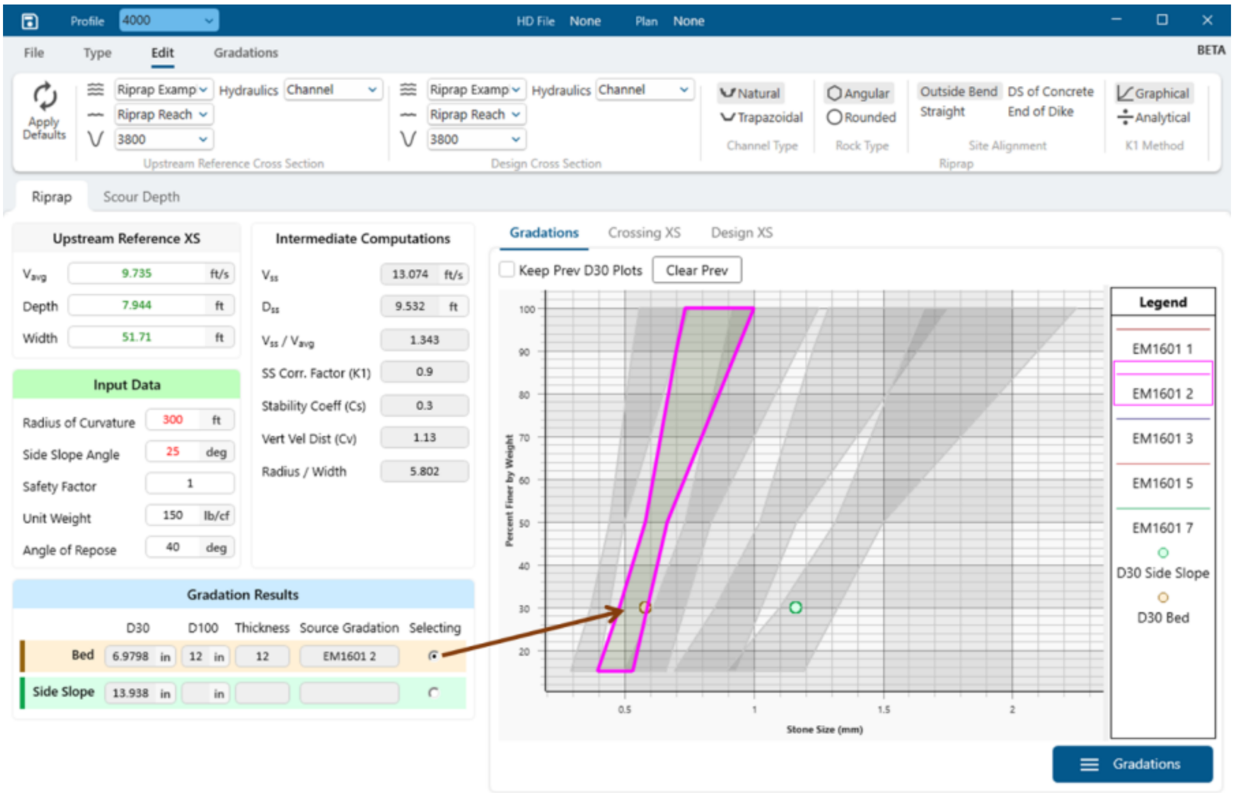
The Maynord equation and EM 1110-2-1601 also include a thickness coefficient C_T. But C_T=1 for the recommended thicknesses of Max($1.0d_{100}$ or 1.5 d_{50}) which is the reported thickness in the Riprap Calculator. Therefore, the interface and documentation do not include this coefficient.

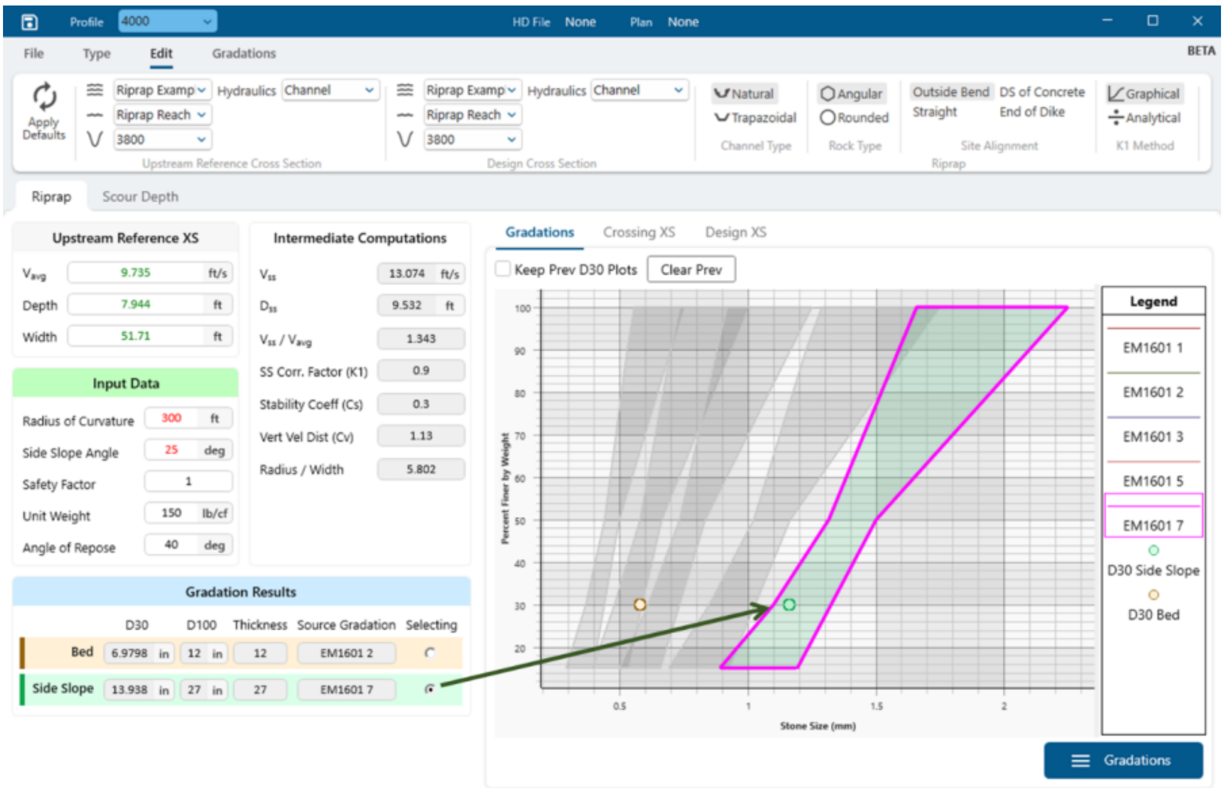
Step 5: Select Gradation to Compute Thickness

The Maynord equation and the Riprap Calculator compute a stable d_{30}. However, you will have to select a gradation to find the d_{50} and d_{100} required to compute the design riprap thickness. The Riprap Calculator uses an interactive plot tool to select a gradation for the bed and side slope computations, to complete the analysis.

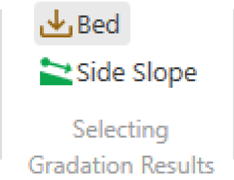
Select a Gradation to Compute Thickness

The Riprap Calculator plots the computed d_{30}s with the selected or user-input gradations. To associate a gradation with the bed or side slope analysis, click the radio button under **Selecting**, and then click on the curve or polygon associated with the gradation.





You can also toggle between the selected gradation with the Bed and Side Slope options in the

Gradation ribbon: 

When you click on a gradation curve or polygon in the plot, to associate it with the bed or bank riprap calculations, the calculator will pull the d_{50} and d_{100} from the curve or area. It will use these sizes to compute the thickness.

EM 1110-2-1601 recommends sizing the riprap thickness to the d100 or 150% of the d50. Therefore, the riprap calculator reports the d_{100} of each selected gradation and the thickness (maximum of d_{100} or 1.5 d_{50}).

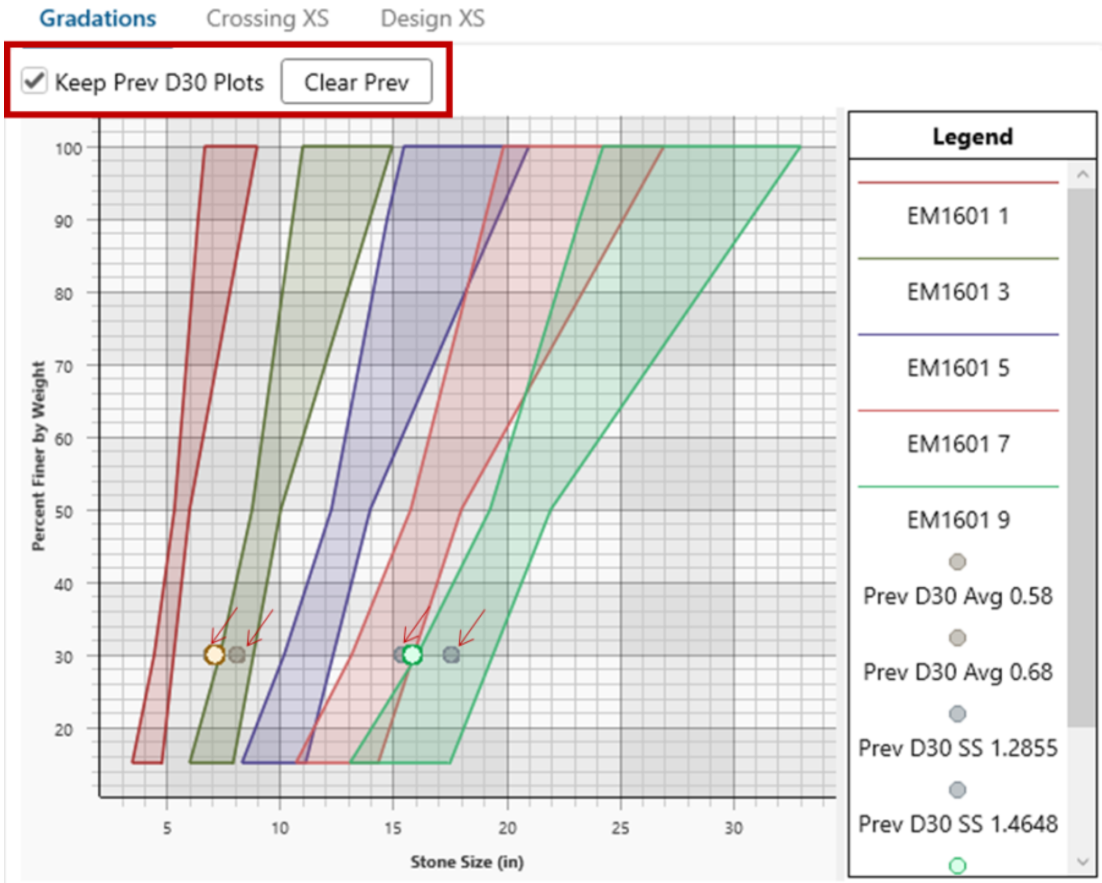
d_{30} Cross Section Sensitivity Analysis

The computed d_{30} is often very sensitive to the reference cross section selected. Selection of a reference cross section is a qualitative judgement, so it is appropriate to evaluate the sensitivity of the result to that decision.

HEC added a "persistent d30" feature to the plot, 

like the persistent XS tool in the cross-section editor to support XS-sensitivity analysis. For example, the plot below includes results for three, candidate, Upstream Reference cross sections. The grey dots indicate d_{30} results from previous selected cross sections, showing the sensitivity of the d_{30} calculations to the Reference

Cross Section selection.

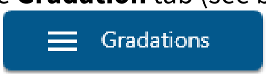


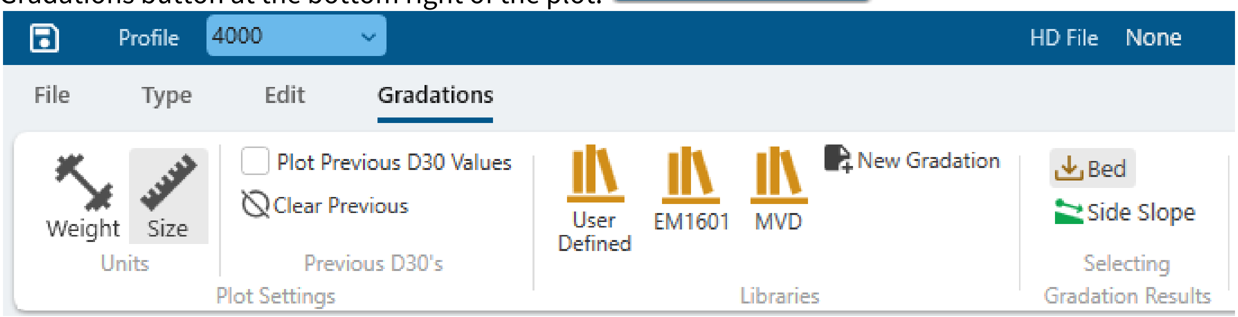
Add New Gradations

The Riprap Calculator includes a few sample gradations to allow initial thickness computations without customized gradations. The default gradations are theoretical riprap size curves from EM 1110-2-1601, which will fill out a d100 and thickness, but are very limited for design.

It is strongly recommended that users enter the gradations available at local quarries or from local suppliers.

To define (or manage) riprap gradations, select the **Gradation** tab (see below) or press the Gradations button at the bottom right of the plot.

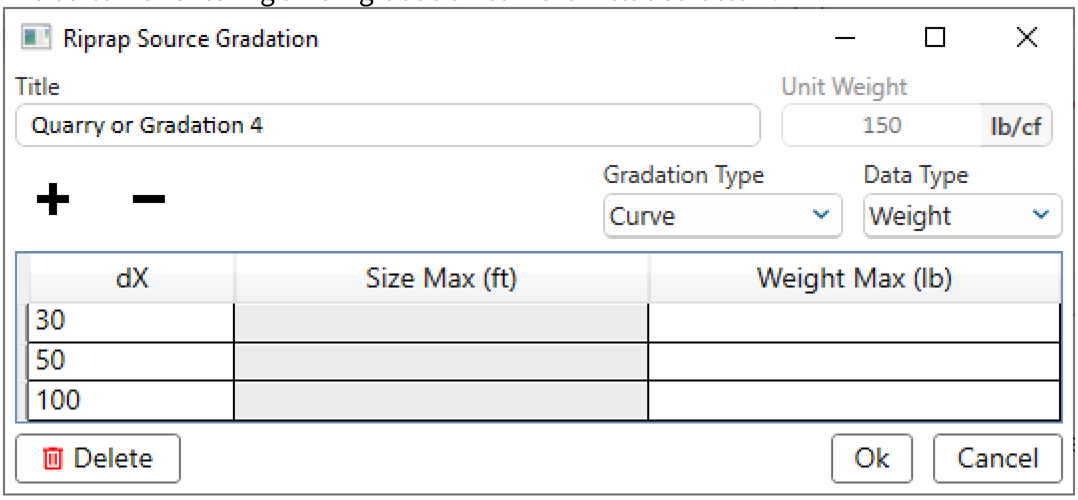




Define a new gradation by pressing **New Gradation** 

on the Gradation tab or pressing the **Gradation** button. 

The editor for entering a new gradation curve is included below:



You can define a gradation curve or polygon (under **Gradation Type** – see below) and can define percent finer or percent lighter. Users can also change the **Name** of the gradation or material. The editor reads the unit weight - which the calculator uses to convert size-to-weight – from the main editor.
A new gradation automatically populates three default grain size percentiles d_{30}, d_{50}, d_{100}. Users can add or delete these using the **+** and **–** buttons. 

Warning

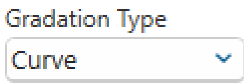
The dxx values are editable, but for the Riprap Calculator to work, a gradation must include a minimum one gradation ≤d_{30} and a d_{100}.

Warning

Percent finer should **Always** be defined in terms of particle weight rather than particle count. The % finer is the % of the total weight that is finer than a particular grain size or weight of rock not the number of particles. See further discussion and guidance below.

Gradation Curves

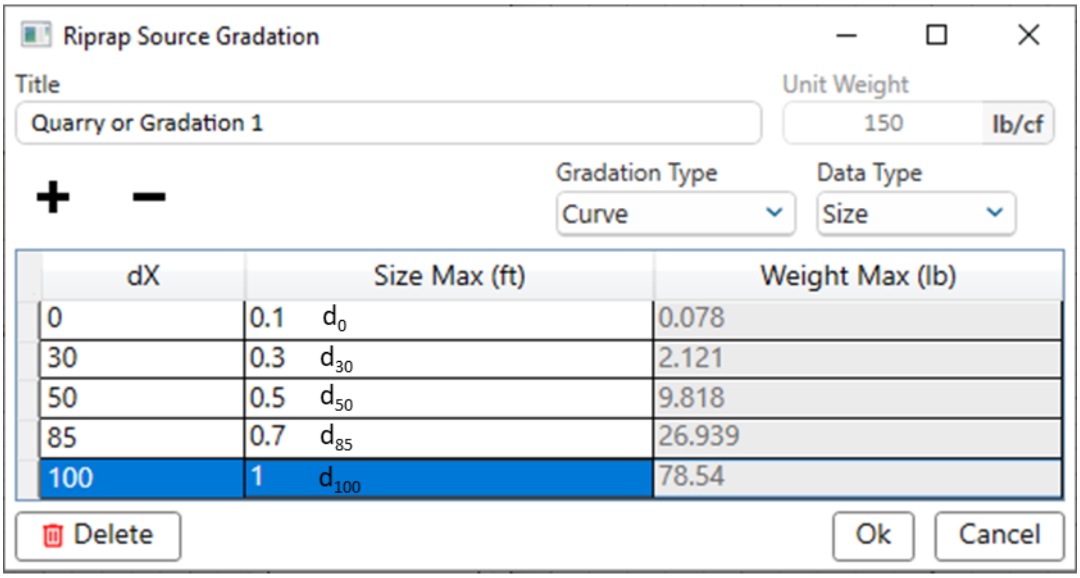
A **Gradation Curve** has a single weight or size associated with each grain-class percentile. It does not include a range and can be represented with a single curve. While the default gradations are polygons, representing a range, the new gradations default to **Curves**, reflecting a single value for each percentile.

To select this approach set **Gradation Type** to **Curve**: 

.

Gradation curves are monotonic relationships between grain class percentile, (e.g. d_{30}, d_{100}, etc) and either size of weight.

In the example below, the user added a d_0 and a d_{85} to the default gradations to define a five-point curve:



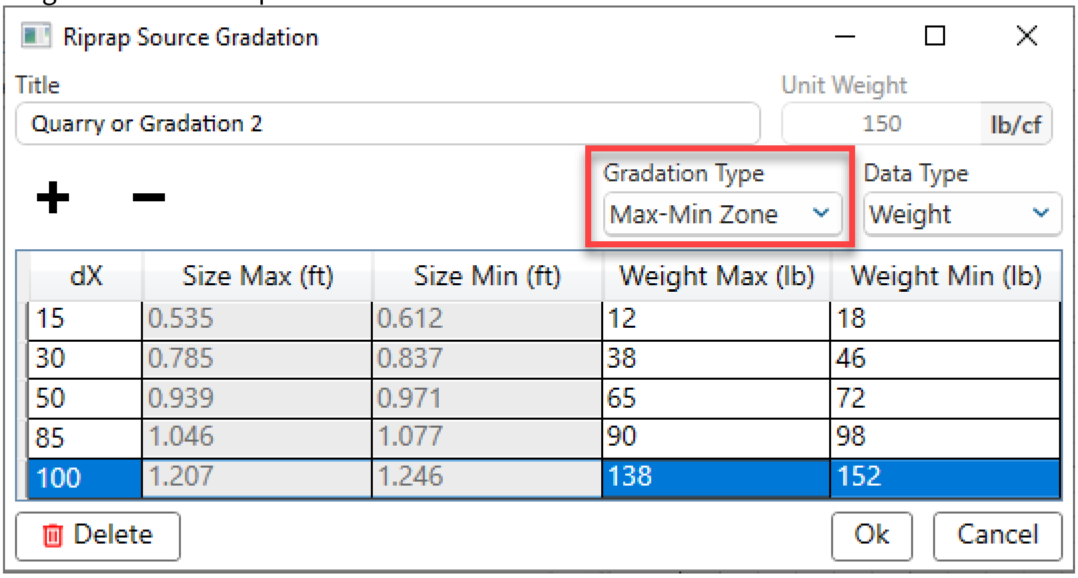
The gradation editor automatically converts size to weight (and visa versa) and stores them together, so the interface can toggle between them. The riprap calculator enforces a standard relationship between size and weight based on the equations:

$$W_{\%} = \frac{\pi \gamma_s d_{xx}^3}{6} \text{ and } d_{xx} = \left(\frac{6W_{\%}}{\pi \gamma_s}\right)^{1/3}$$

Where $W_{\%}$ is the weight percentile, g_s is the unit weight, and d_{xx} is the grain class percentile.

Gradation Polygons

Use gradation polygons for quarry gradations and rock specifications defined with a range of sizes or weights for each size percentile:



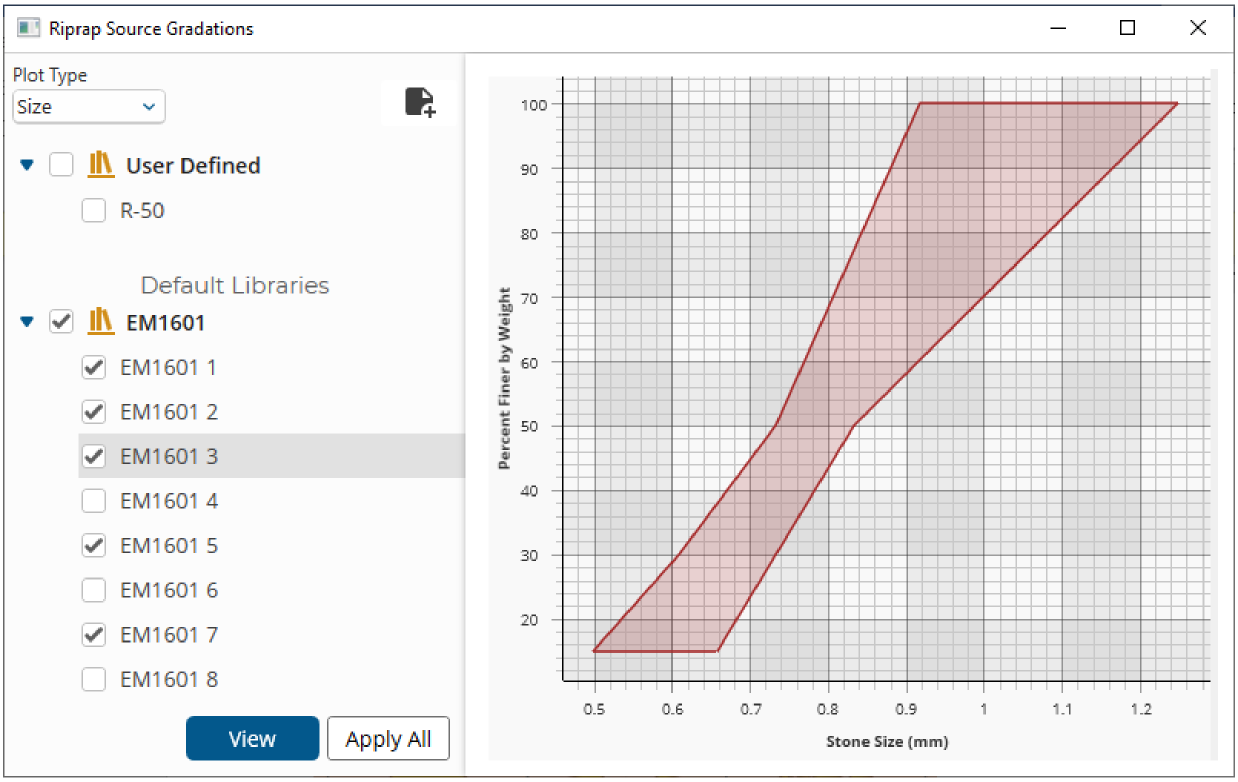
Note:

If you represent a USACE district and have standard gradations you would like to include in the Riprap calculator, please contact HEC.

Managing Gradations

Manage gradations by pressing the gradation button on the main window of the Riprap Calculator.

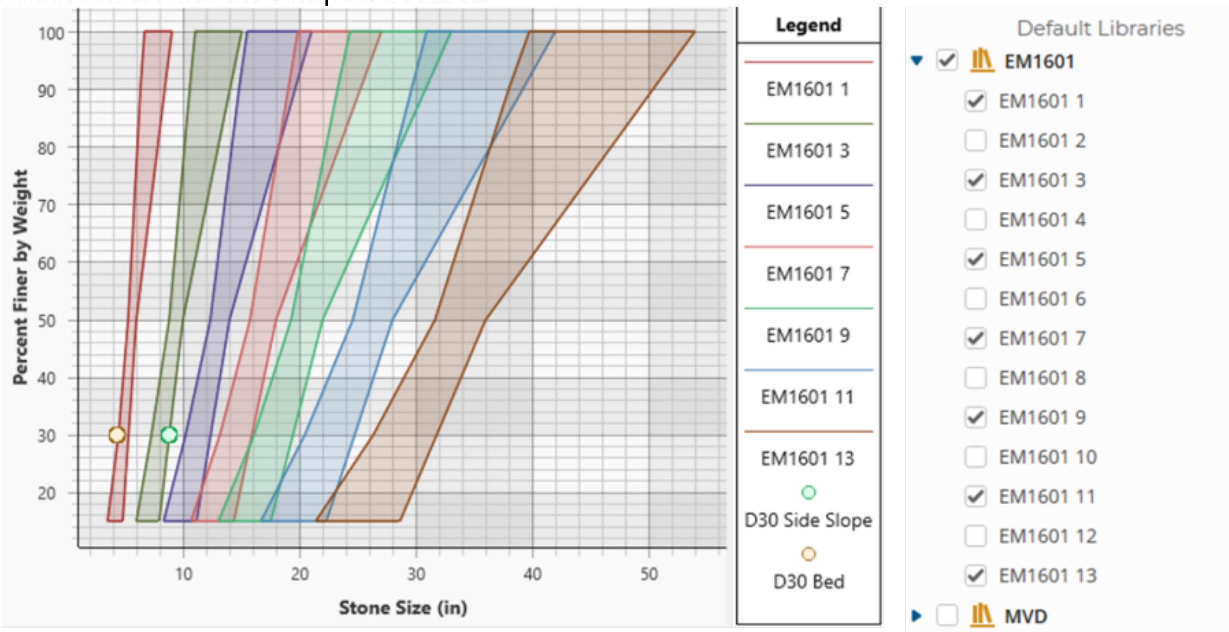
The gradation button launches a riprap gradation editor which allows users to preview gradations and turn them on and off.

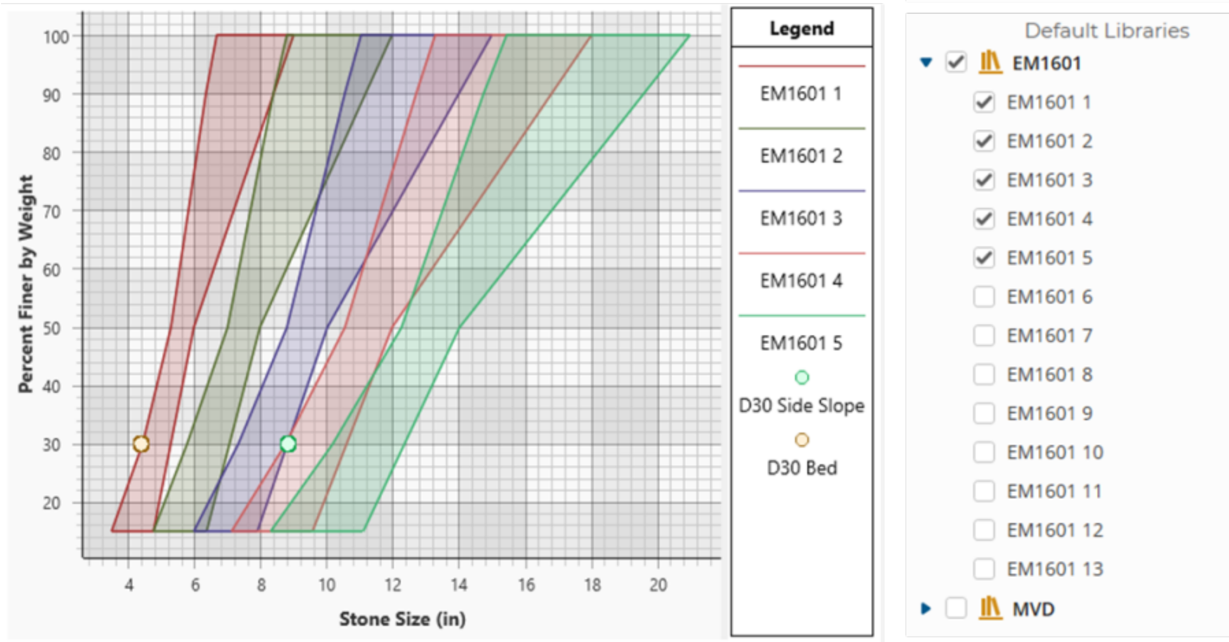


Press the **Apply All** button to add or remove these gradations from the riprap gradation display on the main riprap editor.

The default gradations come from EM 1110-2-1601, the USACE guidance on riprap design. The riprap editor can get cluttered with too many gradations, so the tool starts with every second EM1601 gradation activated. Use the check boxes to turn gradations on and off to get the best resolution around the computed d_{30}s.

The example below includes bank and side slope d_{30} calculations at the bottom of the range of these default gradations. The top pane plots these d_{30}s with every other EM1601 gradation (the default visualization). The bottom pane replaces these with the finest five gradations to provide better resolution around the computed values.

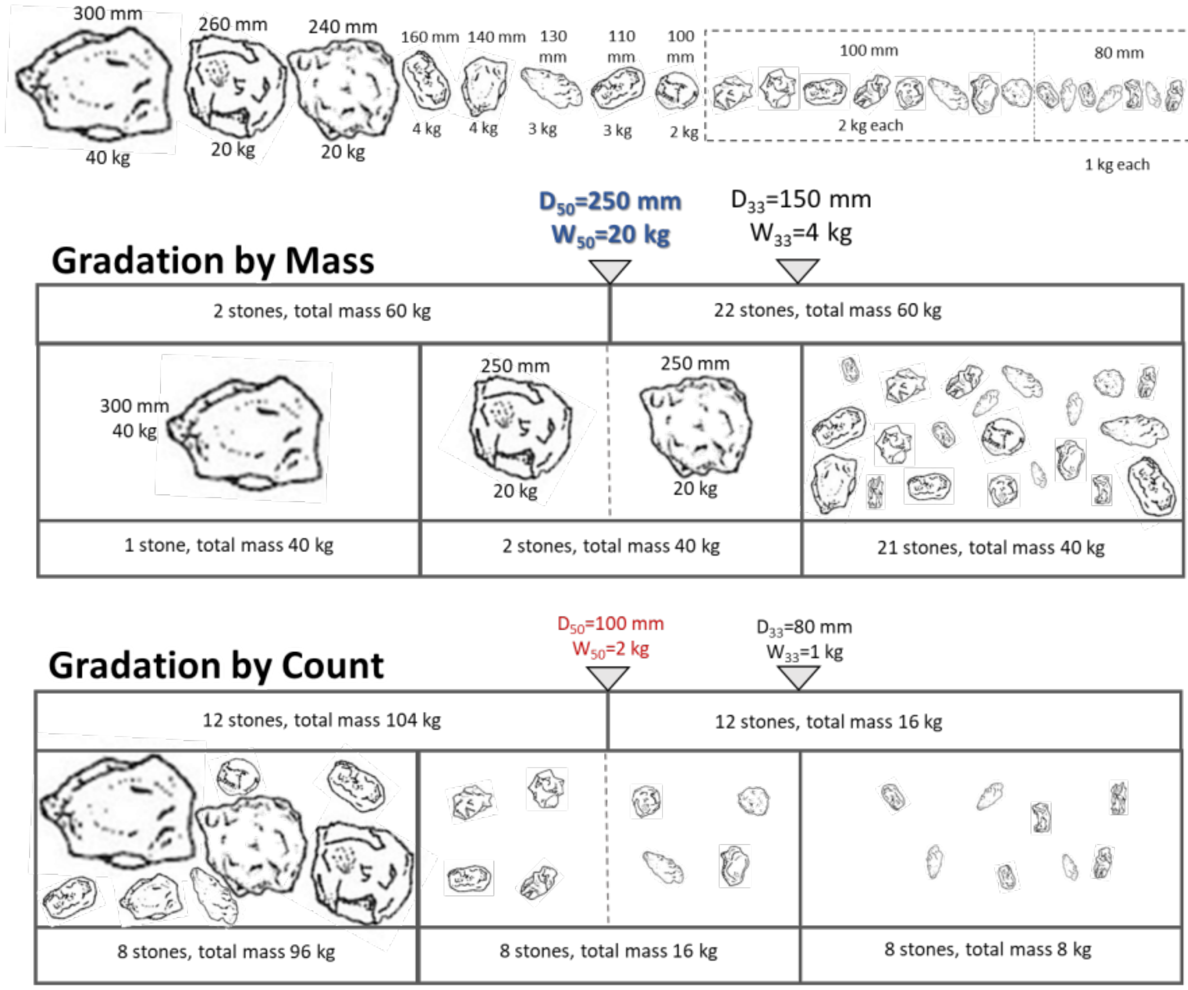




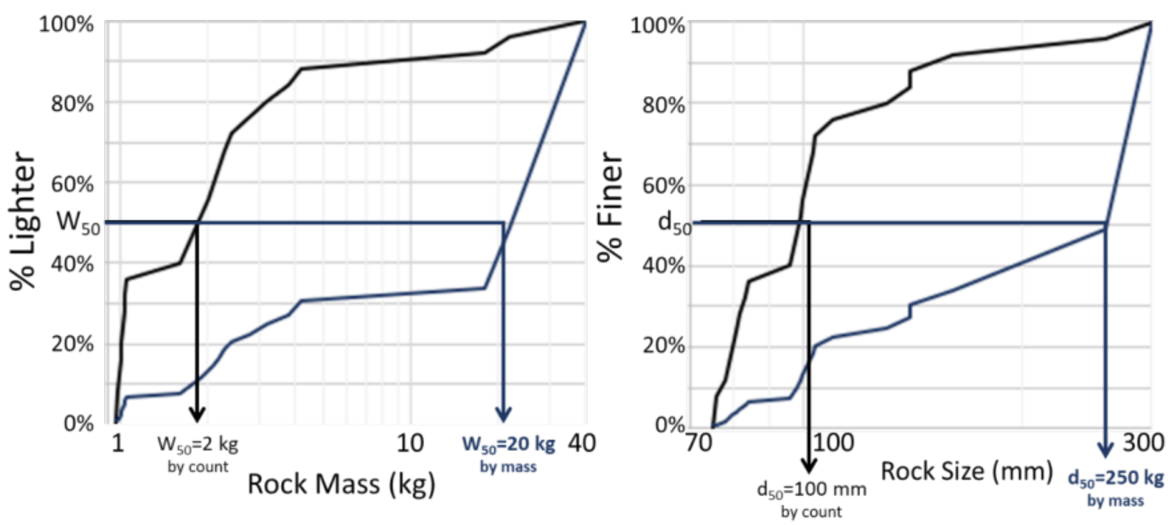
Percent Finer by Weight

All gradation percentiles (e.g. d_{30}) in riprap analysis should be specified in terms of percent-finer by weight (e.g. the d_{50} is the particle size that for which 50% of the aggregate **weight** has smaller diameters). Most standard sieve analyses are reported in percent-finer by weight because the weight of material on each sieve is measured. However, particle counts and some surrogate grain size measurements can report grain size in percent-finer by count (e.g. 50% of the particles counted are smaller than the d_{50}).

The example below for a hypothetical sample of 24 stones illustrates the importance of defining percent-finer in terms of the weight of the finer material, not the particle count. The median particle size by count is less than half the median particle size by mass in this example.



Modified from a diagram developed by Krey Price



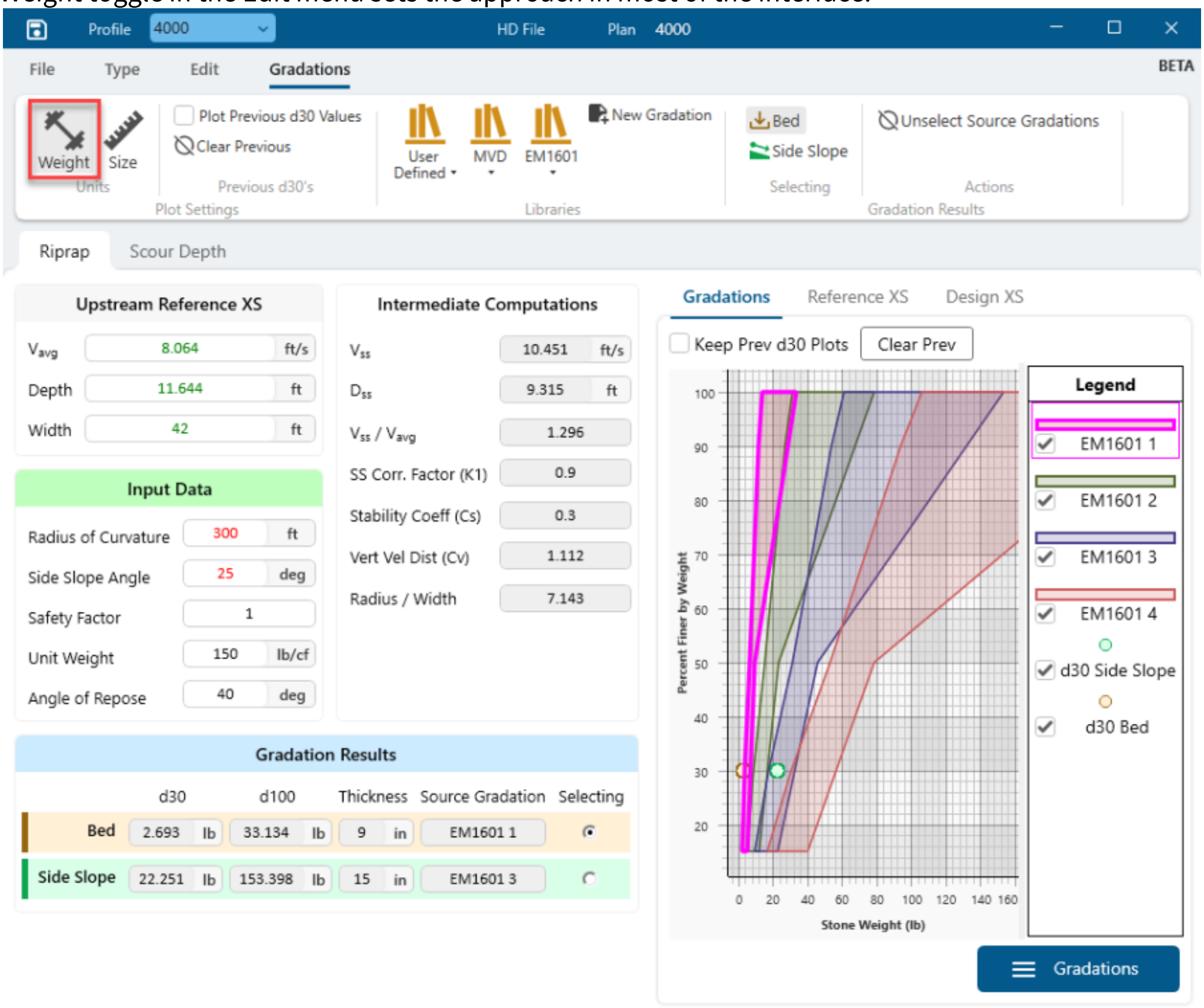
Modeling Note:

The documentation accompanying some riprap sizing methods implies that the percent finer refers to the number of stones; however, this assumes that the count is conducted by sampling a single particle at regular intervals, which corrects for the presence of multiple smaller particles that are not counted. Any documentation referring to “half the particles” assumes the term “by weight,” whether or not it is explicitly stated. -Modeling Note provided by Krey Price

Rock Size and Weight Specifications

Most sediment and geotechnical analyses that quantify soil or rock gradations deal with rock and soil size in terms of diameter. However, riprap design often specifies rock size in terms of the weight of the rock because rock weight is a more direct measurement of the protection provided.

The Riprap Calculator converts between size and weight calculations in several places. The Size/Weight toggle in the Edit menu sets the approach in most of the interface:



Weight mode reports the 30th and 100th percentile particle in weight units (W_{30} and W_{100}) but converts the W_{50} and W_{100} to d_{50} and d_{100} to compute the layer thickness (Max (d_{100}, 1.5d_{50})), which it reports in length units.

The Riprap Calculator uses the following equations to covert between Size and Weight:

$$W_{\%} = \frac{\pi \gamma_s d_{xx}^3}{6} \text{ and } d_{xx} = \left(\frac{6W_{\%}}{\pi \gamma_s}\right)^{1/3}$$

Where $W_{\%}$ is the weight percentile, g_s is the unite weight, and d_{xx} is the grain class percentile.

Limitation: Why Doesn't the Riprap and Scour Calculator use 2D Results?

One of the first questions that arises around these analyses is "why are they limited to one dimensional hydraulics?" HEC-RAS is moving to multi-dimensional hydraulics and many projects are modeled exclusively with 2D. It might seem counter-intuitive to build a 1D model to compute the kind of local velocities required for scour and riprap calculations, when a 2D depth and velocity field would be superior.

While 2D depths and velocities would be more precise, they are not appropriate for the equations. Both the riprap and scour equations are simple, empirical, equations based on cross-section averaged velocity measurements. In most cases, stable rock size and scour depth are not even correlated with the local depth-average velocities, but an idealized, upstream, depth-averaged velocity.

Because these equations are so empirical, they must be used in the manner they were developed. Plugging local, 2D depths and velocities into these equations developed for idealized, upstream, crossing, 1D, velocities violates the assumptions of the equations and is not likely to improve model performance over 1D hydraulics. To use 2D hydraulics with this calculator, a modeler must use a transect to compute a cross-section average hydraulic depth and velocity at an upstream reference cross section, and input it manually into the calculator.

The adjustments that are applied to the average channel velocity in the Maynord equation are intended to represent both horizontal variability (accounted for in 2D models) and vertical variability (not accounted for in depth-averaged 2D models) in the water column that affects localized hydraulic conditions and riprap stability.

Maricopa Method

> **Version 6.4**
>
> These methods will be available in version 6.4

The latest version of HEC-RAS includes the "Maricopa Method" in addition to the USACE method from EM 1601. The Maricopa Method was developed by the Flood Control District of Maricopa County and is described in the 2018 Drainage Design Manual for Maricopa County, Arizona, - Hydraulics (See Section 6.6.3 Riprap Lined Channels). The Maricopa Method is a case-dependent modification of the Ishbash Equation (which is also in the latest version of HEC-RAS). In version 6.3, only Ishbash-related Maricopa County's riprap sizing equations are implemented. Other riprap sizing equations from Maricopa County will be implemented in the future versions

The Maricopa Method modifies the Isbash equation and calculates the d50 (median size) of the riprap for four cases:

- On the Channel Bed or on the Banks
- For Straight or Curved Channels

The Maricopa Method also includes special equations for several specific design conditions (e.g. downstream of a grade control or drop structure) and assumptions to extend the d50 into a gradation.

Channel and Bank Riprap Equations

The Isbash Equation for Riprap is:

$$d_{50} = \frac{V^2}{2gC^2}\left(\frac{\gamma_w}{\gamma_s - \gamma_w}\right) = \frac{V^2}{2gC^2(1-s)}$$

Where:

V=Maximum Velocity (ft/s)
(Estimated at 1.33 times the cross section average velocity in the channel)
Va=Cross Section Average Velocity in the Channel (ft/s) (from HEC-RAS)
(0.86 for high-turbulence; 1.2 for low-turbulence per EM 1601, Appendix F, page F-5)
C=An Empirical Turbulence Coefficient (-)
g=Acceleration of Gravity (ft/s2)
γw = Unit Weight of Water (lb/ft3)
γs = Unit Weight of Soil (lb/ft3)
s = Specific Gravity

The Maricopa Method modifies the Isbash Equation in three ways. It has specific turbulence coefficients *(C)* for straight and curved reaches, it estimates the maximum velocity (*V*) as a function of the average velocity (*V*=1.33*Va*) which HEC-RAS computes *and* it adds a slope factor (cosine of the bank angle, from Vanoni) to the denominator for riprap on the bank:

$$V_{max} = 1.33\, V_{average}$$

$$d_{50} = \frac{V_{max}{}^{2}}{2gC^2\ cos\varphi}\left(\frac{\gamma_w}{\gamma_s - \gamma_w}\right)$$

C = 1.2 if straight
C = 0.86 if curved

$cos\varphi$ = omitted for the channel bed
$cos\varphi$ = included for the channel bank

This works out to four basic equations:

	Channel Bed	Channel Banks
Straight Reach	$d_{50} = \frac{(1.33\ V_a)^2}{2g1.2^2}\left(\frac{\gamma_w}{\gamma_s - \gamma_w}\right)$	$d_{50} = \frac{(1.33\ V_a)^2}{2g1.2^2\ cos\varphi}\left(\frac{\gamma_w}{\gamma_s - \gamma_w}\right)$
Curved Reach	$d_{50} = \frac{(1.33\ V_a)^2}{2g0.86^2}\left(\frac{\gamma_w}{\gamma_s - \gamma_w}\right)$	$d_{50} = \frac{(1.33\ V_a)^2}{2g0.86^2\ cos\varphi}\left(\frac{\gamma_w}{\gamma_s - \gamma_w}\right)$

Multiplying all the constant and coefficients, these equations become:

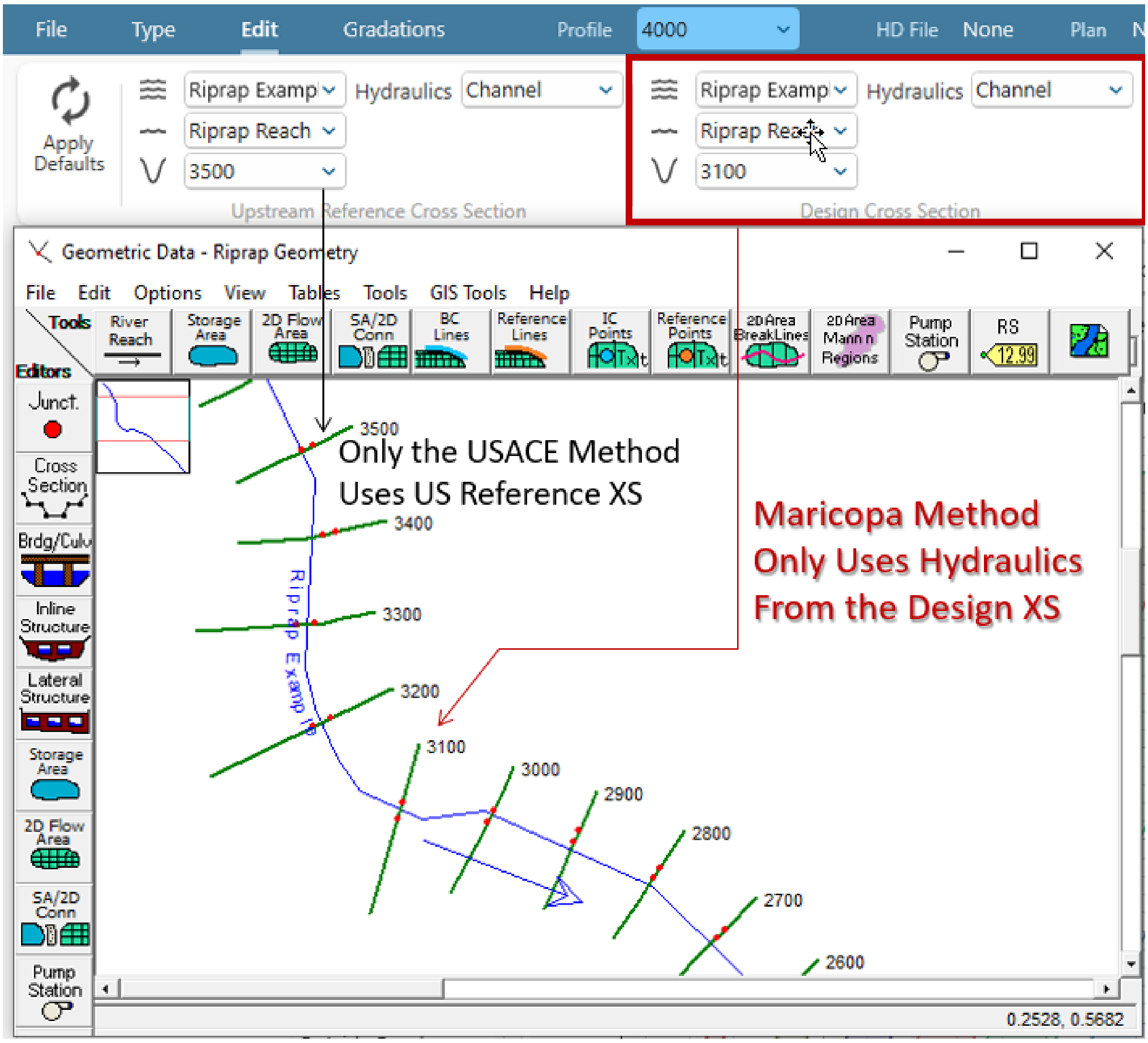
	Channel Bed	Channel Banks
Straight Reach	$d_{50} = 0.0191\ V_a{}^2\left(\frac{\gamma_w}{\gamma_s - \gamma_w}\right)$	$d_{50} = \frac{0.0191\ V_a{}^2}{cos\varphi}\left(\frac{\gamma_w}{\gamma_s - \gamma_w}\right)$
Curved Reach	$d_{50} = 0.0372\ V_a{}^2\left(\frac{\gamma_w}{\gamma_s - \gamma_w}\right)$	$d_{50} = \frac{0.0372\ V_a{}^2}{cos\varphi}\left(\frac{\gamma_w}{\gamma_s - \gamma_w}\right)$

Where φ is the bank angle, already required for the USACE analysis.

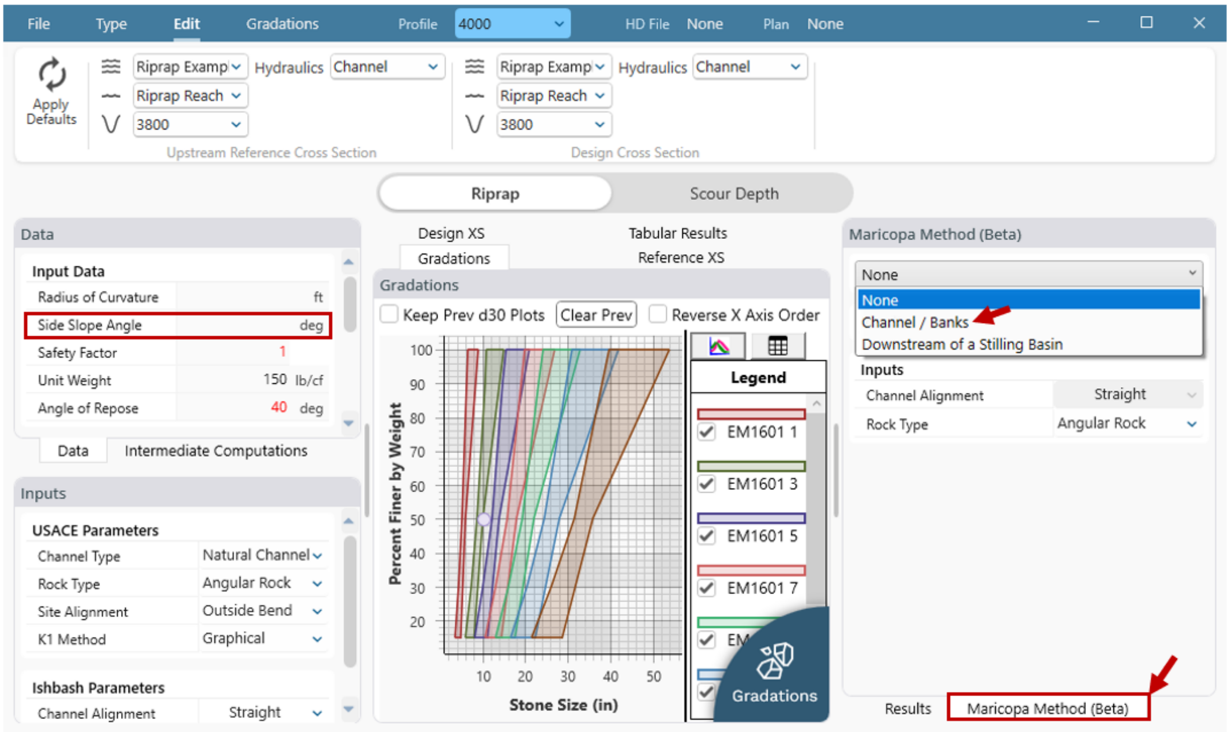
Maricopa Channel and Bank Equations in HEC-RAS - Single Cross Section Analysis

As with the other Riprap and Scour Methods, access the Maricopa Riprap Calculator by selecting the Hydraulic Design Tools and then Selecting **Riprap** from the **Type** menu.

The target cross section is one of the main differences between the Maricopa method and the EM 1601 method. While the USACE method only uses the upstream refernce cross section for the straight, idealized channel above the bend, the Maricopa method uses the hydraulics from the local cross section under evaluation. Therefore, the Maricopa Method will be insensitive to the Reference Cross section Selected:

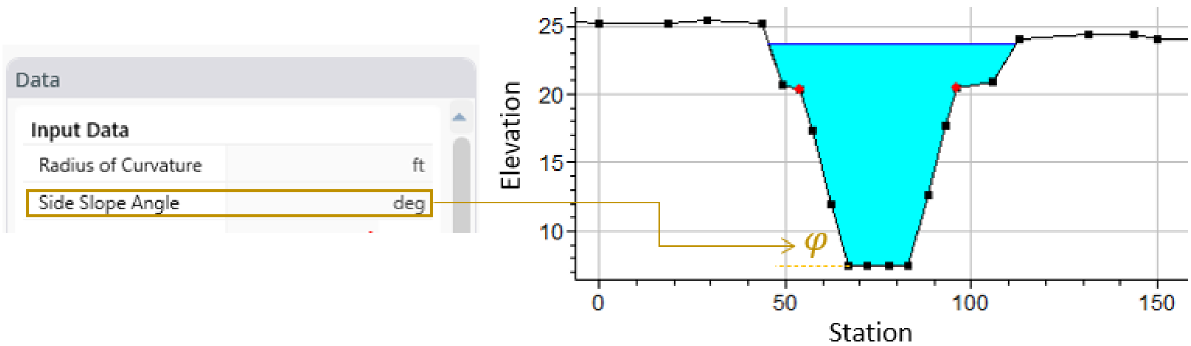


Access the Maricopa Method Inputs by selecting the **Maricopa Method** tab (see figure below). This is a modular tab, so users can move it around and stack it on the USACE Input Tab if they are not using both features. At the to of the Maricopa Editor, select **Channel/Banks** to use the equations above. The Maricopa Method also requires a **Side Slope Angle i**n the global **Input Data** (see below) to compute bank gradations:

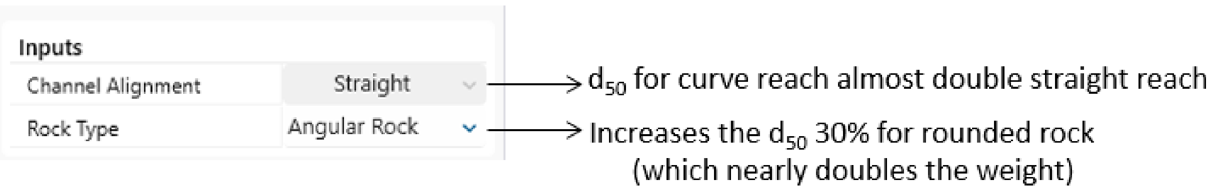


User Input

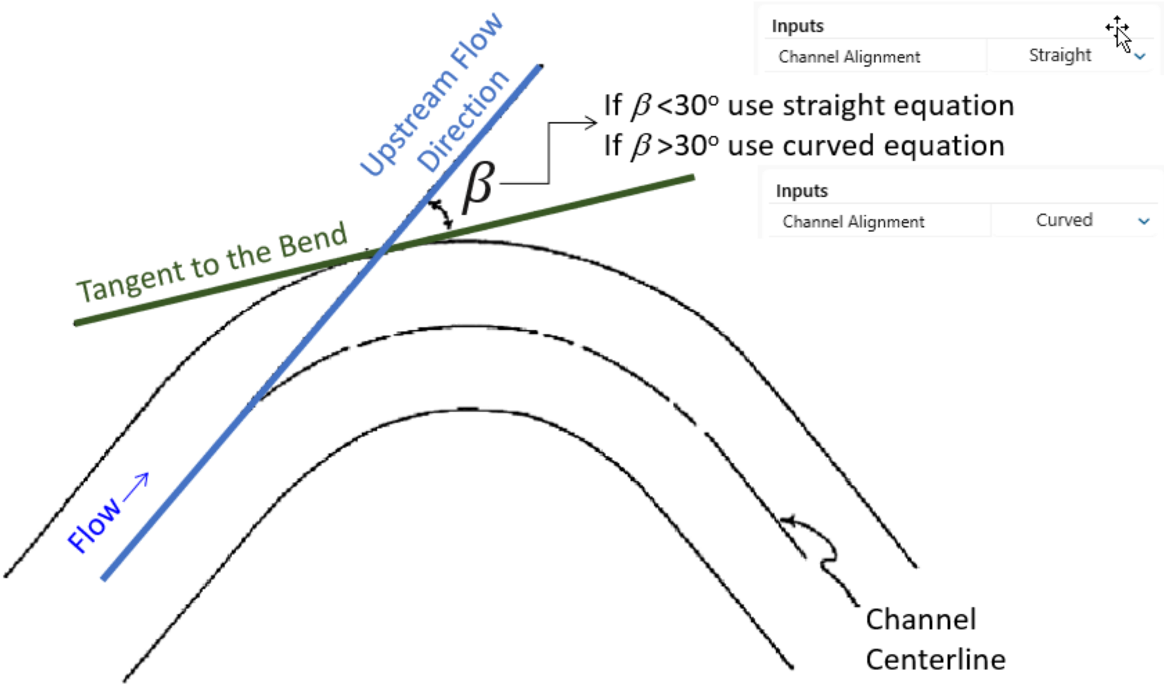
The Maricopa Method only requires three user decision. As mentioned (and illustrated) above, you must define the side slope angle under the general **Input Data**. HEC-RAS will use this side slope for all methods.



Then the user makes two choices under **Inputs**.



Choose a **Channel Alignment** from the drop down. This drop down provides two choices: **Straight** and **Curved**. The Maricopa method recomends the S**traight** equation if the angle between the upstream flow direciton and the tangent of the bend is greater than 30 degrees (see figure below modified from the Maricopa Manual and Simon, Li, and Associates 1981).



Finally, the user must specify whether the rock is angular or rounded. This has the same effect as it does on the USACE riprap method. Rounded rock diameters must be 30% larger (which translates to almost 100% larger by weight).

Single Cross Section Results

Gradations

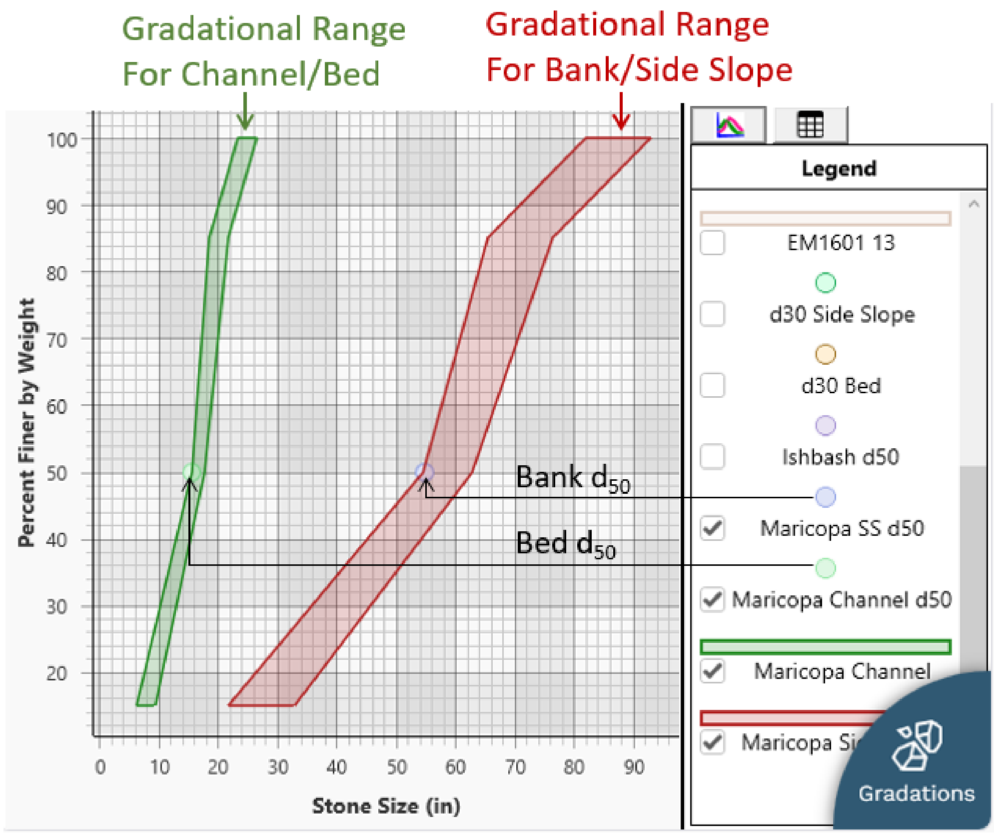
The Maricopa Method computes gradational ranges for the whole riprap mixture based on the d50 (see chart below). For example, the range of acceptable d85s is a range between 1.2 and 1.4 times the d50. Weight ranges are computed the same way, with the weight thresholds of 100%, 85%, 50% and 15% finer all all specified as multiples of the median weight (W50).

d_x	**Range (ft)** (as a function of d_{50})
d_{100}	$1.5\ d_{50} < d_{100} < 1.7\ d_{50}$
d_{85}	$1.2\ d_{50} < d_{85} < 1.4\ d_{50}$
d_{50}	$1.0\ d_{50} < d_{50} < 1.15\ d_{50}$
d_{15}	$0.4\ d_{50} < d_{15} < 0.2\ d_{50}$

W_x	**Range (lb)** (as a function of d_{50})
W_{100}	$3.0\ W_{50} < W_{100} < 5.0\ W_{50}$
W_{85}	$2.0\ W_{50} < W_{85} < 2.75\ W_{50}$
W_{50}	$1.0\ W_{50} < W_{50} < 1.5\ W_{50}$
W_{15}	$0.1\ W_{50} < W_{15} < 0.2\ W_{50}$

- d_x and W_x indicate the fraction of the mixture that is smaller than x%

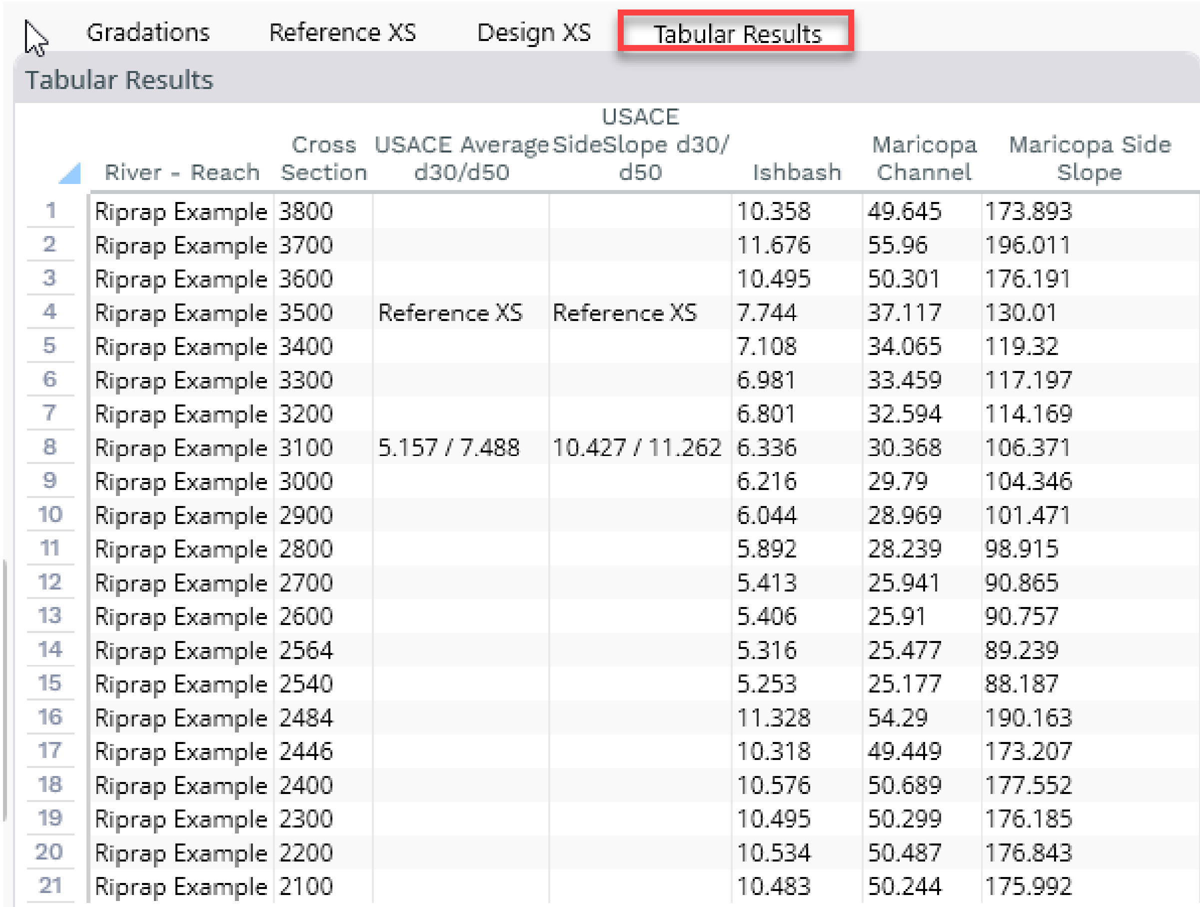
HEC-RAS translates these ranges into gradation bands in the gradation plotter. For example, in the plot below, HEC-RAS computes d50s for the channel and the banks (side slopes) with the Maricopa method. Then it calculates the ranges for the d100, d85, d50, and d15 according to the guidance in the above table, and plots it. This allows users to leverage the gradation tools, and compare locally available aggregate to the gradation bands suggested by the method.



See the documentation on adding customized gradations to learn how to add available rock gradations to the riprap tool and evaluate them based on the gradation ranges plotted. (Note: If the Maricopa method is selected curves and polygons associated with the USACE method are deemphasized in the plot but still available for comparison. Unclick these polygons and points in the legend - as depicted in the figure above - to only plot Maricopa Results).

Multiple Cross Section Results

Because the Maricopa method uses the design cross section instead of an upstream reference cross section HEC-RAS can apply the method to multiple cross sections at once. The Riprap tool provides tabular data of the bank (side slope) and bed (channel) d50s for each cross section based on the categorical coefficients specified in the editor and the local, 1D, hydraulics at each cross section. If the user defines a reference and design cross section as well, these tabular data will also include a single USACE d30 (at the design location, but using the reference cross section hydraulics).



	River - Reach	Cross Section	USACE Average d30/d50	USACE SideSlope d30/ d50	Ishbash	Maricopa Channel	Maricopa Side Slope
1	Riprap Example	3800			10.358	49.645	173.893
2	Riprap Example	3700			11.676	55.96	196.011
3	Riprap Example	3600			10.495	50.301	176.191
4	Riprap Example	3500	Reference XS	Reference XS	7.744	37.117	130.01
5	Riprap Example	3400			7.108	34.065	119.32
6	Riprap Example	3300			6.981	33.459	117.197
7	Riprap Example	3200			6.801	32.594	114.169
8	Riprap Example	3100	5.157 / 7.488	10.427 / 11.262	6.336	30.368	106.371
9	Riprap Example	3000			6.216	29.79	104.346
10	Riprap Example	2900			6.044	28.969	101.471
11	Riprap Example	2800			5.892	28.239	98.915
12	Riprap Example	2700			5.413	25.941	90.865
13	Riprap Example	2600			5.406	25.91	90.757
14	Riprap Example	2564			5.316	25.477	89.239
15	Riprap Example	2540			5.253	25.177	88.187
16	Riprap Example	2484			11.328	54.29	190.163
17	Riprap Example	2446			10.318	49.449	173.207
18	Riprap Example	2400			10.576	50.689	177.552
19	Riprap Example	2300			10.495	50.299	176.185
20	Riprap Example	2200			10.534	50.487	176.843
21	Riprap Example	2100			10.483	50.244	175.992

Evaluate if the Selected Coefficients are Appropriate for Each Cross section

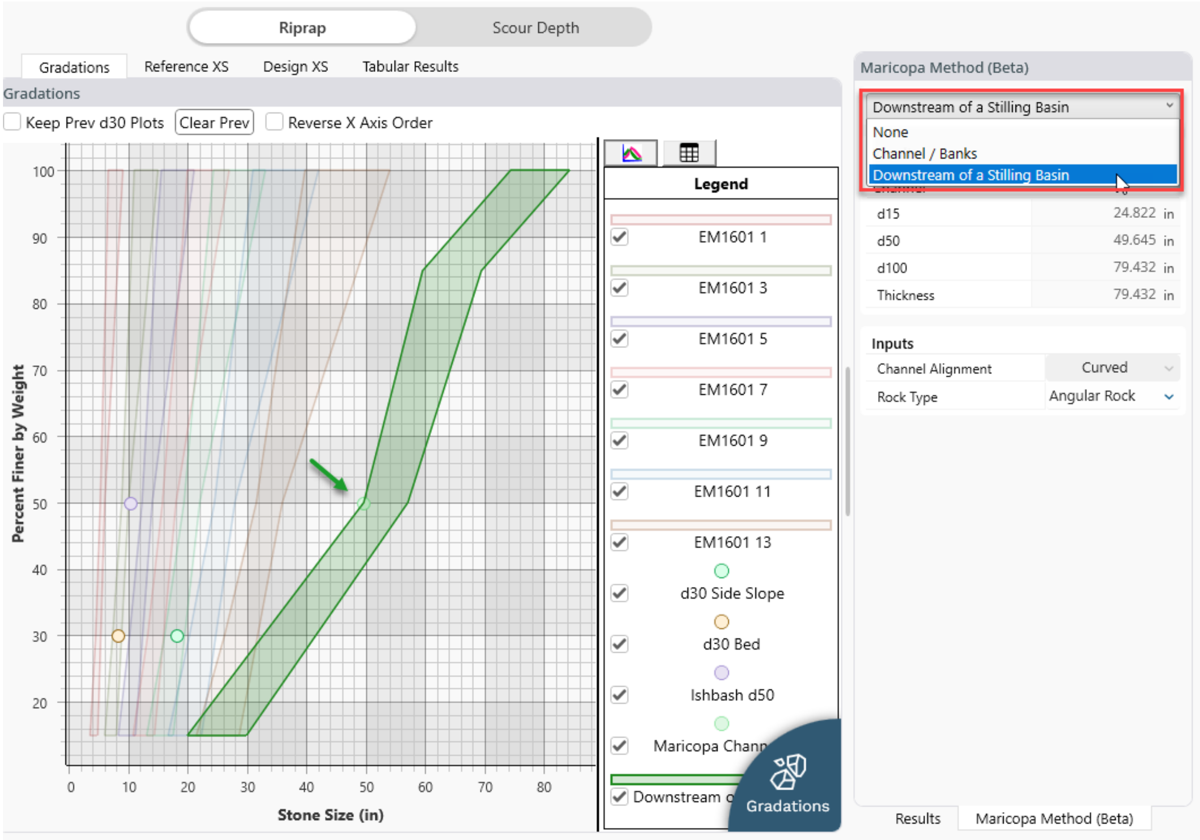
Just because HEC-RAS will apply the Maricopa equations to all of the cross sections at once, does not mean that the equation parameters selected are appropriate for each cross section. The Maricopa approach requires users to specify whether the design cross section is in a straight or curved reach and updates the turbulence coefficient based on that information. Be careful of applying the same equation to long reaches with bends and runs/crossings.

Downstream of a Stilling Basin

The Maricopa method has several customized equations for specialized settings. This version of HEC-RAS includes the method to size the riprap downstream of a stilling basin.

$$d_{50} = 0.0126\, V_a^2$$

To select this method, click the method box at the top of the **Maricopa Method** tab, and select **Downstream of a Stilling Basin** (see figure below). This will shift both the cross section and the global, tabular results to this equation. This method computes a single riprap d50 and gradation for the stilling basin-to-channel transition (i.e. it does not have separate bed and bank values).

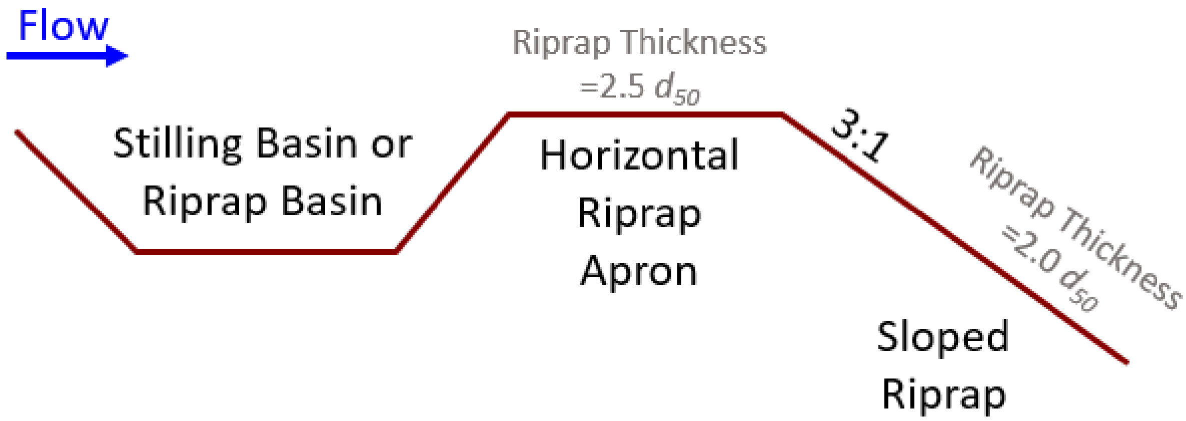


Gradations | Reference XS | Design XS | Tabular Results

Tabular Results

	River - Reach	Cross Section	USACE Average d30/d50	USACE SideSlope d30/d50	Ishbash	Downstream of a Stilling Basin
1	Riprap Example	3800			10.358	49.645
2	Riprap Example	3700			11.676	55.96
3	Riprap Example	3600			10.495	50.301
4	Riprap Example	3500	Reference	Reference	7.744	37.117
5	Riprap Example	3400			7.108	34.065
6	Riprap Example	3300			6.981	33.459
7	Riprap Example	3200			6.801	32.594
8	Riprap Example	3100	5.157 /	10.427 /	6.336	30.368
9	Riprap Example	3000			6.216	29.79
10	Riprap Example	2900			6.044	28.969
11	Riprap Example	2800			5.892	28.239
12	Riprap Example	2700			5.413	25.941
13	Riprap Example	2600			5.406	25.91
14	Riprap Example	2564			5.316	25.477

The riprap thickness calculation for this method is more complicated. It requires a different thickness for the "horizontal" and "sloped" portions of a pre-defined stilling basin design (see figure below).



The thickness on the horizontal apron downstream of a stilling basin is 1.5d100 or 2.5d50. The method uses 2.0d50 for the riprap thickness on a 3:1 slope downstream of the stilling basin.

> **Compute riprap thickness downstream of a stilling basin manually for version 6.3**
>
> HEC-RAS does not compute these thicknesses in version 6.3. Compute these externally, based on your design configurations.

References

Maricopa County, , Drainage Design Manual for Maricopa County, Arizona: Hydraulics, 738 p.

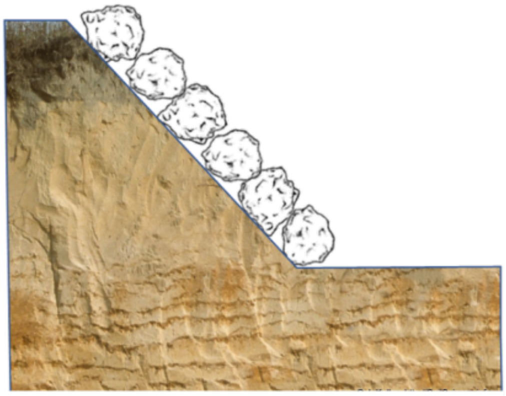
Simons, Li and Associates, Inc., 1981, Design Guidelines and Criteria for Channels and Hydraulic Structures on Sandy Soil, Urban Drainage and Flood Control District and City of Aurora, Colorado.

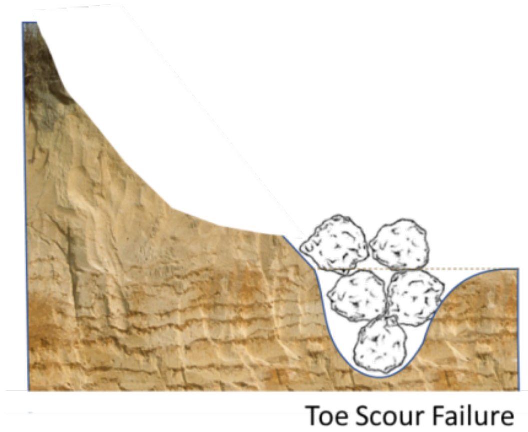
Acknowledgements

This work was funded by the Flood Control District of Maricopa County

Scour Calculator: Computing Launchable Volume

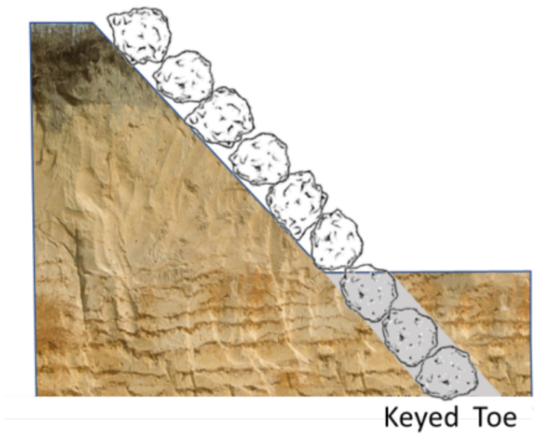
Toe scour and undercutting are common bank protection failure modes. Rivers often scour during floods. Scour, local erosion, often concentrated at the outside toe of a bend, can dig beneath placed rock. Riprap can collapse into a scour hole, after which, it no longer protects the bank.

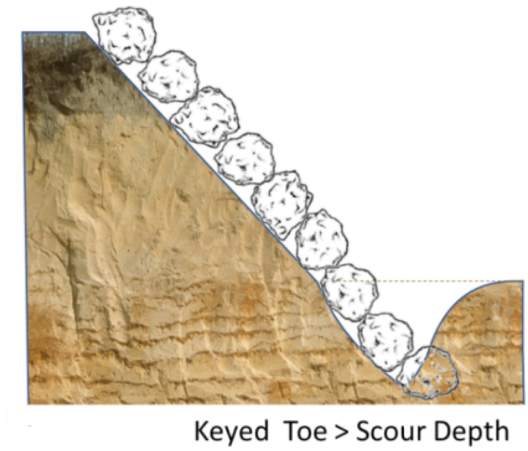




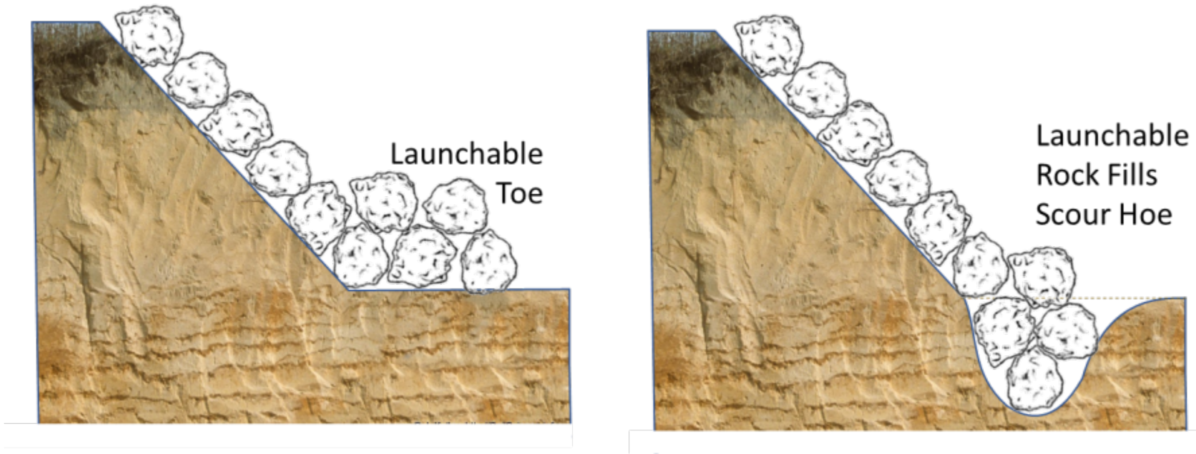
Because toe scour is one of the most common bank protection failure modes, toe protection is a critical bank protection design principle. There are several approaches to protecting the toe of a rock protection or bioengineering project. Two primary approaches include:

1. Burying toe protection to the projected scour depth.





2. Placing "launchable" toe protection, sacrificial rock that will dynamically line a scour hole.



Both these toe protection designs require an estimate of the scour depth. The project team must place a keyed toe deeper than the projected scour depth or compute the correct volume of launchable rock to line the scour hole. In both cases, estimating the scour depth is critical to the design. However, local scour and bend scour are complex processes that are highly sensitive to the local soil properties and the multi-dimensional local flow field. Physical modeling or careful, 3D/CFD modeling paired with extensive soil data collection are the only way to predict local scour depth with any confidence, and even these approaches can have significant uncertainty if they are not calibrated.

Therefore, the riprap and scour calculator includes a suite of simple scour calculators, that take an ensemble approach to scour calculations. The scour calculator applies the most widely used local and bend scour equations to the riprap design cross section, to provide the range of scour depths expected from these empirical approaches. The design team should filter these results, ignoring equations that are not applicable or results that are unreasonable, and use the suite of results with engineering judgement, field observations, expert elicitation, geologic controls, and other quantitative and qualitative metrics to determine a maximum, likely, scour depth.

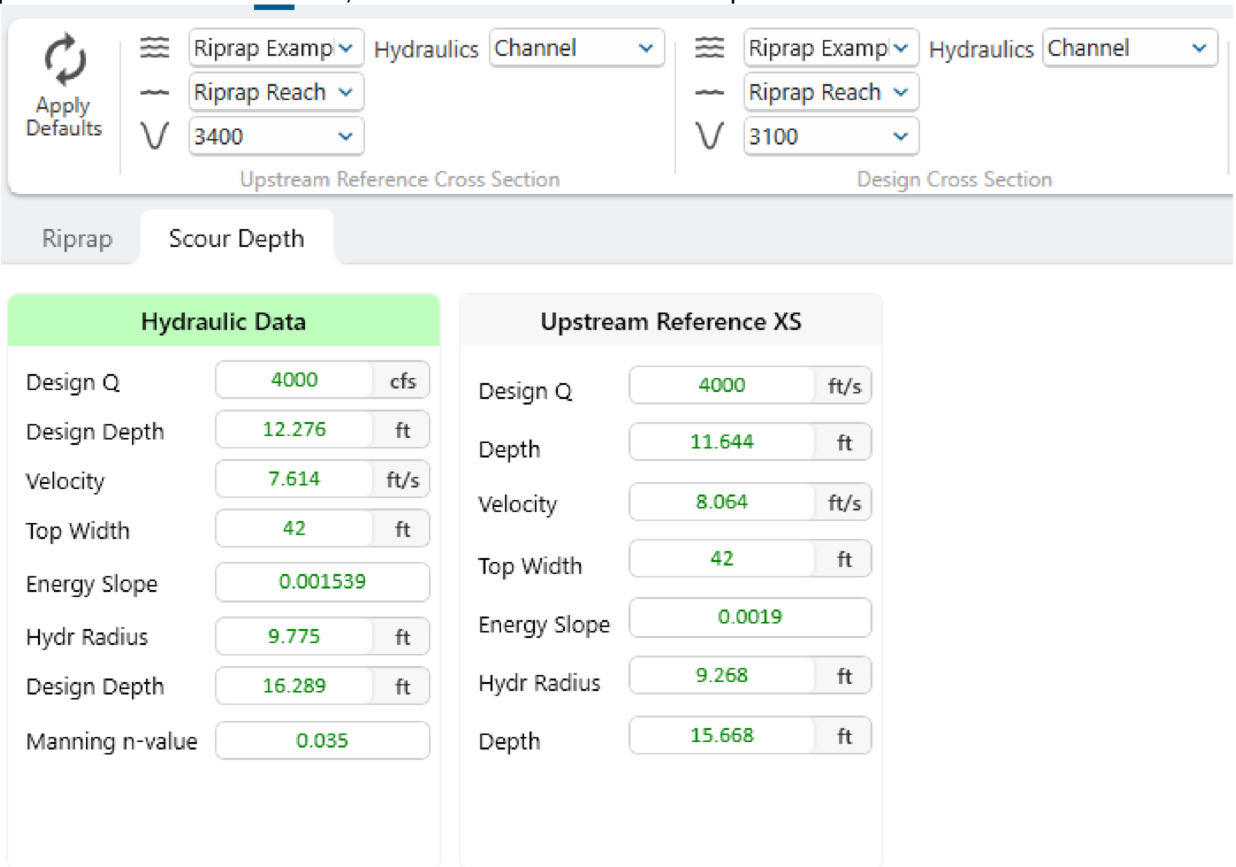
Step 1: Compute Hydraulics

The first two steps of the scour calculation are the same as the first three steps of the riprap calculation. If you are doing these analyses together, use the results from the riprap analysis (or visa versa). If you are only using the calculator to compute scour, see Step 1, Step 2, and the Radius of Curvature section of Step 3 in the riprap portion of the manual. This section includes some scour-specific implications for these analyses where the steps differ from the Riprap Calculator.

Hydraulic Scour Parameters

The Scour Calculator imports more hydraulic results from the HEC-RAS results file (e.g. p01.hdf) than the Riprap Calculator. Each of the seven scour equations uses a small subset of these parameters. But the ensemble approach requires a range of hydraulic inputs. Apart from the Neill equation (which requires manual bankfull data), most of the data for these equations come from the HEC-RAS hydraulics.

The Calculator automatically computes results for each when the required data become available. In most cases, the model results are sufficient for General Scour results (with a categorical sinuosity parameter that has a default) and the Bend Scour results require a manual radius of curvature.

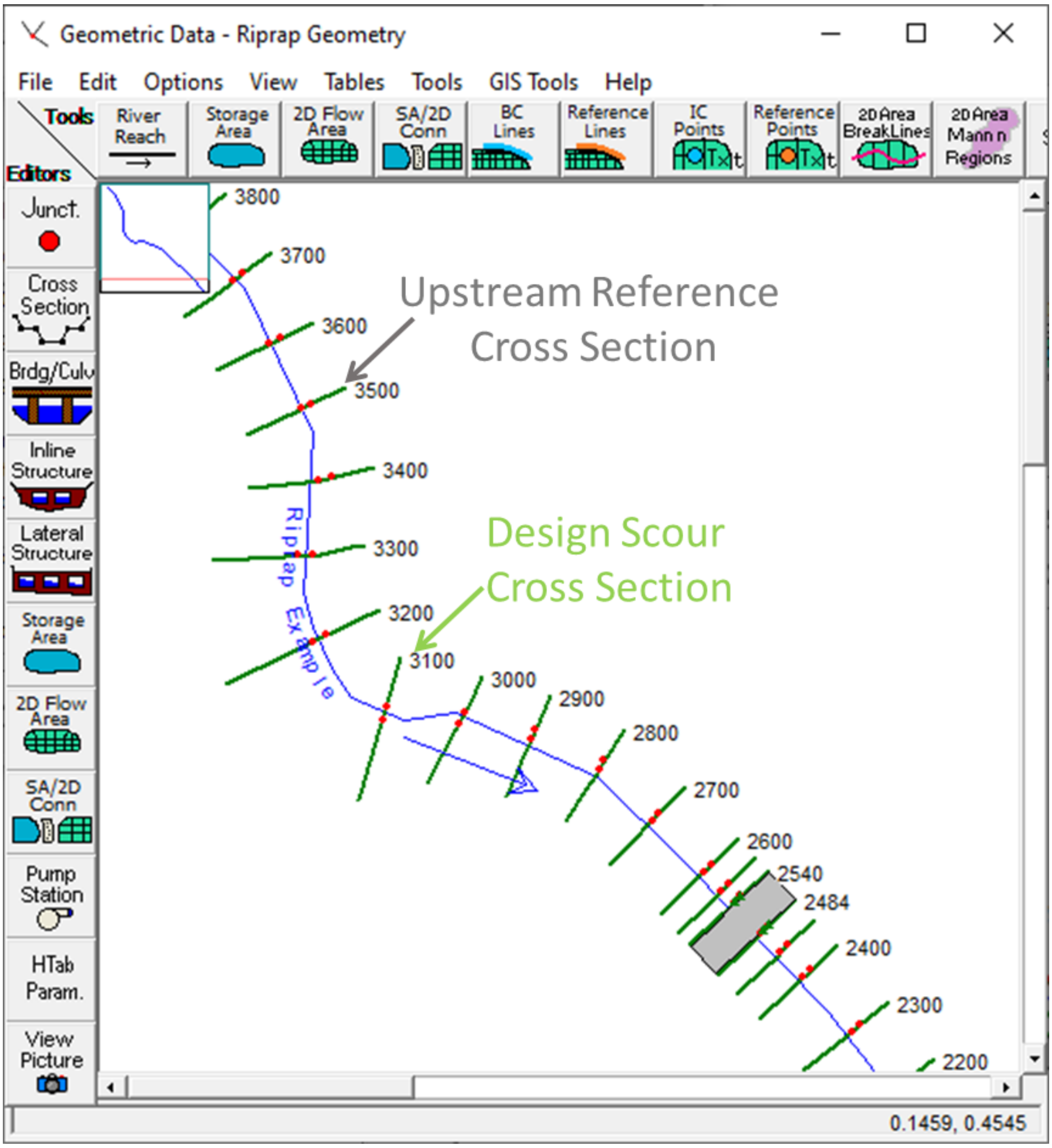


Selecting a Design Flow

Design flow selection for scour analysis follow similar principles as riprap analysis. See that section for reference. However, most of these equations were based on flows at or below bankfull. Maynord 1996 (from Thorne) notes empirical methods are valid up until significant interaction between main-channel and overbank flow. Overbank depth should not exceed 20% of channel depth.

Step 2: Identify Design and Reference Cross Sections

The Scour calculator uses the same "Upstream Reference Cross Section" concept as the riprap calculator. But unlike the riprap calculator, it also uses hydraulic parameters at the design cross section. The figure below illustrates reference and design cross sections on a 1D HEC-RAS model.



In general,

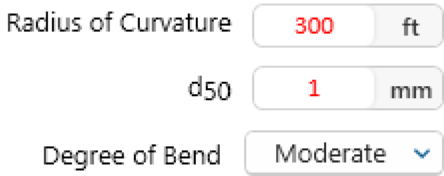
- The **general scour** equations use the **design cross section** hydraulics and
- The **bend scour** equations use the **upstream reference** cross sections.

General scour equations tend to be used for pipe crossings or other analyses on river runs or crossings where flow hydraulics are approximately one-dimensional. Therefore they use the local hydraulics. However, hydrodynamics at the outside of a bend are fundamentally multi-dimensional. Therefore, like the riprap computations, the bend scour regressions use hydraulics from a run or crossing cross section upstream of the more complicated bend geometry.
Bend scour equations correlate complex multi-dimensional processes with one-dimensional hydraulic properties by tying the equation to an upstream "refence" or "approach" cross section. The reference or approach cross section should be a relatively symmetrical upstream section where one-dimensional assumptions are appropriate. This is usually the closest cross section in the straight

crossing or run, upstream of the bend that also has similar hydraulic properties as the bend (i.e. bankfull depths/widths, channel slope, overbank depths/widths, roughness, etc.).

Step 3: Define Manual Input Variables

Like the riprap calculator, the scour equations get most of their required data directly from the HEC-RAS simulation (with the exception of the bankfull data required by Neill). The only three user parameters required are Radius of Curvature, d50, and a categorical assessment of the bend severity.



<u>Radius of Curvature</u>:
The **Radius of Curvature** for the Scour Calculation is the same as the riprap calculation. See the Radius of Curvature section in the Riprap section for a discussion of how to compute this parameter. This parameter should match the Radius of Curvature in the riprap calculator.

<u>d_{50}</u>:
The d_{50} is only used in the Lacey Equation. It is the median grain size of the bed sediment.

<u>Bend Severity</u>:
Finally, the Scour calculator requires a qualitative, categorical, assessment of the reach sinuosity. The bend scour equations use the Radius of Curvature, but the general scour equations still require some information about the channel alignment. Most of the general scour equations use a qualitative factor (*Z*) to scale scour to one of three discrete bend-severity categories: Straight, Moderate, or Severe.

Howard et al. (2021) has quantitate guidance for these categories, based on the ratio of the Radius of Curvature and Width (R/W):

Channel Description (for Z parameter in Table 1)	R/W Range (ratio of radius of curvature to width)
Severe	RW<3 or 4
Moderate	3 or 4<RW<10
Straight	RW>10

The riprap calculator reports the R/W ratio and the recommended sinuosity category below the dropdown box where users can select it to guide this choice.

Step 4: Select the Appropriate Equations

It is very difficult to predict potential flood scour potential without historical measurements or a calibrated numerical model. However, it is important to consider scour failure modes even when data or calibrated models are not available. A suite of simple, empirical equations can bound the potential scour risk in these situations. These equations are not universally applicable and often generate a wide variety of scour depths. But applying the applicable equations - in an ensemble approach - can provide a possible range of scour depths. Many of these methods were collected in the US Bureau of Reclamation design manual (Pemberton and Lara, 1984) and despite their age and limitations remain the standard practice at the time of publication.

But it is critical to carefully select the equations that are appropriate for the design setting, or to weigh the results of each equation relative to their applicability.
The scour equations fall into two categories:

1. General Scour
2. Bend Scour

The first decision users must make is which suite of equations to consider. General scour equations tend to apply to straighter reaches and are often used to determine the depth of a pipeline or other infrastructure buried beneath a river crossing. Bend scour computes maximum local scour on the outside of the bend and is usually used to determine the depth of toe protection required to protect a bank or levee.

Bend scour estimates the multi-dimensional forces that scour the river bed on the outside of a bend. Bend scour equations are very sensitive to the "radius of curvature" of the bend. General Scour equations target straighter reaches, but most of these equations still have a categorical term that increases scour based on the curvature of the reach. These equations are based on 1D cross-section averaged variables and often – particularly the bend scour equations - refer to hydraulic parameters of an upstream, reference cross section. Equation variables that come from the upstream cross section have a subscript "US" below (e.g. DUS). Howard et al (2021) and Baird et al (2019) provide more detailed descriptions of the context and application of the equations summarized in this section.

These scour equations are included in a scour and RipRap calculator in the hydraulic modeling software HEC-RAS, which reads the hydraulic parameters directly from 1D model results and computes the applicable equations. For more information on the Scour equations and an example application, see Howard et al. (2021):
Howard, A., Pak, J., May, D., Gibson, S., Haring, C., Alberto, B., Snyder, M. (2021) "Approaches for Assessing Riverine Scour," Regional Sediment Management Technical Report.

General Scour

The general scour equations were compiled by Neill (1973) to compute scour at "constricted waterways." Pemberton and Lara (1984) present them as a method to "design buried pipe, buried canal siphon, or a bank line structure" and the complete suite are summarized in Baird (2019) and Howard et al. (2021). These equations estimate scour in different river settings, including bends or straighter reaches (Table 1) and are generally based on the hydraulic parameters at the design location (i.e. they do not refer to an upstream reference cross section).

Most of the General Scour equations (Neill Incised, Blench, Lacey, and USBR average velocity) have a similar form and using an empirical factor (Z) to account for sinuosity. Z is a categorical reduction factor with three options for "straight", "moderate", and "severe bends". The value of Z varies for the different equations based on the bend category collected. But the Z coefficient ranges from 0.25 to 0.75 for most natural river settings, reducing scour more (lower Z) for straighter reaches. Assigning a quantitative reduction factor to qualitative bend categories introduces uncertainty (and nonlinearity/step functions) into the analysis. But USACE Subject Matter Experts have some rule-of-thumb approaches to calculating these categories based on the ratio of the radius of curvature (*Rc*) and the bank-full channel width (*W*), summarized in Table 2.

Table 1: General Scour Equations

Method	Equation	Parameters	Assumptions and Conditions
Neil◊	$\Delta y = Z \cdot \bar{D}_{bf}\left(\frac{Q_d/W}{Q_{bf}/W_{bf}}\right)^m$	$Z = \begin{cases} 0.5\ if\ Straight \\ 0.6\ if\ Moderate \\ 0.7\ if\ Severe\ \blacksquare \end{cases}$ $m = \begin{cases} 0.67\ for\ sand\ * \\ 0.85\ for\ gravel \end{cases}$	See Table 2 for quantitative metrics for Z categories Valid for reaches with channel constrictions
Lacey◊	$\Delta y = Z \cdot 0.47\left(\frac{Q_d}{1.76\sqrt{d_m}}\right)^{\frac{1}{3}}$	$Z = \begin{cases} 0.25\ if\ Straight \\ 0.5\ if\ Moderate \\ 0.75\ if\ Severe\ \blacksquare \end{cases}$	Silt bed rivers. Zero bedload conditions.
USBR Mean Velocity (Pemberton and Lara, 1984)	$\Delta y = Z\bar{D}$	$Z = \begin{cases} 0.25\ if\ Straight \\ 0.5\ if\ Moderate \\ 0.75\ if\ Severe \end{cases}$	
Blench◊	$\Delta y = Z \cdot \frac{\left(Q_d/W\right)^{\frac{2}{3}}}{(F_{B0})^{\frac{1}{3}}}$	$Z = 0.6$ $F_{B0} = f(d_m)$ $F_{B0}\ from\ chart$	Clear water flow
USBR Envelope Curve	$\Delta y = \begin{cases} 2.47 + \frac{0.937\left(Q_d/W\right)}{3.45} \\ K\left(Q_d/W\right)^{0.24} \end{cases}$	$If\ \left(Q_d/W\right) < 3.45$ $If\ \left(Q_d/W\right) \geq 3.45$	$K = \begin{cases} 2.45\ US\ Cust \\ 1.32\ SI \end{cases}$ Valid for: Relatively steep slopes $0.004 < S < 0.008$ MS-CS bedload $0.5 < d_m < 0.7$ $\left(Q_d/W\right) < 3.45$

■Both Neil and Lacey have higher values of Z (1-1.25) for right angle bends or vertical rock banks.

◊Neil, Lacey and Blench in this document are from Peberton and Lara, 1984, which have been modified from the original documents.

* This equation applies a smaller power for sand than gravel, which tends to predict more scour for gravel than sand. This emerged from the data in this study but may not be broadly applicable

Where:
Δy is the scour depth below the initial channel invert
Qd is the design flow
dm median grain size
D is depth. Depth takes several forms in these equations including:
Dh, the hydraulic depth, which is the area divided by the top width
Dbf, the average bankfull cross section depth, but is often approximated with Dh and
D_Max, the maximum cross section depth.
Z is an empirical parameter accounting for channel sinuosity based on a categorical classification (See chart).
W is the flow width of the design event
Wbf is the banfull flow width

Qbf is the bankfull flow
FB0 is Blench's Zero Bed Factor from the figure below.

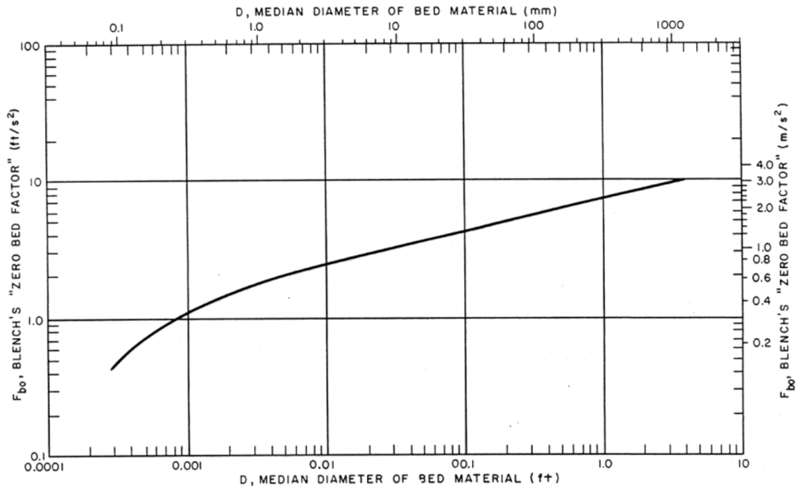


Chart to determine Blench's Zero Bed Factor as a function of *dm* (from Pemberton and Lara (1984) after Blench (1969)).
Radius of curvature to width ratios for curvature categories used to determine the Z factor.

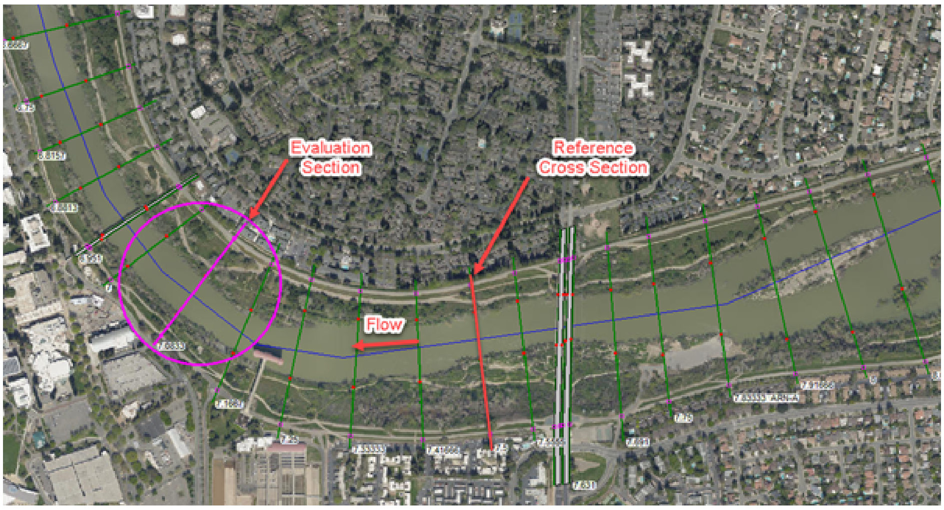
Channel Description (for Z parameter in Table 1)	R/W Range (ratio of radius of curvature to width)
Severe	R/W<3 or 4
Moderate	3 or 4<R/W<10
Straight	R/W>10

Pemberton form of Lacey Equation

Richards (2018) points out that the form of the Lacey equation in Pemberton and Lara (1984) - which is based on the total flow and is currently used in this calculator - is the regime form from the Lacey (1930) paper. Richards argues that the general version that uses unit flow is more appropriate in most situations. HEC and USACE are evaluating this finding. For now, the scour calculator uses the Bureau of Reclamation equation above, which is also applied by multiple other State and Federal agencies. But we are evaluating this equation and - for now- use this result with caution.

Bend Scour Equations

The bend scour equations try to account for multi-dimensional forces on the outside of a bend by quantifying the bend severity based on the bend curvature and computing constriction and avoiding the complexities of multi-dimensional hydraulics at the bend by tying the equations to an upstream "crossing" or "run" reference cross section (illustrated in the Figure below).



Most of these equations were based on flows at or below bankfull. Maynord 1996 (from Thorne) notes empirical methods are valid up until significant interaction between main-channel and overbank flow. Overbank depth should not exceed 20% of channel depth.

Method	Equation	Assumptions and Conditions
Maynord*	$\Delta y = \bar{D}_{US}\left(1.8 - 0.051\left(\frac{Rc}{W_{US}}\right) + 0.0084\left(\frac{W_{US}}{\bar{D}_{US}}\right)\right) - \bar{D}_{US}$	Sand bed S ≤ 2%, $1.5 < \frac{Rc}{W_{US}} < 10$** Recommends a safety factor of 1.0 to 1.19
USACE EM 1110-2-1601	$\Delta y = \begin{cases} \bar{D}_{US}\left(-1.51\log_{10}\left(\frac{Rc}{W}\right) + 3.37\right) - D_{Max}\ for\ sand \\ \bar{D}_{US}\left(-1.62\log_{10}\left(\frac{Rc}{W}\right) + 3.375\right) - D_{Max}\ for\ gravel \end{cases}$	This method uses much of the same data as Thorne
Zeller†	$\Delta y = \frac{0.0685 \cdot D_{US\_Max} V_{US}^{0.8}}{D_{h\_US}^{0.4} S_{US}^{0.3}} + \left(2.1\left(\frac{W}{4Rc}\right)^{0.2} - 1\right)$	Sand bed channels.
Thorne	$\Delta y = \bar{D}_{US}\left(2.07 - 0.19\ln\left(\frac{Rc}{W_{US}} - 2\right)\right) - \bar{D}_{US}$	Includes data from large sand bed rivers and smaller gravel-cobble systems $\frac{Rc}{W_{US}} < 2$

* For a factor of safety of 1. The method recommends a factor of safety between 1.0 and 1.19 based on the percentage of "significantly unconservative data".

**The algorithm has alternate forms for $\frac{Rc}{W_{US}} < 10$ and $\frac{Rc}{W_{US}} < 1.5$.

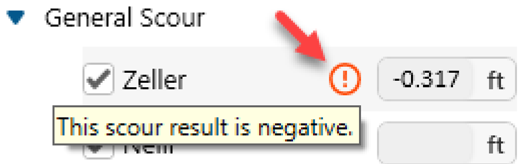
†This form replaces $\frac{\sin^2\frac{\alpha}{2}}{\cos\alpha}$ with the equivalent $\frac{W}{4Rc}$.

Where:

- Δy is the scour depth below the initial channel invert
- W is the flow width (within the banks)
- W_{US} is the flow width (within the banks) at the upstream, reference cross section
- R_c is the radius of curvature
- D is depth. Depth takes several forms in these equations including:
  - D_h, the hydraulic depth, which is the area divided by the top width
  - $\bar{D}_{US}$, the average cross section depth at the upstream, reference cross section, but is often approximated with D_h and
  - D_{Max}, the maximum cross section depth before scour at the evaluation cross section.

Warning and Error Messages

The Scour calculator will display a warning icon next to the computed value if it is problematic. Hover the cursor over the warning icon for a description of the error.



Negative Scour:

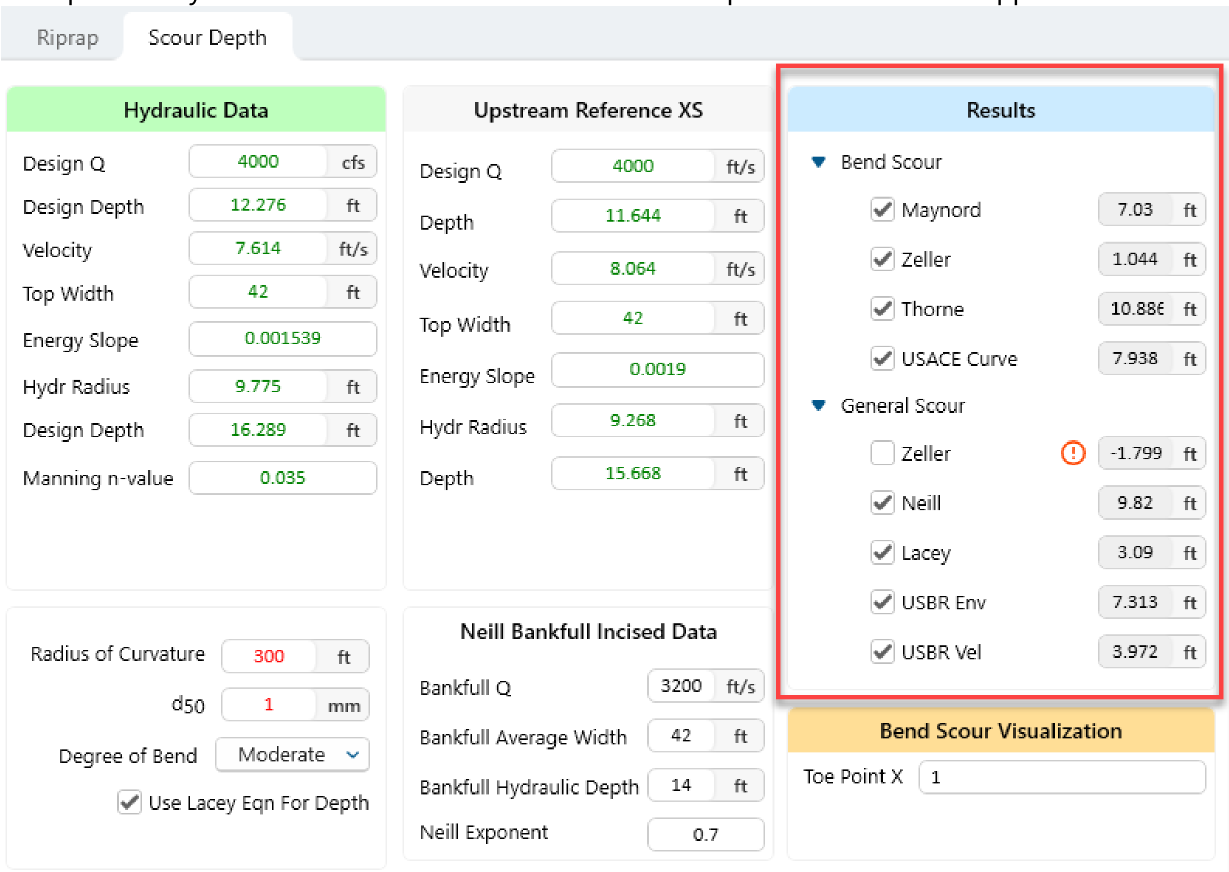
In the current version, negative scour values will be the main reason for the warning icon. Because these equations are simple regressions of limited data sets, it is relatively common for them to report negative scour. But negative scour should ***never*** be included in a statistical analysis or interpreted as deposition. A negative scour is just a numerical artifact of a simple regression equation pushed outside its limits. Some practitioners and calculators report negative scour as 0, interpreting everything in the negative range as stable. In some cases, it may be appropriate to consider negative results part of a larger body of evidence that scour will be low. But the HEC-RAS scour calculator intentionally leaves these values negative to signal that the equation is outside the range of the equation and should be interpreted with care.

Outside the Equation Range:

Some equations will also show an error button if the calculator is applying the equation outside the stated range of the equation. The user can decide if the results are still valuable outside this range but should consider these warnings when selecting an applicable suite of equations.
In future versions HEC will add warnings for equations that are applied outside of their intended range. But for now, it is the user's responsibility to figure out which equations are site-appropriate.

Step 5: Compute Ensemble Scour Results

The Scour Calculator automatically populates results for each equation as soon as the required data are available and updates them immediately in response to user edits. The calculator selects all of the equations by default. Use the check boxes to deselect equations that are not applicable.

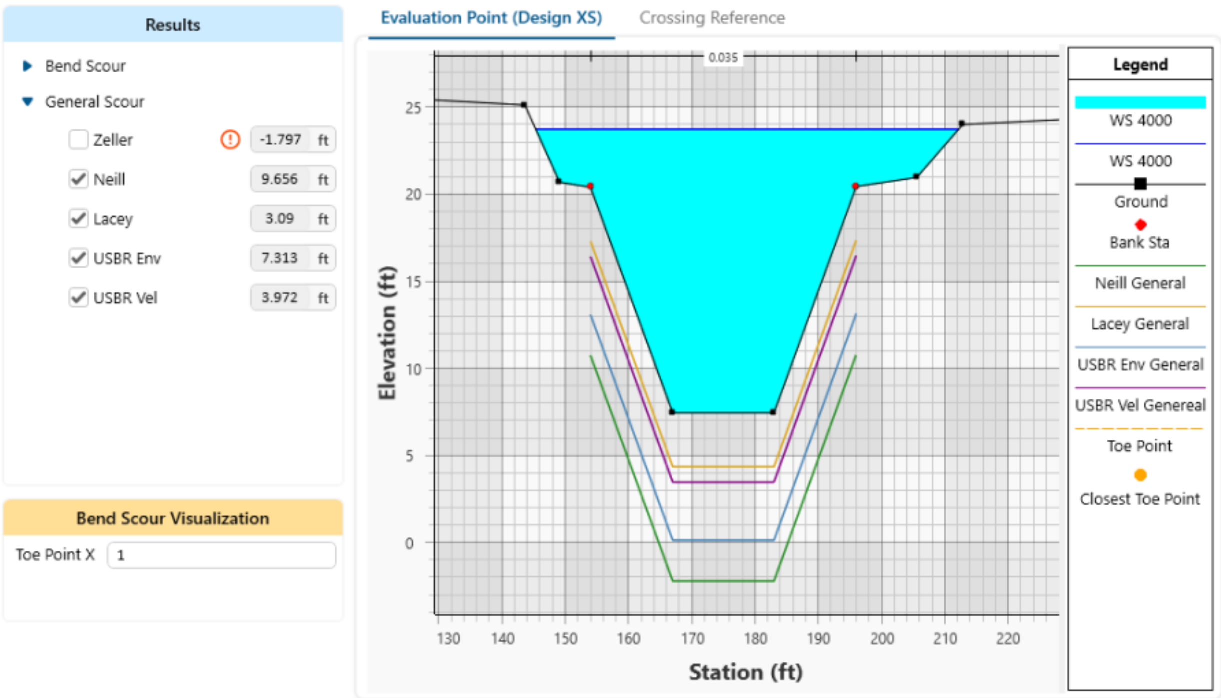


Step 6: Visualizing Scour Results

The riprap and scour calculator will plot selected results with the design cross section to help visualize the magnitude and range of computed scour.

Visualizing General Scour

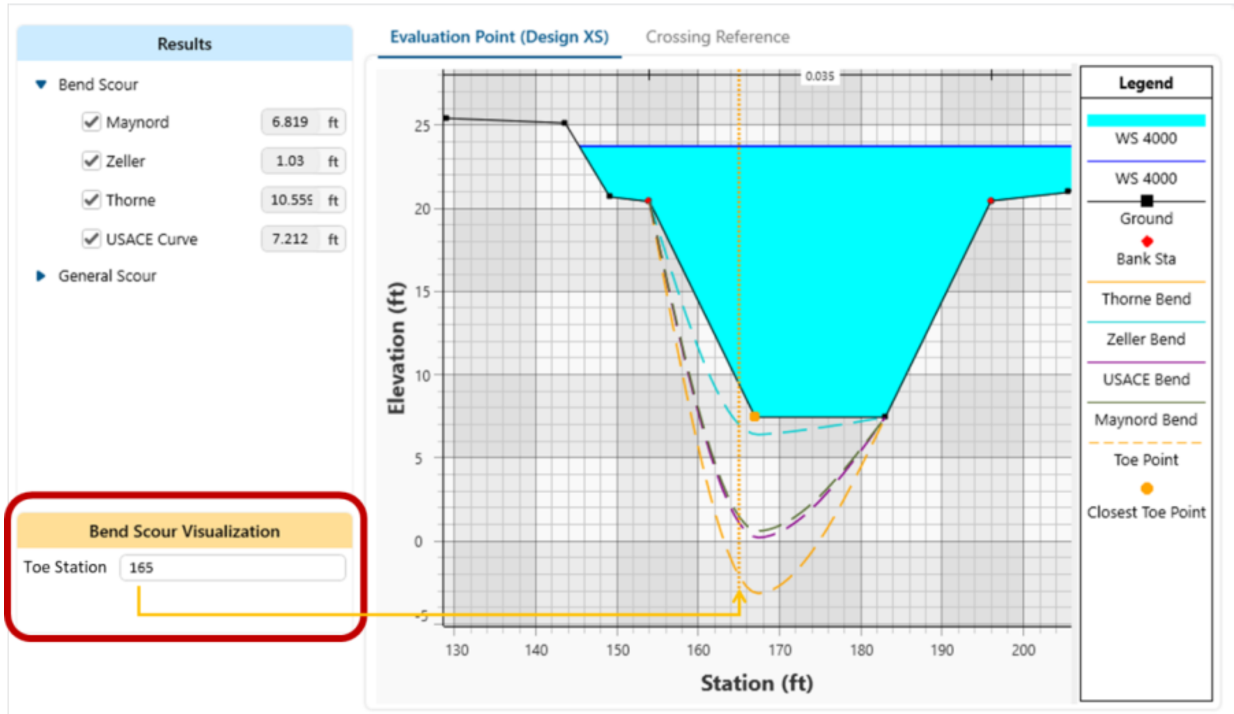
The general scour results plot automatically, reproducing the portion of the cross section between the channel banks, offset vertically by the scour result.



Visualizing Bend Scour

Visualizing bend scour requires user input. Bend scour is not distributed across the whole channel, but is generally concentrated at the toe of one bank. So the Riprap and Scour calculator requires a **Toe Station** to display the bend scour results correctly.

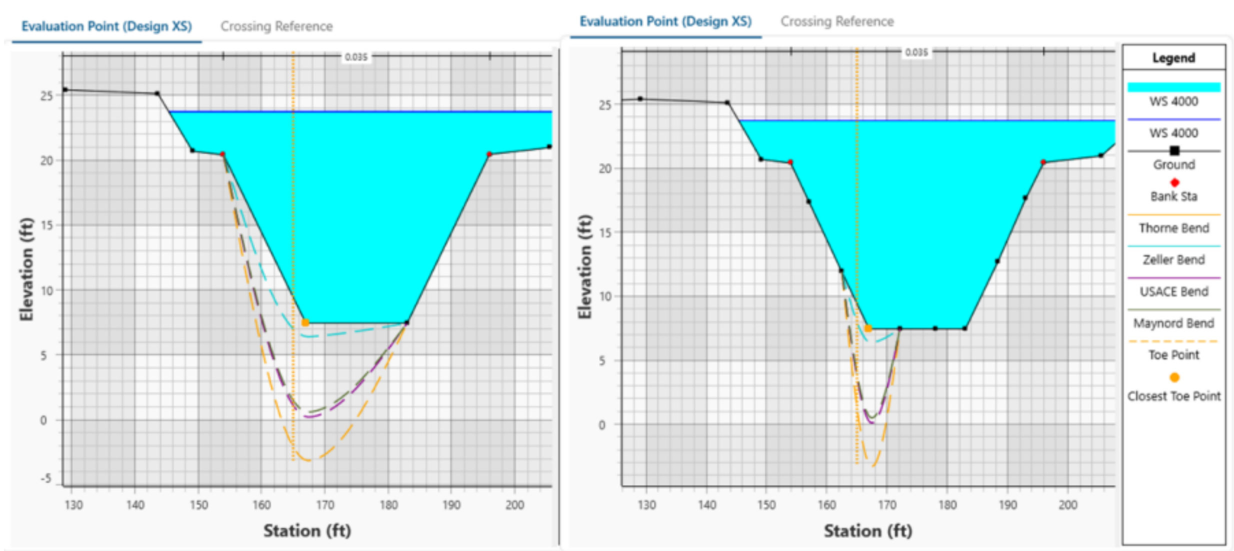
In the following figure, the **Toe Station** is 165. The display includes an orange, dotted, line to indicate the location of this user-defined **Toe Station**. The cross section has no station-elevation point right at station 165, so it selects the closest point (which is at the left toe of the engineered, trapezoidal channel).



The bend scour visualization applies the computed scour depths to the selected station-elevation point, and connects them to the adjacent station-elevation points.

Note:

The bend scour visualization is dependent on the number and location of station elevation points. For example, the bend scour visualization above would look very different if the modeler used more station-elevation points to define the cross section.



Step 7: Select a Reasonable Scour Depth Based on Calculations, Regional Geology, and Engineering Judgement

The scour equations are simple and empirical, regressions of data from systems that likely diverge from the system you are analyzing in several ways. The scour calculator includes a suite of these equations – in part – to help users and managers to understand the uncertainty in these calculations. The calculator does not automatically combine results into a single scour metric (e.g. average, max, or geometric mean) because these results should inform a broader decision and design process that also includes qualitative information, system observations, expert judgment, and common sense. The ensemble scour calculations provide a range of results that can bound the design scour depth (and communicate uncertainty). But the final scour depth requires the project engineer to take responsibility for the scour depth decision.

These equations are best used in the following decision approach:

1. Exclude equations that are not applicable to the setting or generate unrealistic results (e.g. negative scour). This requires review of the assumptions associated with each equation and deciding if each equation is appropriate for the design setting.

2. Report the median value, and the range. Look for clusters of results (several equations with similar scour depths) but recognize that some equations artificially generate similar results because they have similar forms or structure. Because some equations tend to produce similar results, the scour calculations cannot be treated as "independent observations" for statistical analysis.

3. Use these results with other qualitative assessments, local system expertise, and subject matter experts to agree on a design depth that reflects the likely scour depth, the risk tolerance, and the desired factor of safety.

Ongoing Work and Wish List

HEC is working on the following developments for future versions:

- Add the Maricopa County Riprap Design Approach
- Add the Blench Scour Calculation
- Automatically read bankfull hydraulics for Neill equation by selecting a second HEC-RAS profile
- Automate the Radius of Curvature Calculation in RASMapper
- Import Cross-Section Averaged 2D Results Directly from a User Selected Transect

Acknowledgement

This tool was funded by the Regional Sediment Management (RSM) R&D project.

David Biedenharn, David May, and Chris Haring provided substantial technical contributions and review.

Funding was also provided by the Flood Control District of Maricopa County, with review and contributions from Bing Zhao.

HEC used a scour calculation spreadsheet developed by PBS&J to help guide and validate the scour calculations: PBS&J Scour Analysis Spreadsheet (2008) Version 1.2

Dan Pridal and Krey Price reviewed the user manual and provided useful content.

Scour References

Baird, D., Sixta, M., Foster, M., Neff, K. (2019) Guidelines for Evaluating Pipeline Channel Crossing Hazards to Ensure Effective Burial, US Bureau of Reclamation, Technical Service Center Manuals and Standards, 209 p.

Federal Highway Administration. (2012). Hydraulic Engineering Circular No. 18, Evaluating Scour at Bridges, Fifth Edition. Washington, DC: U.S. Department of Transportation.

Howard, A., Pak, J., May, D., Gibson, S., Haring, C., Alberto, B., Snyder, M. (2021) "Approaches for Assessing River Scour," Regional Sediment Management Technical Report.

Maricopa County Flood Control District. (2013). Drainage Design Manual for Maricopa County, Arizona. Phoenix, AZ: Maricopa County, AZ.

Pemberton, E. L., & Lara, J. M. (1984). Computing Degradation and Local Scour, Technical Guideline for Bureau of Reclamation. Denver, CO: Bureau of Reclamation, Engineering and Research Center.

Thorne, C. R., & Abt, S. R. (1993). Velocity and Scour Prediction in River Bends. Washington, DC: U.S. Army Corps of Engineers.

U.S. Army Corps of Engineers. (1994). Hydraulic Design of Flood Control Channels. Washington, D.C.: Department of the Army.

Appendix A: Example Calculations

Riprap Examples

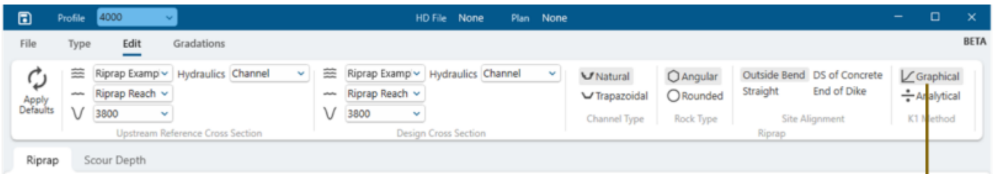
Riprap Calculator Example Calculations:
EM 1110-2-1601 Example H1 (from Appendix H)

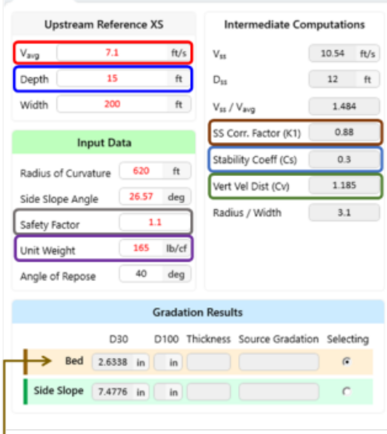
Appendix H
Examples of Stone Size Calculations

H-1. Problem 1

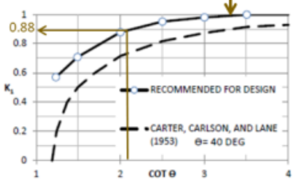
a. Problem. Determine stable riprap size for the outer bank of a natural channel bend in which maximum velocity occurs at bank-full flow. Water-surface profile computations at bank-full flow show an average channel velocity of 7.1 ft/sec and a depth at the toe of the outer bank of 15 ft. The channel is sufficiently wide so that the added resistance on the outer bank will not significantly affect the computed average channel velocity (true in many natural channels). A nearby quarry has rock weighing 165 pcf and can produce the 12-, 18-, and 24-in. D_{100}(max) gradations shown in Table 3-1. A bank slope of 1V on 2H has been selected based on geotechnical analysis. A blanket thickness of 1D_{100}(max) will be used in this design. Bend radius is 620 ft and water-surface width is 200 ft.

b. Solution. Using Plate 33, the maximum bend velocity V_{SS} is 1.48(7.1) or 10.5 ft/sec. The side slope depth at 20 percent up the slope is 12 ft. Using either Equation 3-3 or Plates 37 and 40, the required D_{30} is 0.62 ft. From Table 3-1, the 18-in. D_{100}(max) gradation is the minimum available gradation that has D_{30}(min) greater than or equal to 0.62 ft. This example demonstrates the added safety factor that often results from using standard gradations to avoid the extra production costs incurred by specifying a custom gradation for every design condition.





$$\frac{R}{W} = \frac{620\,ft}{200\,ft} = 3.1$$

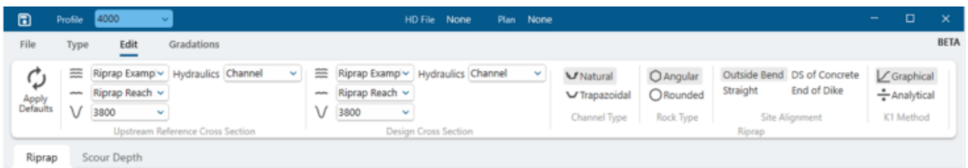


$$\cot\theta = \cot(26.77^{o}) = 2.0$$

$$C_v = 1.283 - 0.2\log\left(\frac{R}{W}\right) = 1.283 - 0.2\log(3.1) = 1.185$$

$$d_{30(Bed)} = SF \cdot C_s C_v D_{Avg}\left[\sqrt{\frac{\gamma_w}{\gamma_s - \gamma_w}}\frac{V_{Avg}}{\sqrt{K_1 g D_{Avg}}}\right]^{2.5}$$

$$2.63in \leftarrow 0.22\,ft = 1.1 \cdot 0.3 \cdot 1.185 \cdot 15ft\left[\sqrt{\frac{62.4\frac{lb}{ft^3}}{165\frac{lb}{ft^3} - 62.4\frac{lb}{ft^3}}}\frac{7.1\,ft/s}{\sqrt{0.88 \cdot 32.2\frac{ft}{s^2} \cdot 15ft}}\right]^{2.5}$$



$$\frac{V_{ss}}{V_{avg}} = 1.74 - 0.52log\left(\frac{R}{W}\right) = 1.484$$

$$V_{ss} = 1.484\,V_{avg} = 1.484 * 7.1\frac{ft}{s} = 10.5\,ft/s$$

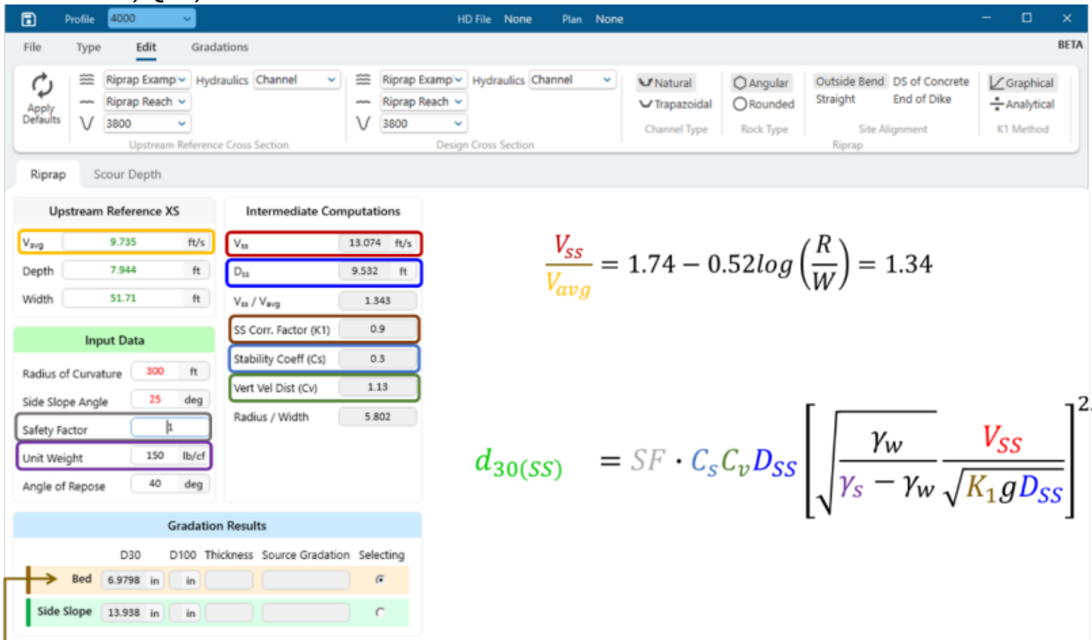
$$D_{ss} = D - 0.2\sqrt{D^2 + \left(\frac{D}{\tan(\theta)}\right)^2} * \sin(\theta)$$

$$D_{ss} = 15\,ft - 0.2\sqrt{15\,ft^2 + \left(\frac{15\,ft}{\tan(26.57^{o})}\right)^2} * \sin(26.57^{o}) = 12\,ft$$

$$d_{30(SS)} = SF \cdot C_s C_v D_{SS}\left[\sqrt{\frac{\gamma_w}{\gamma_s - \gamma_w}}\frac{V_{SS}}{\sqrt{K_1 g D_{SS}}}\right]^{2.5}$$

$$7.5\,in \leftarrow 0.623\,ft = 1.0 \cdot 0.3 \cdot 1.185 \cdot 12ft\left[\sqrt{\frac{62.4\frac{lb}{ft^3}}{165\frac{lb}{ft^3} - 62.4\frac{lb}{ft^3}}}\frac{10.5\,ft/s}{\sqrt{0.9 \cdot 32.2\frac{ft}{s^2} \cdot 12ft}}\right]^{2.5}$$

Example Data Set, Q=4,000 cfs

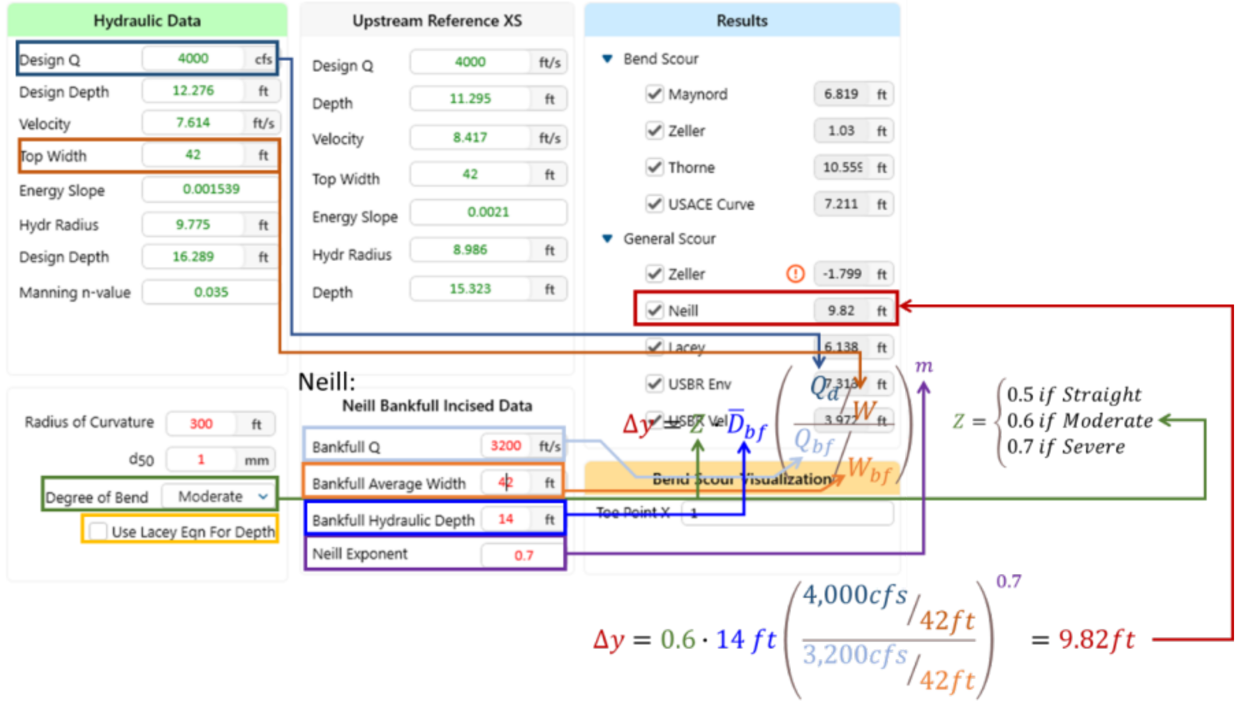


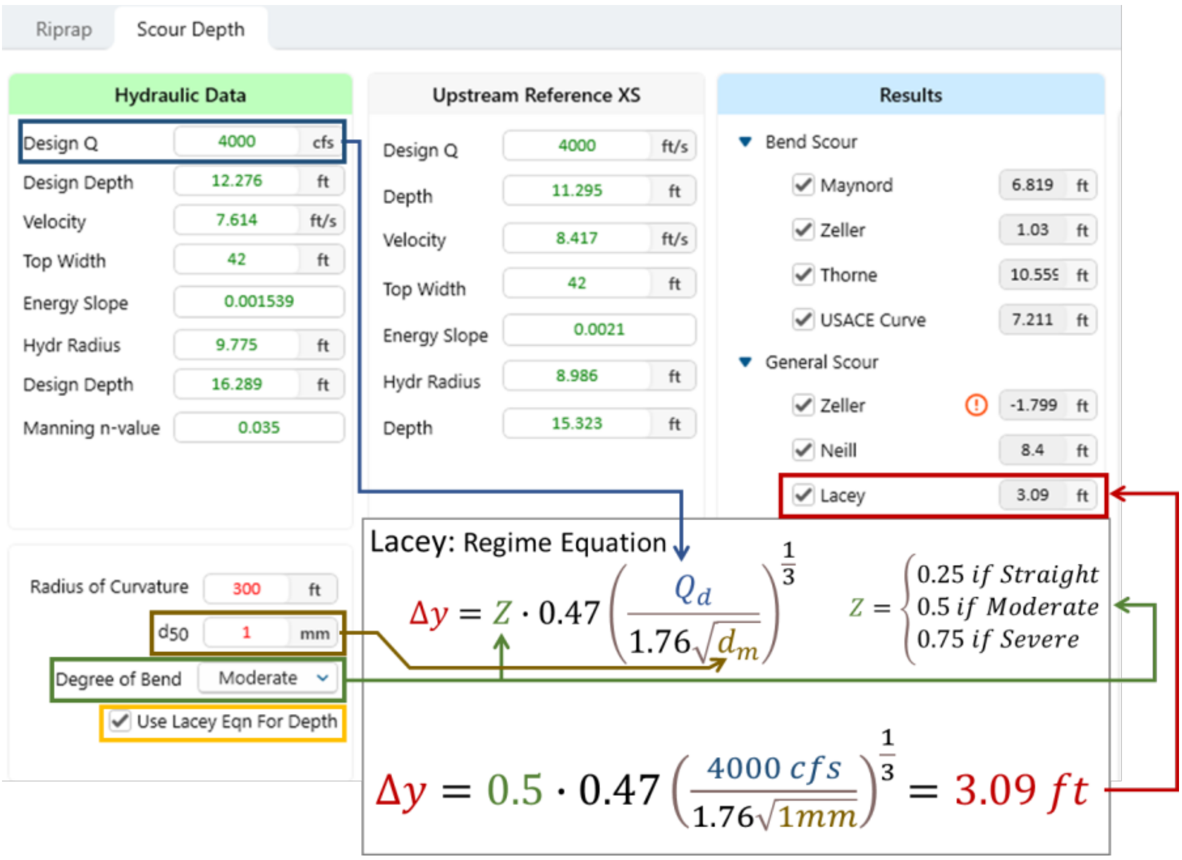
$$\frac{V_{SS}}{V_{avg}} = 1.74 - 0.52 log\left(\frac{R}{W}\right) = 1.34$$

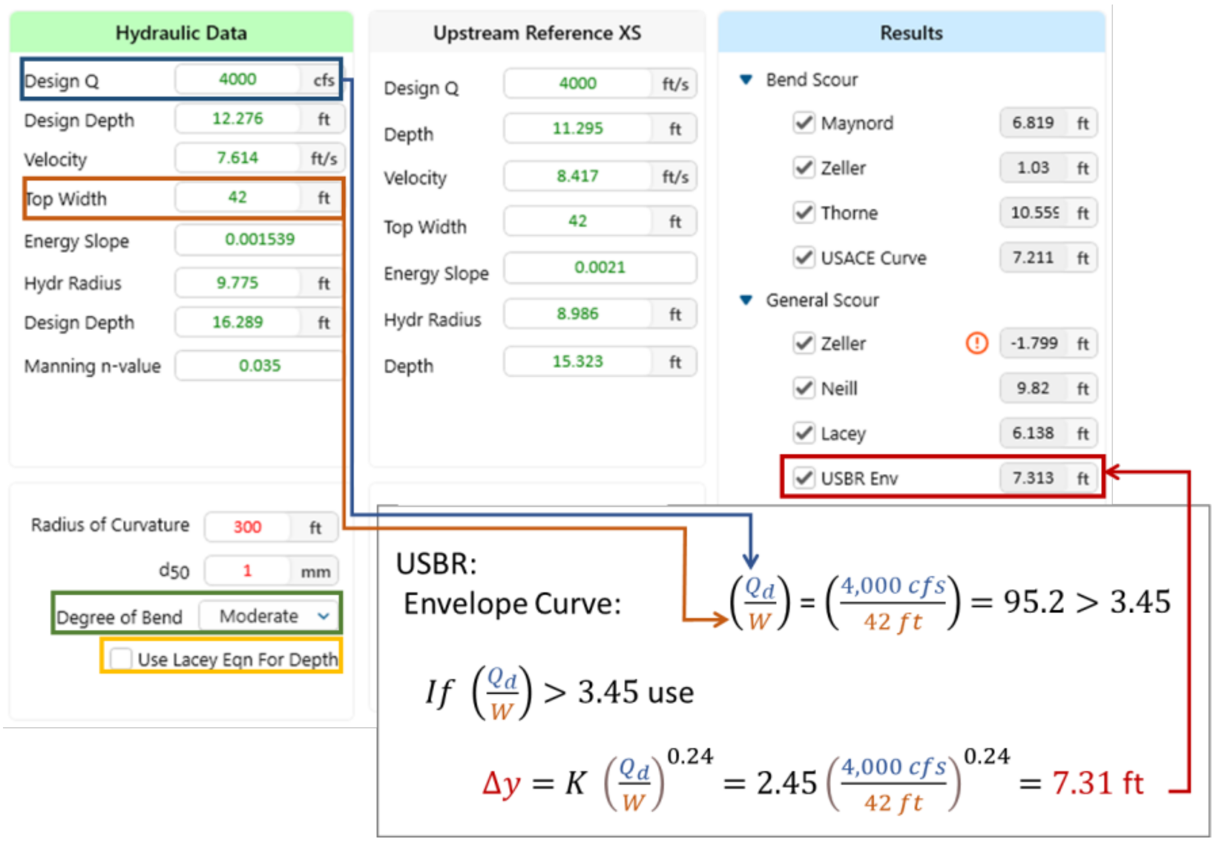
$$d_{30(SS)} = SF \cdot C_s C_v D_{SS}\left[\sqrt{\frac{\gamma_w}{\gamma_s - \gamma_w}}\frac{V_{SS}}{\sqrt{K_1 g D_{SS}}}\right]^{2.5}$$

$$6.979\ in \leftarrow 0.58\ ft = 1.0 \cdot 0.3 \cdot 1.18 \cdot 9.6ft\left[\sqrt{\frac{62.4\frac{lb}{ft^3}}{150\frac{lb}{ft^3} - 62.4\frac{lb}{ft^3}}}\frac{13.1\ ft/s}{\sqrt{0.9 \cdot 32.2\frac{ft}{s^2} \cdot 9.6ft}}\right]^{2.5}$$

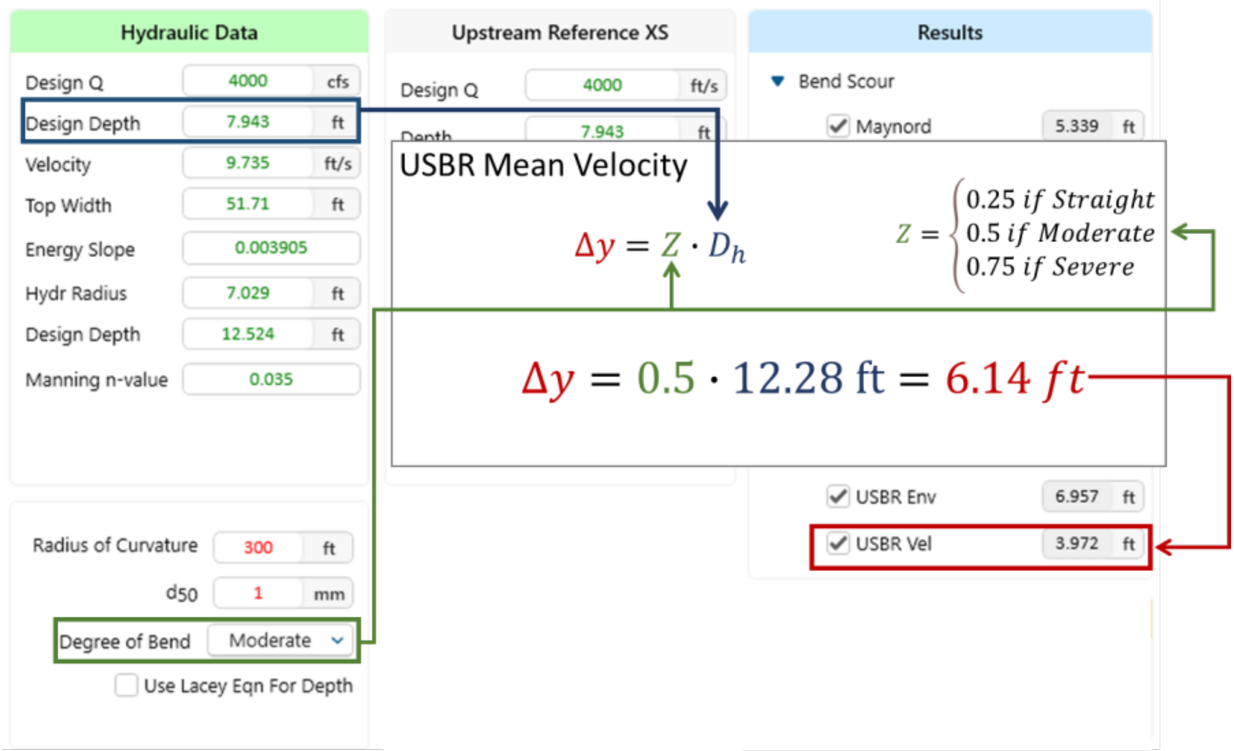
Scour Examples







Hydraulic Data
Design Q 4000 cfs
Design Depth 12.276 ft
Velocity 7.614 ft/s
Top Width 42 ft
Energy Slope 0.001539
Hydr Radius 9.775 ft
Design Depth 16.289 ft
Manning n-value 0.035
Radius of Curvature 300 ft
d50 1 mm
Degree of Bend Moderate
Use Lacey Eqn For Depth
Upstream Reference XS
Design Q 4000 ft/s
Depth 11.295 ft
Velocity 8.417 ft/s
Top Width 42 ft
Energy Slope 0.0021
Hydr Radius 8.986 ft
Depth 15.323 ft
Results
Bend Scour
Maynord 6.819 ft
Zeller 1.03 ft
Thorne 10.559 ft
USACE Curve 7.211 ft
General Scour
Zeller -1.799 ft
Neill 9.82 ft
Lacey 6.138 ft
USBR Env 7.313 ft
USBR:
Envelope Curve:
$\left(\frac{Q_d}{W}\right) = \left(\frac{4{,}000\ cfs}{42\ ft}\right) = 95.2 > 3.45$
$If\ \left(\frac{Q_d}{W}\right) > 3.45$ use
$\Delta y = K\left(\frac{Q_d}{W}\right)^{0.24} = 2.45\left(\frac{4{,}000\ cfs}{42\ ft}\right)^{0.24} = 7.31$ ft



Hydraulic Data
Design Q 4000 cfs
Design Depth 7.943 ft
Velocity 9.735 ft/s
Top Width 51.71 ft
Energy Slope 0.003905
Hydr Radius 7.029 ft
Design Depth 12.524 ft
Manning n-value 0.035
Radius of Curvature 300 ft
d50 1 mm
Degree of Bend Moderate
Use Lacey Eqn For Depth
Upstream Reference XS
Design Q 4000 ft/s
Depth 7.943 ft
Results
Bend Scour
Maynord 5.339 ft
USBR Mean Velocity
$\Delta y = Z \cdot D_h$
$Z = \begin{cases} 0.25\ if\ Straight \\ 0.5\ if\ Moderate \\ 0.75\ if\ Severe \end{cases}$
$\Delta y = 0.5 \cdot 12.28\ \text{ft} = 6.14\ ft$
USBR Env 6.957 ft
USBR Vel 3.972 ft

Uniform Flow Computations

The uniform flow computations are performed by opening the **Hydraulic Design Functions** window and selecting the **Uniform Flow** from the **Type** menu item. Once this option is selected the program will automatically go to the geometry file and plot a cross section with the station and elevation data entered into the table. The user can select any cross section from the available rivers and reaches. The Hydraulic Design window for uniform flow will appear as shown in Figure 13-1.

As shown in Figure 13-1, the Uniform Flow window contains the input data, a graphic, and a window for summary results. Input data tabs included are the S/Q/y/n tab and the Width tab. The S/Q/y/n tab is used for calculating the normal slope, discharge, depth, or roughness for the current cross section. The Width tab is used to calculate the bottom width for a uniform flow solution of a user-entered compound channel (with up to 3 trapezoidal templates). The station, elevation, and roughness values for both the current cross section and the user-defined cross section can easily be manipulated in the table and applied to the current geometry file. The user is required to enter only a minimal amount of input and the computations can be performed.

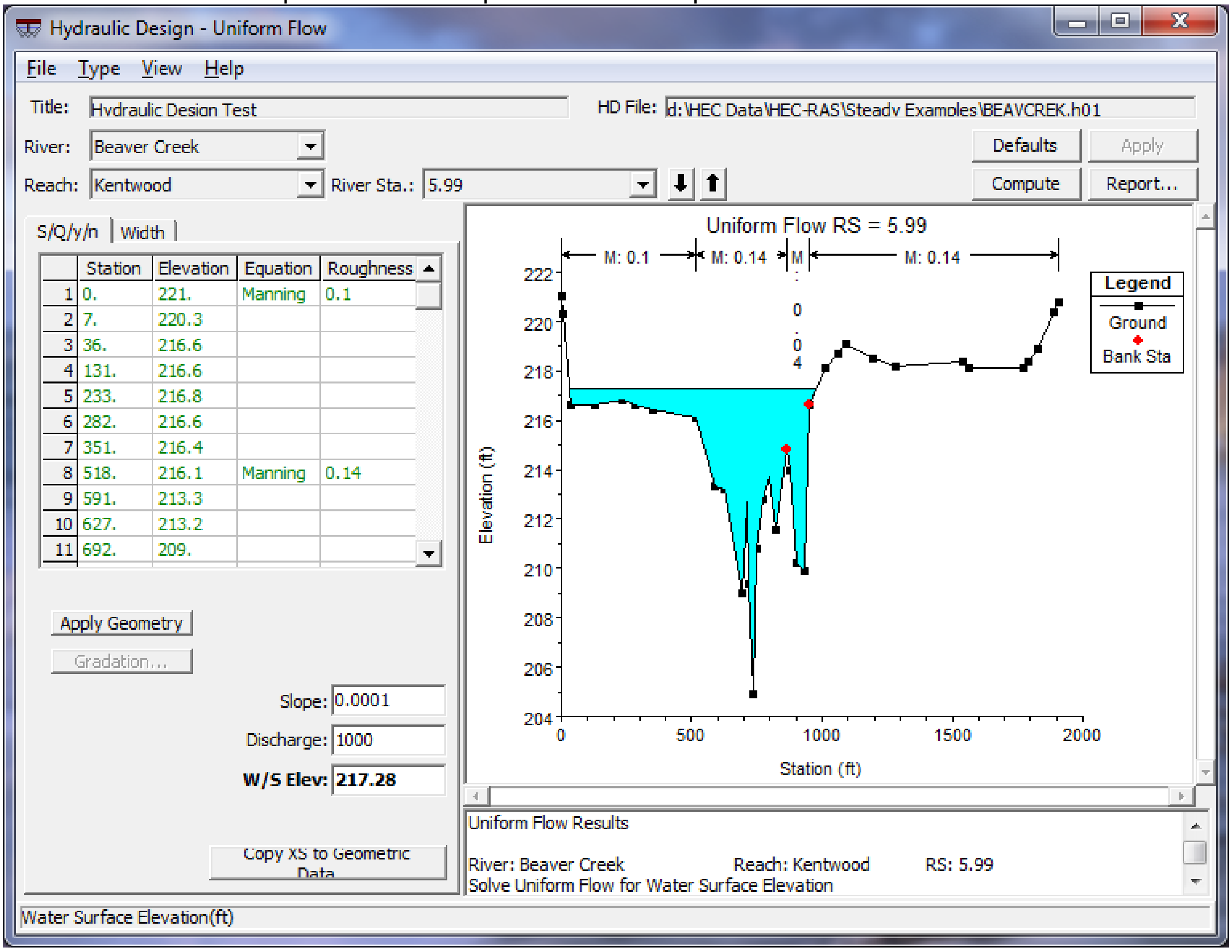


Figure 13 1. Hydraulic Design Window for Uniform Flow

Solving for Slope, Discharge, or W/S Elevation

When the S/Q/y/n tab has been selected, to calculate a slope that satisfies the uniform flow equations for the current cross section, simply enter values into the Discharge and a W/S Elev fields and press the Compute button. A value for the slope is then automatically entered into the Slope field. Likewise, for solving for discharge or water surface elevation, enter values for the other two parameters.

The roughness values are automatically taken from the geometry file, but these can be changed to better represent the bed characteristics of the cross section. In addition to changing the value of the roughness factor (in the default case, Manning's n), the function for defining roughness can be changed. To do this, click on any cell in the equation column of the table and select a function from the dropdown list. The available functions to choose from are Manning's, Keulegan, Strickler, Limerinos, Brownlie, and five grass-lined channel methods. Each of these functions is discussed in detail in Chapter 15 of the Hydraulic Reference Manual.
For the Limerinos and Brownlie functions, gradation distribution is necessary and can be entered by pressing the Gradation button. Only one gradation distribution can be used for a given cross section and should be applied only to the main channel, as these functions were developed for bed material. The Gradation window is shown in Figure 13-2. The following gradation variables are defined as the following:

- **d84**: The sediment particle size for which 84% of the sediment mixture is finer (mm).
- **d50**: The sediment particle size for which 50% of the sediment mixture is finer (mm).
- **d16**: The sediment particle size for which 16% of the sediment mixture is finer (mm).

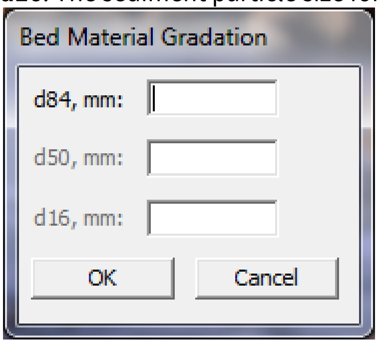


Figure 13 2. Gradation Window

The Brownlie function requires a sediment specific gravity to be entered and the Keulegan function requires a temperature to be entered. The Compute button only becomes active once all required input is entered.
To solve for a roughness value, click on and delete only one of the roughness values in the table. Only one roughness section can be solved for at a time. Make sure Slope, Discharge, and W/S Elev are specified and all other required input are entered. RAS then computes a Manning's n value to satisfy the uniform flow equation for the portion of the cross section that is desired. Then, the roughness value is back-calculated to match the selected roughness function. Only Manning, Keulegan, and Strickler functions can be used to solve for roughness, since the other functions do not have a representative roughness value to solve for.
Once one computation has been made, the value that was solved for will be shown in bold font. For subsequent computations, any of the four uniform flow parameters that is emboldened will be what is solved for to avoid having to delete out the value every time. Once a new parameter is deleted out, it will then be solved for and emboldened.

Solving for Bottom Width

Bottom width can be solved for the uniform flow equation only with a compound channel that is defined by the user. The compound channel may contain up to three trapezoidal templates, a low flow channel, the main channel, and the overbank channel. The bottom width of either the main channel or the overbank may be solved for. The addition or subtraction of width may be applied to right of centerline, left of centerline or equally to both sides.
When the bottom width tab is selected, the window shown in Figure 13-3 is displayed. To define the compound channel, enter the appropriate values into the compound channel table, which is located below the station elevation table. Data for the Overbank, Main, and Low Flow channels can be entered, however data for the low flow channel can only be applied if a main channel is also defined. The following variables are defined as follows:

- **SSL**: The side slope of the left side of the channel. Entering a value of "0" provides a vertical slope (1Vertical : __Horizontal).
- **SSR**: The side slope of the right side of the channel. Entering a value of "0" provides a vertical slope (1Vertical : __Horizontal).
- **WL**: The bottom width of the left side of the channel from the centerline of the channel to the toe of the side slope (ft or m).
- **WR**: The bottom width of the left side of the channel from the centerline of the channel to the toe of the side slope (ft or m).
- **Height**: The height of the respective channel from its invert to the top of its side slope (ft or m).
- **Invert**: The invert of the respective channel (ft or m).

Once the channel template data is entered, the user may plot the data by selecting Apply Geometry. When this button is selected, the channel design is shown in the plot window and entered in the station elevation table with the default roughness information. A Manning's n value of 0.03 will be applied to each of the channel templates defined. The user may then adjust the roughness values, change the roughness functions, or add more roughness change locations within the cross section on the station elevation table. Any changes made can be reapplied to the plot by pressing Apply Geometry. See Figure 13-4. If either the Brownlie or Limerinos functions are chosen, gradation data will have to be entered.

A value for the energy slope, discharge, and water surface elevation must be entered in the appropriate fields. The user can then select how to solve for the bottom width by using the dropdown boxes in the "Compute Widths" section. Either the main channel or the overbank channel can be solved for and the width can be applied to the left side of the channel (Left of CL only), the right side of the channel (Right of CL only), or equally to both (Total).

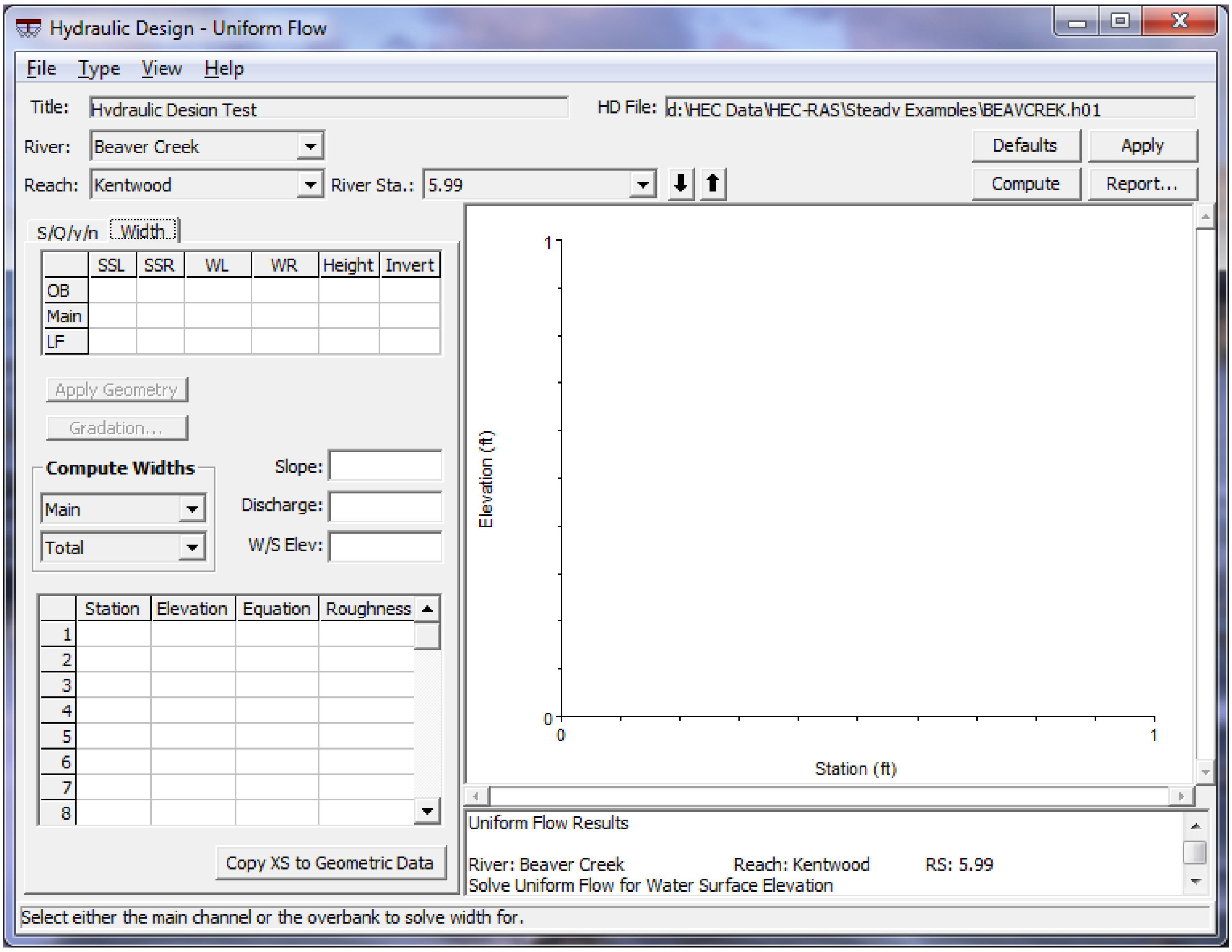


Figure 13 3. Bottom Width Calculation

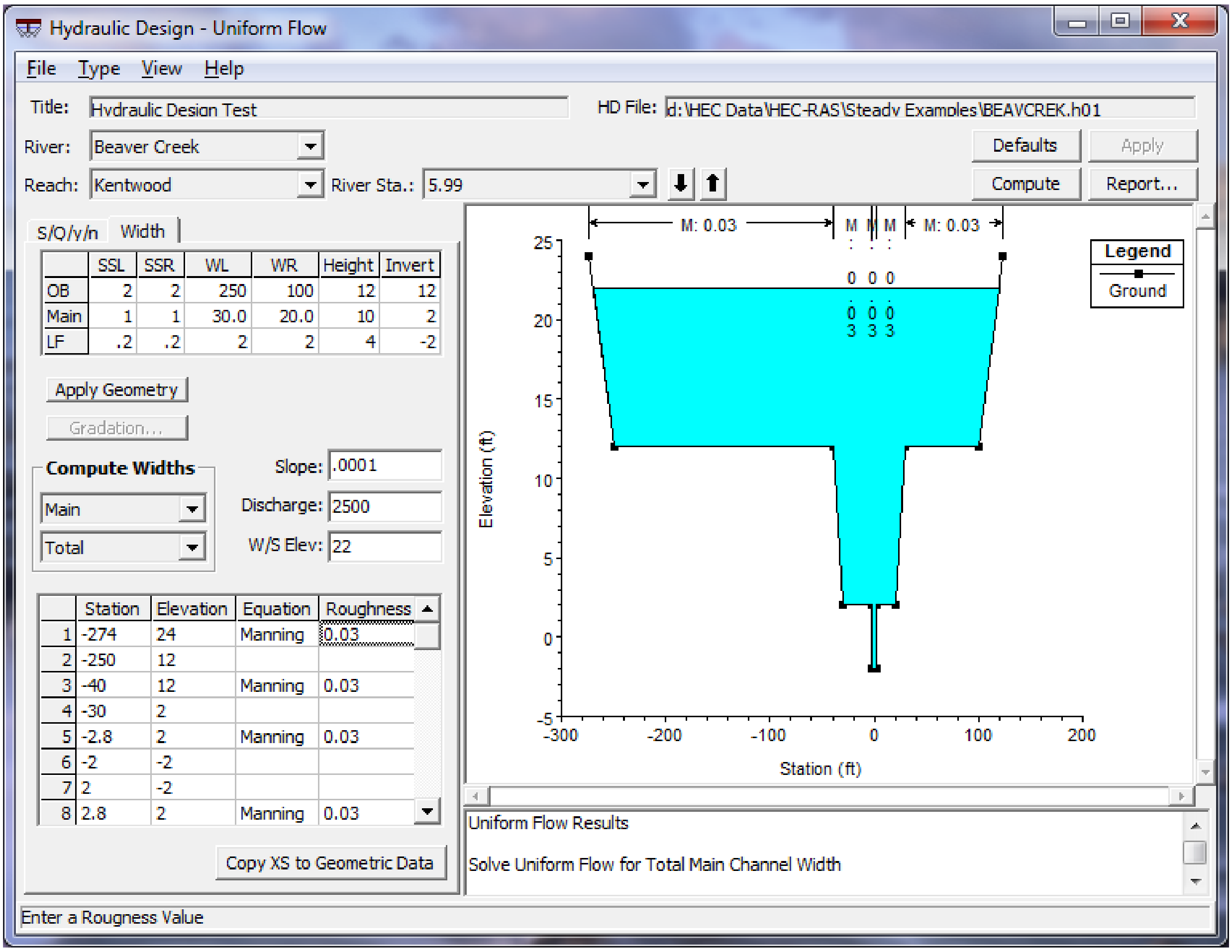


Figure 13 4. Example Bottom Width Data Entry

When all required data is entered, the Compute button will become active. The computations are constrained from creating unrealistic geometries. One example is the overbank bottom width cannot become less than the top width of the main channel. Likewise, the main channel bottom width cannot become less than the low flow channel top width. If this situation occurs within the computations, the user is notified and a course of action is suggested. However, if the top width of a lower channel becomes greater than the bottom width of the channel above it within the calculations, the program automatically increases the upper channel's bottom width to compensate. When a solution is obtained, the new widths are updated in the compound channel table, the station elevation table and the plot.

Applying Uniform Flow Data to the Geometry File

The resulting cross section, displayed in the plot window can be added to the existing geometry data by clicking on the "Copy XS to Geometric Data" command button. The following window will appear:

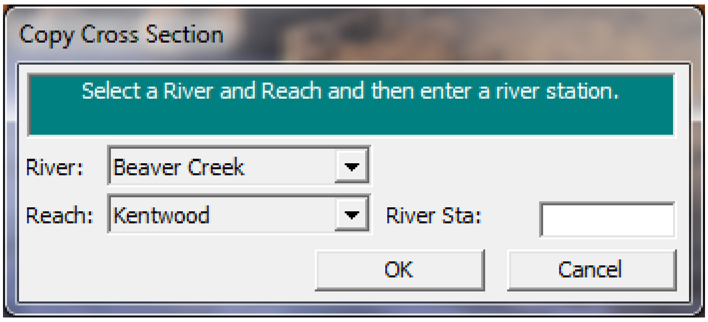


Figure 13 5. Copy Cross Section Window

Enter in the river station you want this cross section to be applied to. If the selected river station already contains a cross section, RAS will ask if you want to copy over it. If there is no cross section at the entered river station, RAS will automatically adjust the distances between the new cross section and its adjacent ones. Make sure that once the new cross section has been copied to the geometry, appropriate values for the bed elevations are reentered. This can easily be done by selecting "Adjust Elevations…" in the Option menu of the Cross Section Data window.

Saving Uniform Flow Data

To save the uniform flow data, click on File…save. This will add all pertinent data from all the HD Functions to an ascii file with the extension *.h##. The content of this file can easily be read within any word processing program.

Stable Channel Design Functions

The channel design functions within HEC-RAS are based upon the methods available in the SAM Hydraulic Design Package for Channels (USACE, 1998), developed by the U.S. Army Corps of Engineers Waterways Experiment Station. This chapter presents the data input required for computing uniform flow parameters, stable channel dimensions, and sediment transport capacity for a given cross section.

For information on the Channel Design Functions equations and theory, please see Chapter 15 of the HEC-RAS Hydraulic Reference Manual.

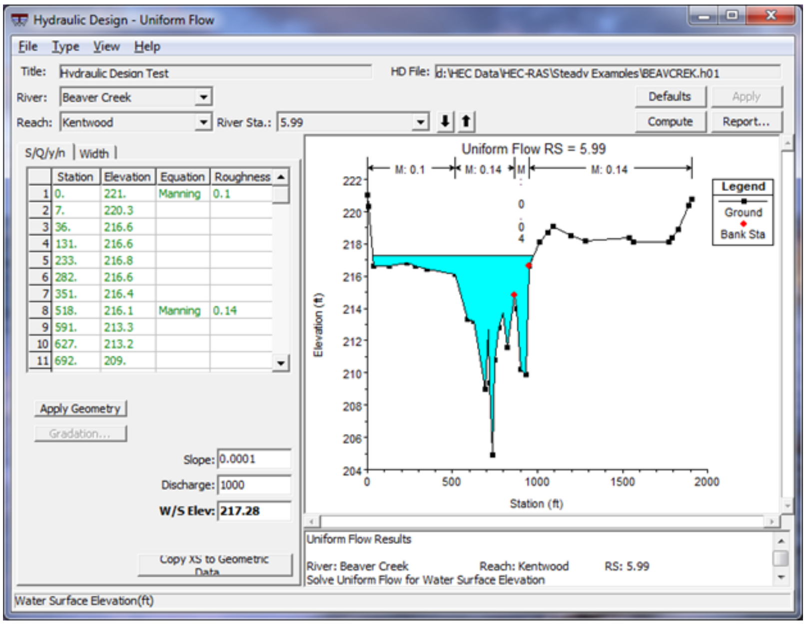
General Modeling Guidelines

The Stable Channel Design Functions within HEC-RAS are meant to be used as an aid in the design of stable channels. The purpose of this application is to provide the qualitative, easy-to-use methodology of the SAM software package within the HEC-RAS framework. Specifically, the Stable Channel Design Functions will allow the user to easily compute the hydraulic parameters of a given cross section, use that information to design a stable channel with regard to its size and armoring, and determine the sediment transport capacity of that cross section.

General Command Buttons

The general command buttons can be seen in the top right-hand corner of the window shown in Figure 13-1. The **Defaults** button restores the current hydraulic design function's fields to the default values. The **Apply** button will store the entries on the current window into memory. These values will remain in memory until a new hydraulic design file is opened or the user exits HEC-RAS. The

Compute button initiates the computations for whatever hydraulic design function is currently active. The **Report** button displays a printable report providing detailed hydraulic design information. Output will be displayed in the report window if the computations have been run.

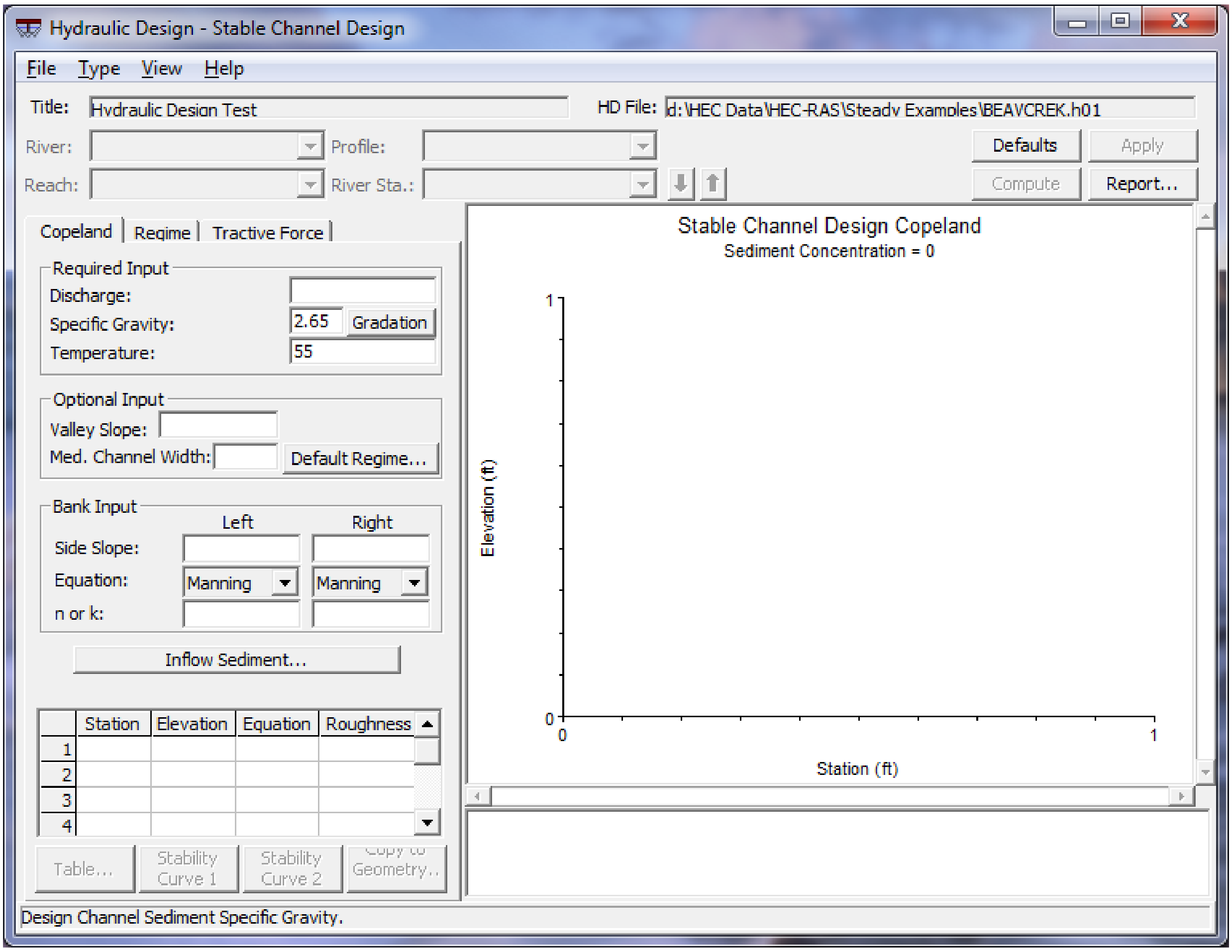


Stable Channel Design

Stable channels can be computed using three different methods:

- Copeland
- Regime
- Tractive Force

To access the stable channel design window, click on Type…Stable Channel Design in the Hydraulic Design Window. The following window will become active:



Stable Channel Design Window

Copeland Method

Dr. Ron Copeland developed the "Copeland Method" (aka the Stable Channel Analytical Method) as a simplified tool to screen channel restoration alternatives. It is a useful method to quickly evaluate a range of possible slope-width-depth combinations that are likely to remain in relative continuity with the sediment transport (e.g. less likely to erode or deposit). The method combines a sediment transport function (Brownlie) with a roughness equation to compute a suite of slope-with and slope-depth pairs that would be in rough continuity with the computed sediment load.

Sorry, the widget is not supported in this export.
But you can reach it using the following URL:

http://youtube.com/watch?v=VV5uGG_NBGM

To use the Copeland Method, select the tab named "Copeland." There are a number of required and optional fields to enter data into for both the design section and the upstream section. To enter in data for the design section, simply add data to the fields shown.

Discharge: The design discharge. Can be the 2-year, 10-year, bankfull, etc. Must represent the channel forming discharge (cfs or m3/s).

Specific Gravity: Particle specific gravity. Default is 2.65. Rarely changes.

Temperature: A representative temperature of the water. Default is 55 degrees F or 10 degrees C.

Valley Slope: (Optional) The maximum possible slope for the channel invert (i.e. no channel sinuosity). If the slope returned is greater than the valley slope, HEC-RAS will indicate that this is a "sediment trap."

Med. Channel Width: (Optional) Median channel width. The median width of the array of 20 bottom widths that are solved for. There will be 9 widths less than and 10 widths greater than the median channel width all at an increment of 0.1 X Med. Channel Width (ft or m). If this is left blank, the median width assigned will be equal to the regime width by the following equation: B = 2Q0.5

Side Slope: Slope of the left and right side slopes. (1Vertical : __Horizontal).

Equation: Can choose from Mannings or Strickler to solve for the side slope roughness.

n or k: If Mannings is selected, enter a Mannings "n" value. If Strickler is selected, enter a "k" value (ft or m for k values).
Gradation of the sediment is required for Copeland method and can be entered by clicking on the Gradation command button. Values for d84, d50, and d16 must be entered.
The user has the ability to designate the default regime for the computations. The HEC-RAS default is lower regime, but this can be changed by clicking on the "Default Regime…" button and selecting "Upper Regime". Any time the computations result in a solution that is in the transitional regime, the default regime will be used and the user will be notified in the output table that this occurred. See chapter 12 of the Hydraulic Design Manual for more information.

Once all required data for the design section has been entered, click on the "Inflow Sediment…" command button to input information about the upstream section for sediment concentration computations. The window shown in Figure 13-7 becomes active. The user can either enter in a value for the inflowing sediment concentration or let HEC-RAS calculate it. If HEC-RAS is to calculate the inflow sediment concentration, then the following information about the upstream section must be entered:

Supply Reach Bottom Width: Width of the bed of the supply reach (ft or m).

Supply Reach Bank Height: A representative value of the bank elevation minus the channel invert elevation of the supply section. This is only used in the computations to target a depth and does not limit the solution to this height (ft or m).

Supply Energy Slope: A representative energy slope at the supply section. Water surface slope is typically used.

Side Slope: Slope of the left and right side slopes of the supply section. (1Vertical : __Horizontal).

Equation: Can choose from Mannings or Strickler to solve for the side slope roughness of the supply section.

n or k: If Mannings is selected, enter a Mannings "n" value. If Strickler is selected, enter a "k" value for the supply section (ft or m for k values).

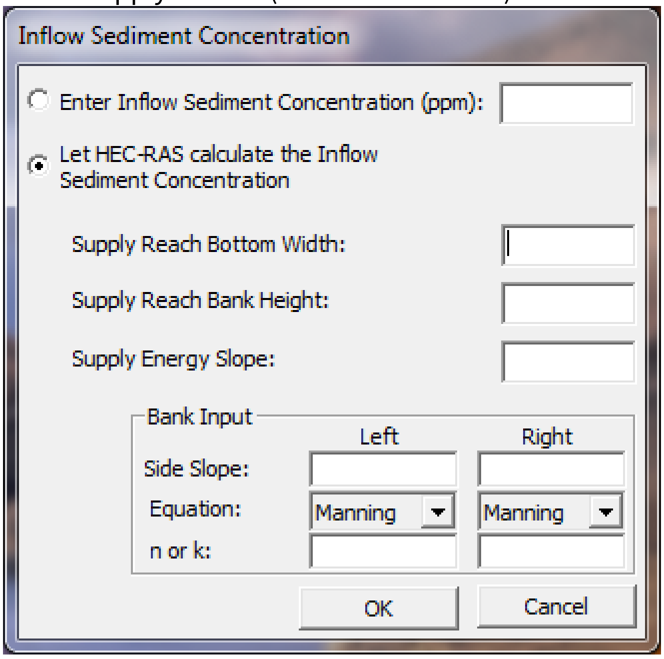
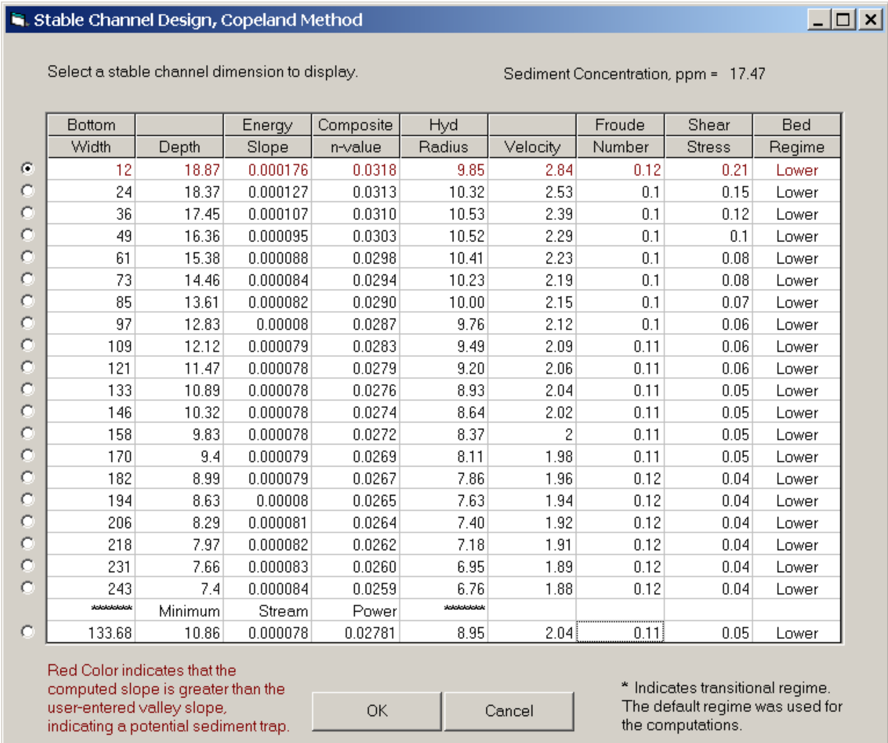


Figure 13 7. Inflow Sediment Concentration Window

Click OK to apply the input and return to the main HD Functions window. Once all of the required input has been entered, the Compute button will be activated. Click the Compute button to run the computations. When the computations are complete, the output table will be shown. The output table lists all of the channel widths solved for along with the corresponding depth, slope, composite n value, hydraulic radius, velocity, Froude number, shear stress and bed transport regime. An example is shown in Figure 13-8. There will be twenty different stable channel geometries plus one for the minimum stream power. The user can select one of these geometries for display on the plot window. Once the desired section is selected, click OK and the HD Functions window will become active with the selected section plotted in the plot window.

When the computations have been run, the Table button, the two Stability Curve buttons and the Copy to Geometry button become active. The Table button simply allows the user to pull up the output table again, and select a different stable section, if desired. Clicking on the Stability Curve 1 button will bring up a plot of the stability curve showing slope versus width, indicating for what slope/width combination aggradation or degradation can be expected. Figure 13-9 shows an example.



Bottom Width	Depth	Energy Slope	Composite n-value	Hyd Radius	Velocity	Froude Number	Shear Stress	Bed Regime
12	18.87	0.000176	0.0318	9.85	2.84	0.12	0.21	Lower
24	18.37	0.000127	0.0313	10.32	2.53	0.1	0.15	Lower
36	17.45	0.000107	0.0310	10.53	2.39	0.1	0.12	Lower
49	16.36	0.000095	0.0303	10.52	2.29	0.1	0.1	Lower
61	15.38	0.000088	0.0298	10.41	2.23	0.1	0.08	Lower
73	14.46	0.000084	0.0294	10.23	2.19	0.1	0.08	Lower
85	13.61	0.000082	0.0290	10.00	2.15	0.1	0.07	Lower
97	12.83	0.00008	0.0287	9.76	2.12	0.1	0.06	Lower
109	12.12	0.000079	0.0283	9.49	2.09	0.11	0.06	Lower
121	11.47	0.000078	0.0279	9.20	2.06	0.11	0.06	Lower
133	10.89	0.000078	0.0276	8.93	2.04	0.11	0.05	Lower
146	10.32	0.000078	0.0274	8.64	2.02	0.11	0.05	Lower
158	9.83	0.000078	0.0272	8.37	2	0.11	0.05	Lower
170	9.4	0.000079	0.0269	8.11	1.98	0.11	0.05	Lower
182	8.99	0.000079	0.0267	7.86	1.96	0.12	0.04	Lower
194	8.63	0.00008	0.0265	7.63	1.94	0.12	0.04	Lower
206	8.29	0.000081	0.0264	7.40	1.92	0.12	0.04	Lower
218	7.97	0.000082	0.0262	7.18	1.91	0.12	0.04	Lower
231	7.66	0.000083	0.0260	6.95	1.89	0.12	0.04	Lower
243	7.4	0.000084	0.0259	6.76	1.88	0.12	0.04	Lower
*******	Minimum	Stream	Power	*******				
133.68	10.86	0.000078	0.02781	8.95	2.04	0.11	0.05	Lower

Figure 13 8. Copeland Method Output Table

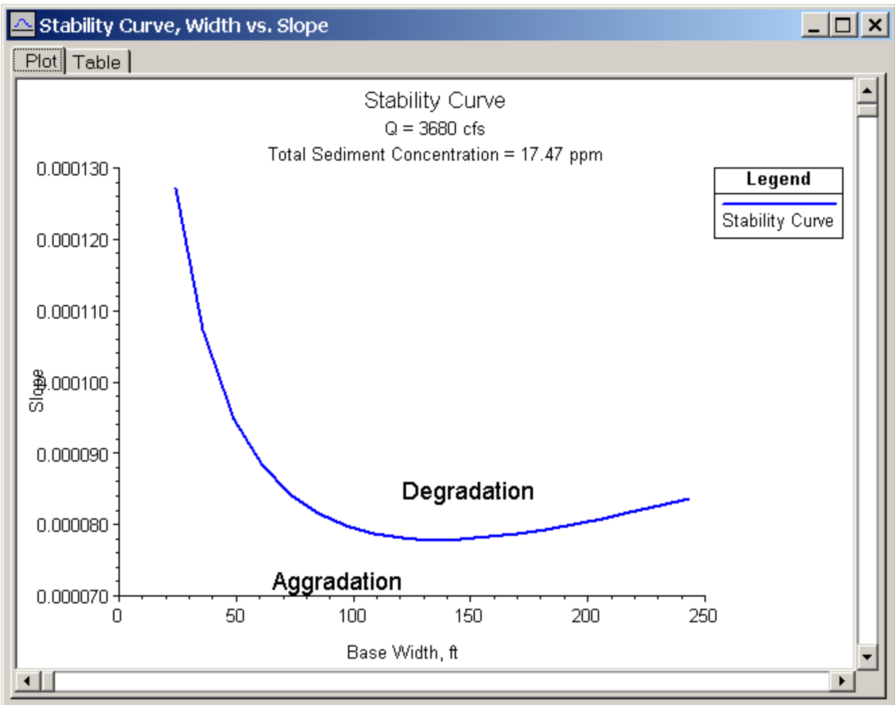


Figure 13 9. Stability Curve

Stability Curve 2 brings up a similar plot, only with slope compared to depth. In addition to viewing the plots, the table tab can be clicked to view the stability curves in tabular form.

As with the uniform flow computations, the section that has been plotted from the Copeland Method can be applied to the current geometry file by clicking on the Copy to Geometry button.

Brownlie is Limited to Sand Beds

The version of the Copeland Method currently in HEC-RAS only uses the Brownlie equations for transport and roughness. The Brownlie equations are limited to sand bed streams and designed for rivers with bedforms. The orriginal Copeland method also provided a MPM option for gravel bed streams. But the HEC-RAS method is limited to Brownlie and Sand Bed Streams.

Wish List - MPM Copeland Method

HEC would like to include the MPM version of the Copeland method for gravel bed streams.

Technical Reference

Regime Method

To use the Regime Method, select the tab named "Regime." The window shown in Figure 13-10 becomes active.

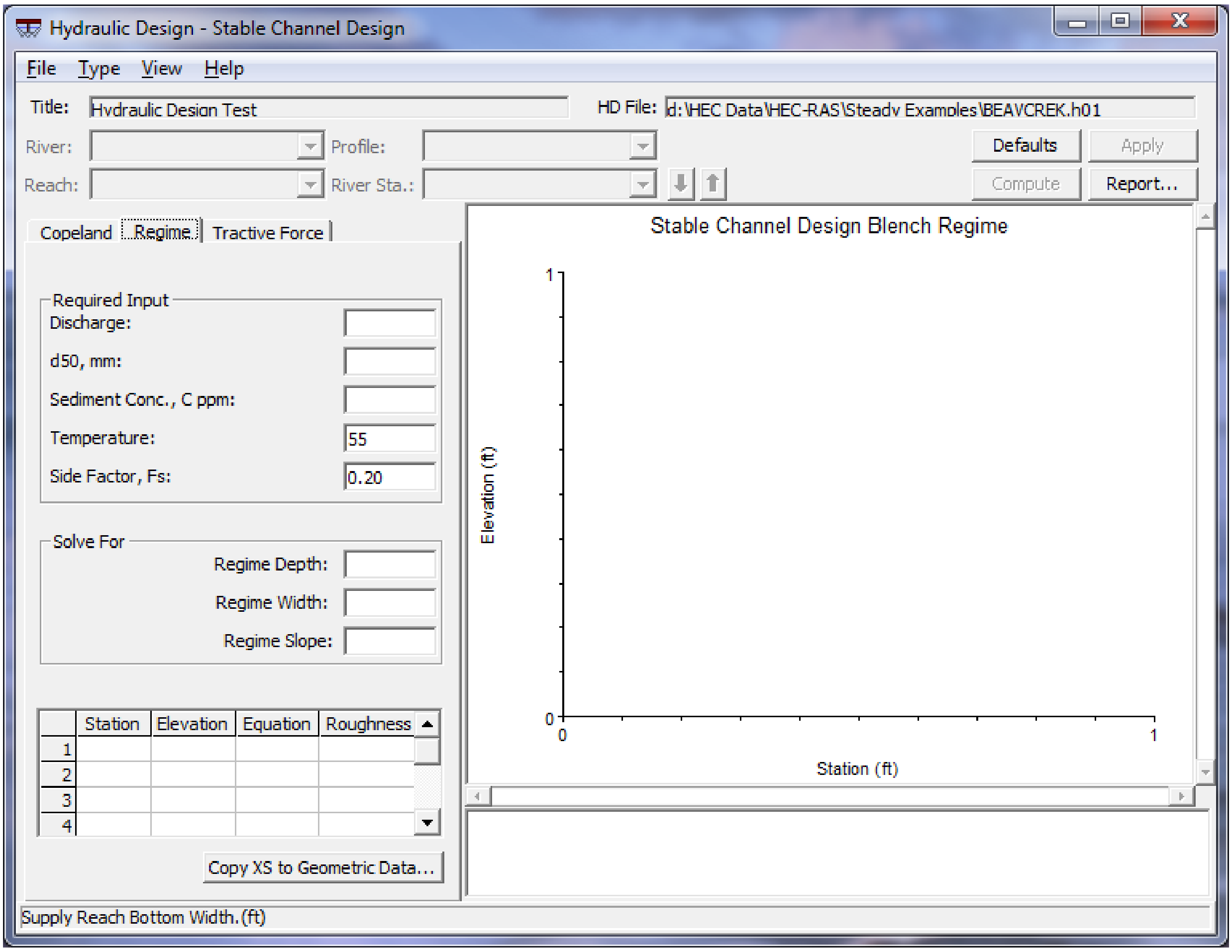


Figure 13 10. Regime Method

Enter in all required input which are:

Discharge: Channel forming discharge (cfs or m3/s).

d50: Median particle size (mm).

Sediment Conc, C ppm: The bed material sediment concentration, in ppm.

Temperature: A representative temperature of the water. Default is 55 degrees F or 10 degrees C.

Side Factor, Fs: The side factor as defined by Blench. Blench suggests 0.1 for friable banks, 0.2 for silty, clayey, or loamy banks, or 0.3 for tough clay banks. Default value is 0.2.
Once these values are entered, the compute button becomes activated and the stable channel regime values for depth, width, and slope will be solved for and entered into the appropriate fields. In addition, the plot window will display the resulting cross section.
The displayed cross section can be added to the existing geometry file by clicking on "Copy XS to Geometric Data."

Tractive Force Method

To use the Tractive Force Method, select the tab named "Tractive Force." The window shown in Figure 13-11 becomes active.

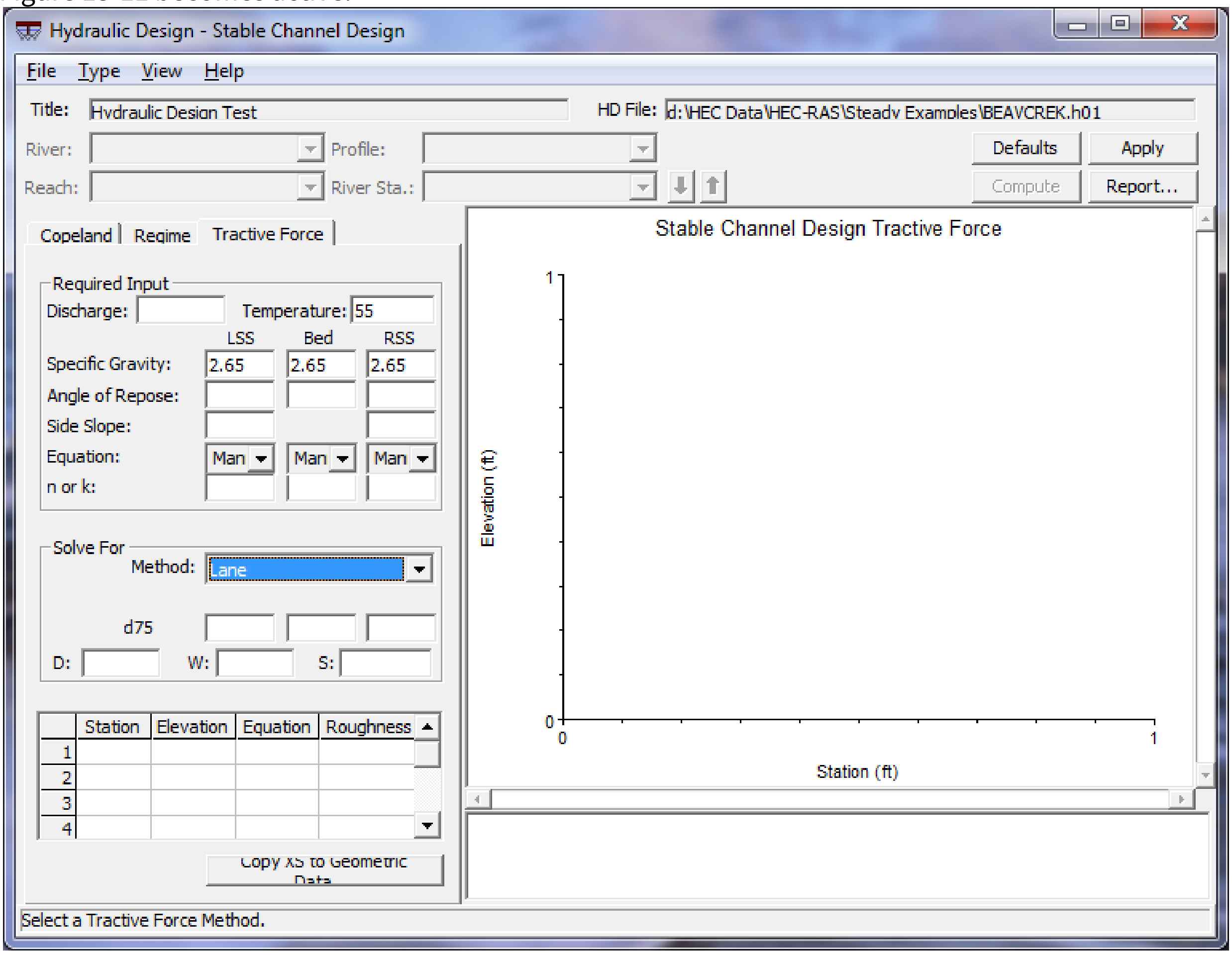


Figure 13 11. Tractive Force Method

Enter in all required input which are:

Discharge: Design discharge (cfs or m3/s).

Temperature: Temperature of the water. Default is 55 degrees F or 10 degrees C.

Specific Gravity: Specific gravity of the sediments for the left side slope, bed, and right side slope.

Angle of Repose: The angle of repose of the sediment for the left side slope, bed, and right side slope. See Figure 11-9 in the HEC-RAS Hydraulic Reference Manual for suggested values.

Side Slope: Left side slope and right side slope (1Vertical : __Horizontal).

Equation: the roughness equation for the left side slope, bed, and right side slope. Mannings and Strickler are available for use.

n or k: If Mannings is selected, enter a Mannings "n" value. If Strickler is selected, enter a "k" value for the left side slope, bed, and right side slope (ft or m for k values).

Method: Solve for critical shear using either Lane, Shields, or by entering in your own critical mobility parameter.
The remaining values are the dependant variables. Only two can be solved for at a time. The other two must be entered by the user. The three fields for particle diameter (left side slope, bed, right side slope) are considered one variable such that any one of the remaining variables plus any or all of the particle diameters can be solved for.

d50/d75: The particle diameter in which 50%/75% of the sediment is smaller, by weight. d50 is used for Shields and user-entered. d75 is used for Lane (mm).

D: The depth of the stable cross section (ft or m).

B: The bottom width of the stable cross section (ft or m).

S: The slope of the energy grade line at the stable cross section.

Once the required values plus two of the dependent variables are entered, the compute button becomes activated and the stable channel values for the remaining dependent variables will be solved for and entered into the appropriate fields. In addition, the plot window will display the resulting cross section.
The displayed cross section can be added to the existing geometry file by clicking on "Copy XS to Geometric Data."

Sediment Transport Capacity

The sediment transport capacity computations can only be run once steady or unsteady flow computations have been run. Sediment Transport Capacity for any cross section can be computed using any of the following sediment transport functions:

- Ackers-White
- Engelund-Hansen
- Laursen
- Meyer-Peter Müller
- Toffaleti
- Yang

To access the sediment transport capacity window, click on Type…Sediment Transport Capacity in the Hydraulic Design Window. The following window will become active:

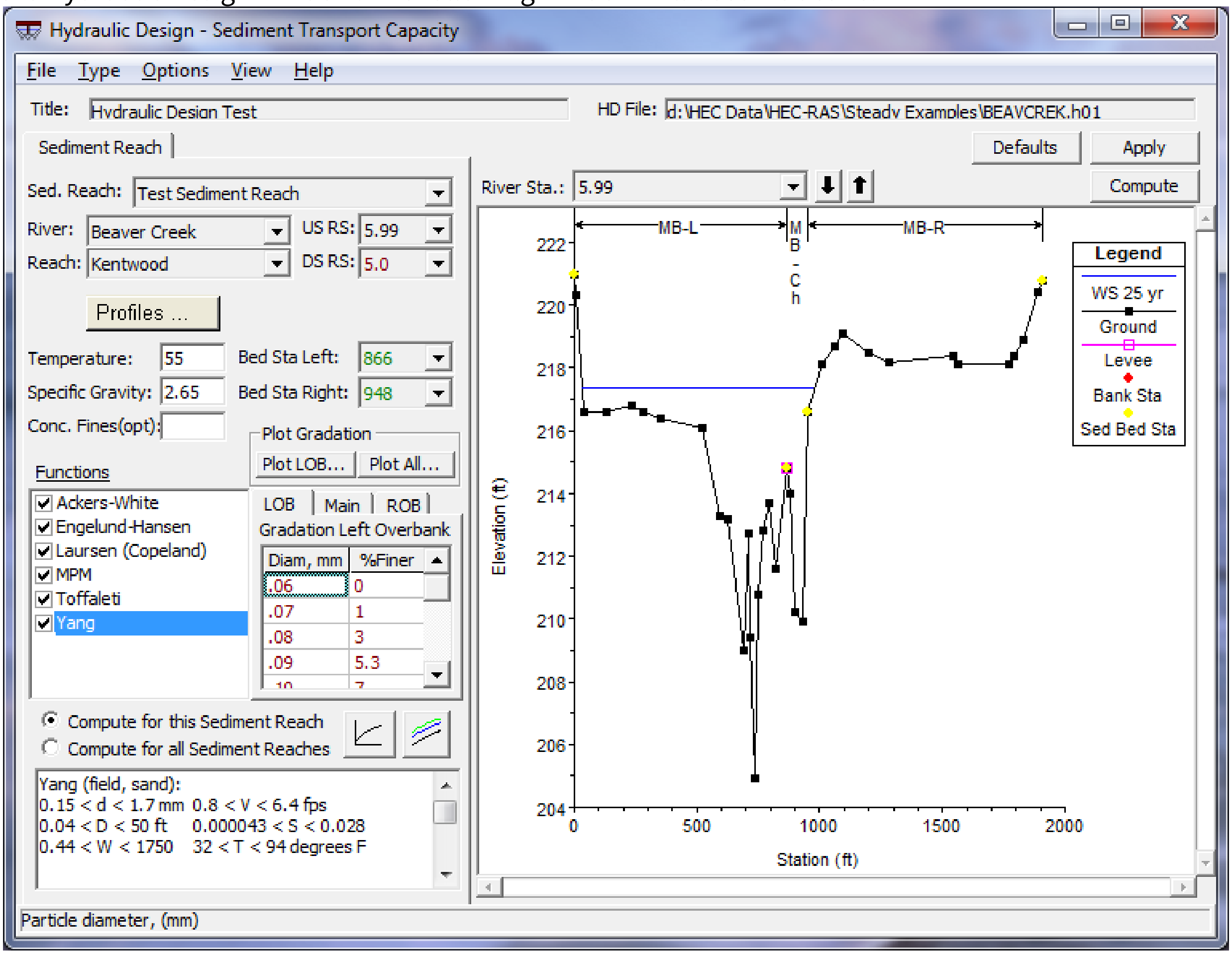


Figure 13 12. Sediment Transport Capacity Window

To perform sediment transport capacity computations, the user must define one or more sediment reaches. A sediment reach indicates for which cross sections transport rates will be computed and contains information necessary to fulfill the computations. Sediment reaches can vary spatially within the geometry, can have different input parameters such as temperature, specific gravity, and gradation, or can simply use different sediment transport functions. A sediment reach cannot span more then one river reach, however there can be multiple sediment reaches within one river reach. **Sediment reaches cannot have overlapping cross sections**.
When the sediment transport capacity window is opened, if there are not any previously defined sediment reaches defined for the current hd file, the user will be automatically prompted to name a new sediment reach. To create a new reach otherwise, click on File…New Sediment Reach. The user also has the option of copying, deleting, and renaming existing sediment reaches under the File menu option. The name selected for the new sediment reach will appear in the Sed. Reach dropdown box along with all other existing sediment reaches for the particular hydraulic design file.

Once a new sediment reach has been named, the user must define its spatial constraints by selecting the river, reach, and the bounding upstream and downstream river stations. Next, one of the existing profiles must be selected.

Sed.Reach: Indicates which sediment reach is active. This dropdown box lists all existing sediment reaches for the current hydraulic design file.

River: The river where the current sediment reach is located.

Reach: The reach where the current sediment reach is located.

US RS: The upstream bounding river station of the current sediment reach.

DS RS: The downstream bounding river station of the current sediment reach.

Profiles: The profile to be used in the sediment transport computations for the current sediment reach.

River Sta: The river station currently displayed on the plot.

Temperature: Temperature of the water. Default is 55 degrees F or 10 degrees C.

Specific Gravity: Specific gravity of the moveable sediments. Default is 2.65.

Bed Sta Left/Right: The cross section stations that separate the left overbank from the main channel from the right overbank for sediment transport capacity computations. Defaults are the main bank stations. These values can be changed for every cross section within the sediment reach. The selected stations appear on the cross section plot as yellow nodes, and are bracketed by "MB" (mobile bed) location arrows on the top of the plot.

Conc. of Fines (opt): The concentration of fine sediments (wash load) in the current sediment reach. This is an optional value and is used to adjust the transport rate based on Colby's (Colby, 1964) findings regarding the effects of fine sediment and temperature on kinematic viscosity, and consequently particle fall velocity. Values are given in parts sediment per one million parts water, by weight.

Functions: The user can select one or more sediment transport functions from this list box. By clicking the checkbox, a check will appear and RAS will compute for that function. When clicking on the name of the function, a brief description of the function and its applicability will appear in the text box below.

Gradation: This is entered for the left overbank (LOB), main channel (Main) and right overbank (ROB) as defined by the left and right bed stations. The user can enter nothing or up to 50 particle size/ percent finer relationships. By right-clicking on one of the tabs, the grid can be expanded for easier viewing. Right-click again to return the grid to its compact display. Typically 5 to 10 gradation points are enough to represent a typical gradation curve. The particle diameter is entered in mm under the column header Diam, mm, and the percent of the representative sediment that is finer than that particle diameter is entered under the column header %Finer. RAS then takes this gradation input to determine the fraction of the sediment that is in each standard grade size class. If a zero percent value and/or a 100% value are not entered by the user, the program will assign zero percent to the next lowest grade class and 100% to the next highest grade class. See the hydraulic reference manual for more detail.

Plot Gradation: This button gives the user a graphical representation of the sediment gradation. The user has the option to compute sediment transport capacity rates for the currently selected sediment reach **(Compute for this Sediment Reach)** or for all existing sediment reaches **(Compute for all Sediment Reaches)** within the currently opened hydraulic design file.

A text box is provided for brief descriptions of selected transport functions. In addition to a summary of the selected function, the range of input parameters, from both field and laboratory measurements, used in the development of the respective function is also provided. Where available, these ranges are taken from those found in the SAM package user's manual (Waterways Experiment Station, 1998) and are based on the developer's stated ranges when presented in their original papers. The ranges provided for Engelund and Hansen are taken from the database (Guy, et al, 1966) primarily used in that function's development.
The following variables are used in the summaries:

- d, overall particle diameter
- dm, median particle diameter
- s, sediment specific gravity
- V, average channel velocity
- D, channel depth
- S, energy gradient
- W, channel width
- T, water temperature

Defaults: The Defaults button will restore all input boxes for the currently selected sediment reach to the default values.

Apply: The Apply button will be enabled any time new input has been added which has not been stored into memory. By clicking on the Apply button, all input for the current sediment reach will be stored to memory.

Compute: The compute button will be enabled once all required input is entered. Pressing the compute button initiates the computations for sediment transport capacity.

Options Menu: The Options Menu drop down list is on the top of the Sediment Transport Capacity form and includes:

Fall Velocity: This option allows the user to select the method of fall velocity computation. If "Default" is selected, the method used in the research and development of the respective function is chosen. Otherwise, any functions used in the computations will use the selected fall velocity method. The three fall velocity methods available are: Toffaleti, Van Rijn, and Rubey.

Depth/Width: This allows the user to select which depth and width parameters to use in the solution of the transport functions. If "Default" is selected, the program will use the depth/width combination used in the research of the selected functions(s). If any of the other depth/width combinations is used, all selected functions will be solved using those specific parameters.

Eff. Depth/Eff. Width: Used in HEC 6, this is the effective depth and effective width. Effective Depth is a weighted average depth and the effective width is calculated from the effective depth to preserve $aD^{2/3}$ for the cross section:

$$EFD = \frac{\sum_{i=1}^{n} D_{avg} a_i D_{avg}^{\frac{2}{3}}}{\sum_{i=1}^{n} a_i D_{avg}^{\frac{2}{3}}} \qquad EFW = \frac{\sum_{i=1}^{n} a_i D_{avg}^{\frac{2}{3}}}{EFD^{\frac{5}{3}}}$$

Hyd. Depth/Top Width: The hydraulic depth is the area of the cross section divided by the top width.

Hyd. Radius/Top Width: The hydraulic radius is the Area divided by the wetted perimeter. Is equivalent to hydraulic depth for relatively wide, shallow streams.

Hiding Factor for Ackers-White: An optional "hiding factor" adjustment is available for the Ackers-White function only. The user can choose whether or not to use this feature. The default is "No."

Compute for Small Grains Outside Applicable Range: By default, RAS will perform calculations for grain sizes which are smaller than the applicable range of a given transport function. By selecting "No", the user can override this and have RAS compute for only the grain sizes within the applicability range of each sediment transport function, as defined in Table 12.7 in the Reference Manual.

 Sediment Rating Curve Plot/Table: This button displays a plot of the sediment transport capacity rates for a selected cross section within a sediment reach. It is only enabled once computations for that reach have been performed. Display options can be selected from the dropdown buttons. Figure 13-13 shows a sediment rating curve plot. In addition to viewing the plots, the table tab can be clicked to view in tabular form.

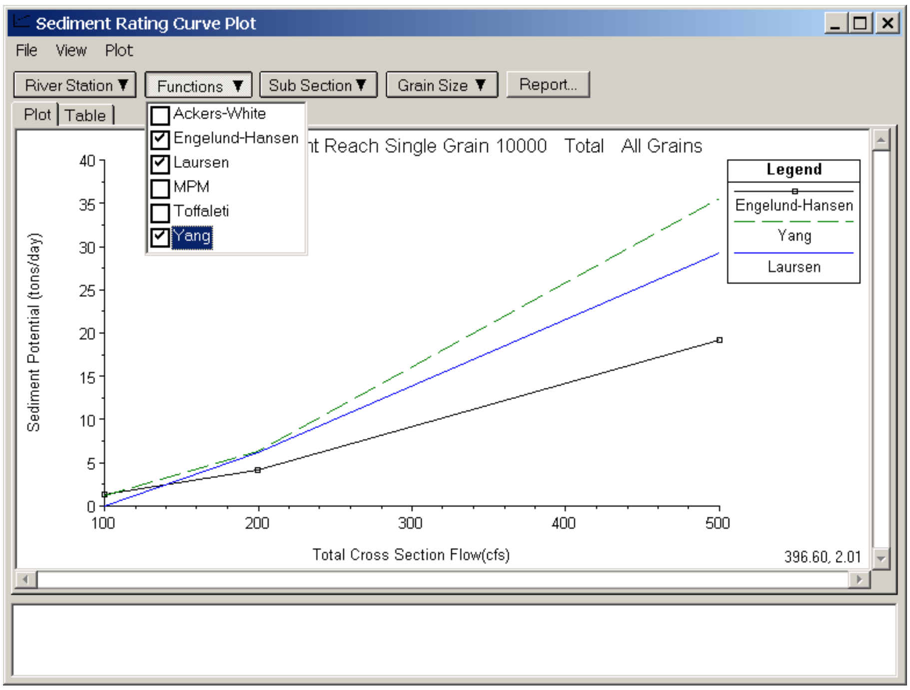


Figure 13 13. Sediment Transport Capacity Rating Curve

 Sediment Transport Profile Plot/Table: This button displays a plot of the sediment transport capacity rates along a selected sediment reach. It is only enabled once computations for that reach have been performed. Display options can be selected from the dropdown buttons. Figure 13-14 shows the sediment transport profile plot. In addition to viewing the plots, the table tab can be clicked to view in tabular form.

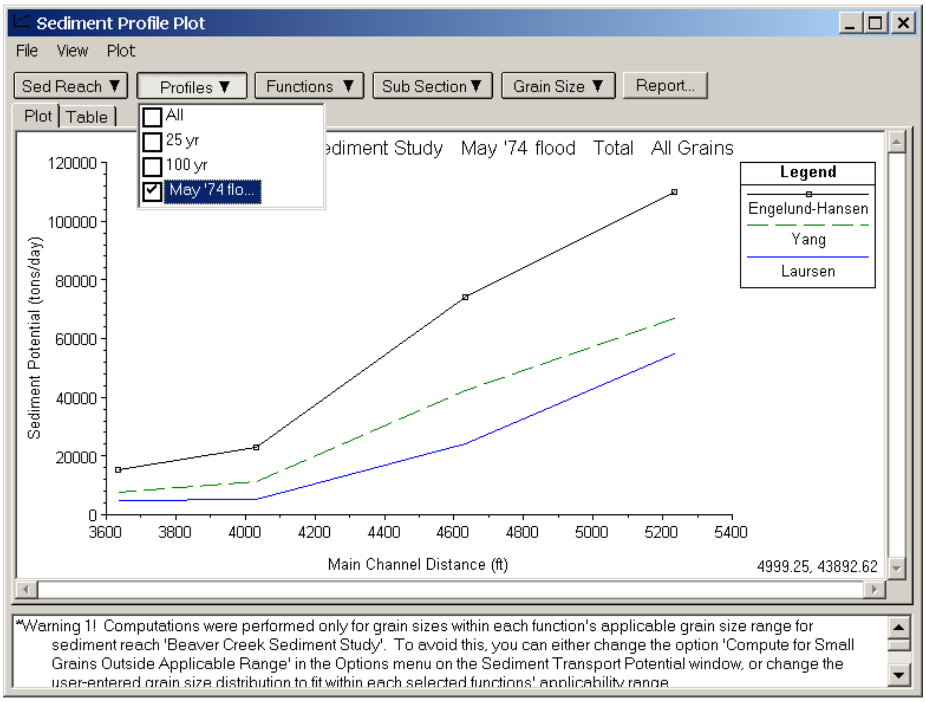
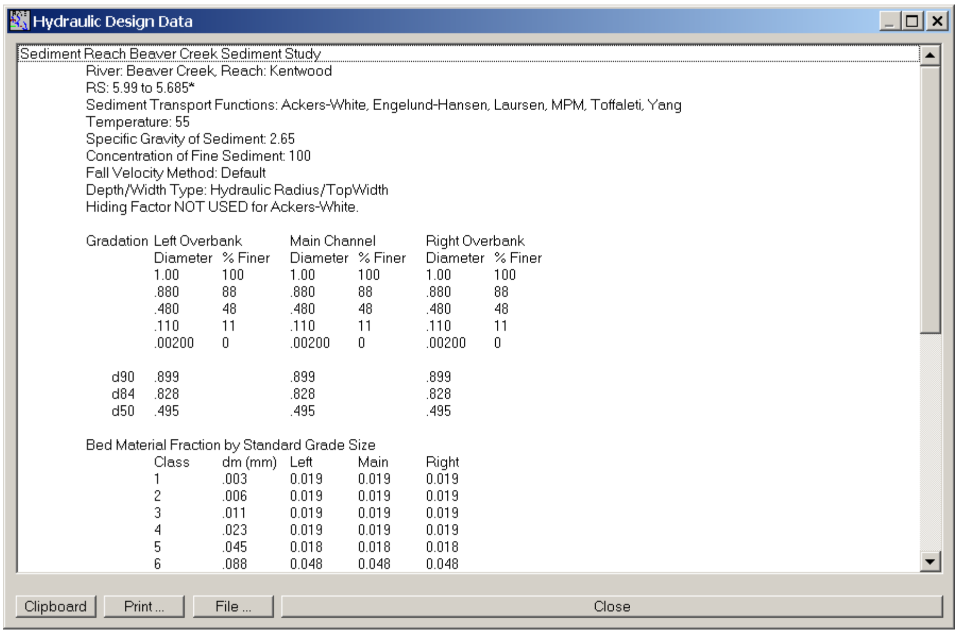


Figure 13 14. Sediment Transport Capacity Plot

Both plot windows have a list box at the bottom with warning messages. These warnings are meant to make the user aware of how sediment transport rates are being computed. If the user selects the option to compute sediment transport rates for all grade sizes within the user-specified range, a warning stating this will be shown. If the user selects the option to compute sediment transport rates for only those grade sizes within the respective function's applicability range, then a warning a different warning message will appear.

The "Compute for Small Grains Outside Applicability Range" option is located in the menu item "Options" on the Hydraulic Design window for sediment transport capacity.

Report: The Report button is located in the plot window and generates a report summarizing the input and output data. The output data is displayed as per the selections made in the dropdown buttons. Because the amount of output has the potential for being quite large, the report that is generated can likewise be very large. Figure 13-15 shows an example of the sediment transport capacity report. As with other report windows found in HEC-RAS, the user has the ability to send this report to the clipboard, print it, or save it as a text file.



Hydraulic Design Data

Sediment Reach Beaver Creek Sediment Study
River: Beaver Creek, Reach: Kentwood
RS: 5.99 to 5.685*
Sediment Transport Functions: Ackers-White, Engelund-Hansen, Laursen, MPM, Toffaleti, Yang
Temperature: 55
Specific Gravity of Sediment: 2.65
Concentration of Fine Sediment: 100
Fall Velocity Method: Default
Depth/Width Type: Hydraulic Radius/TopWidth
Hiding Factor NOT USED for Ackers-White.

Gradation	Left Overbank		Main Channel		Right Overbank	
	Diameter	% Finer	Diameter	% Finer	Diameter	% Finer
	1.00	100	1.00	100	1.00	100
	.880	88	.880	88	.880	88
	.480	48	.480	48	.480	48
	.110	11	.110	11	.110	11
	.00200	0	.00200	0	.00200	0
d90	.899		.899		.899	
d84	.828		.828		.828	
d50	.495		.495		.495	

Bed Material Fraction by Standard Grade Size

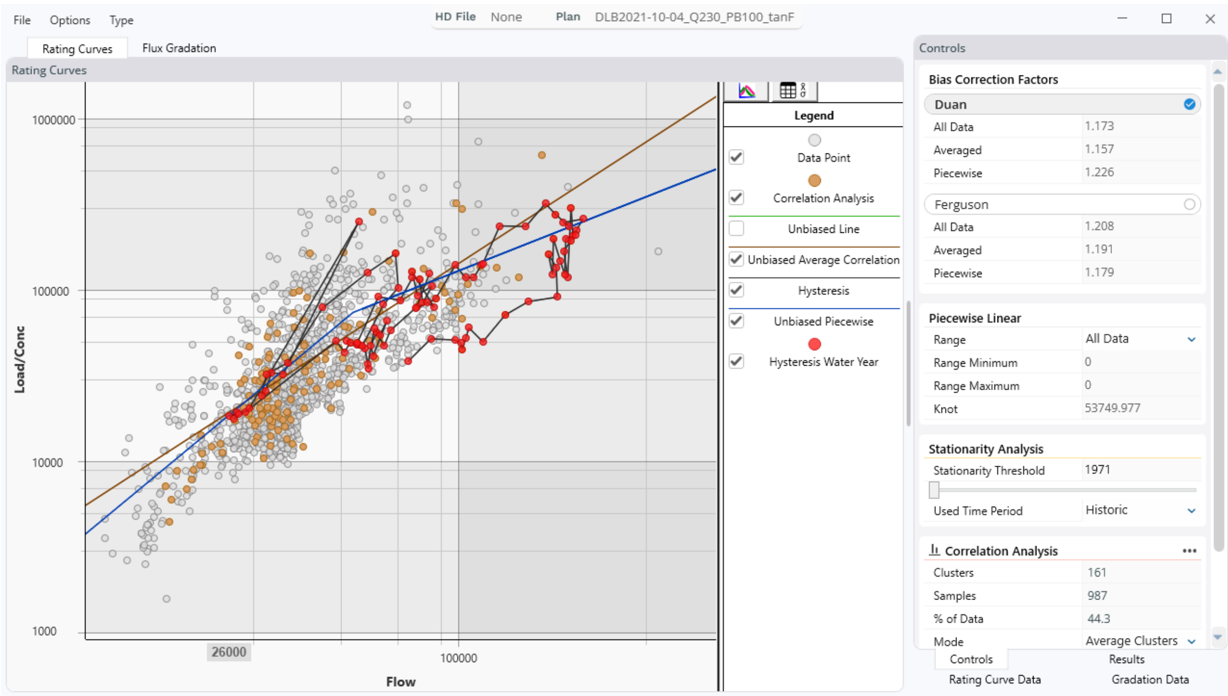
Class	dm (mm)	Left	Main	Right
1	.003	0.019	0.019	0.019
2	.006	0.019	0.019	0.019
3	.011	0.019	0.019	0.019
4	.023	0.019	0.019	0.019
5	.045	0.018	0.018	0.018
6	.088	0.048	0.048	0.048

Clipboard | Print ... | File ... | Close

Figure 13 15. Sediment Transport Capacity Report

Sediment Rating Curve Analysis Tool

The Sediment Rating Curve Analysis Tool downloads sediment loads, concentrations, and gradations directly from the USGS (or uploads them from a tab delimted file or Excel) and applies a range of statistical analyses and visualizations to help modelers and scientists understand their data and develop rating curves or trends to include in sediment budgets or models.



This video is a brief demo of the capabilities in the 6.2 release version.

Sorry, the widget is not supported in this export.
But you can reach it using the following URL:

http://youtube.com/watch?v=278wsFaVtBc

This video provides an overview of the methods in an alpha version of this new tool. The release version has much more functionality, especially direct download capabilities for USGS sediment data and a different layout/look/feel (see above video)- but this one goes into more depth on the statistics and methods.

Sorry, the widget is not supported in this export.
But you can reach it using the following URL:

http://youtube.com/watch?v=-Lh0bp2Wgy4

Sediment Rating Curve Challenges and Best Practices

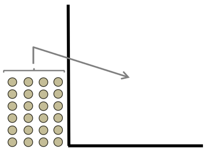
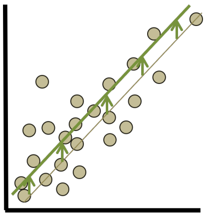
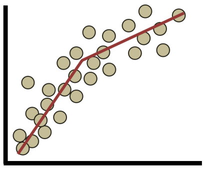
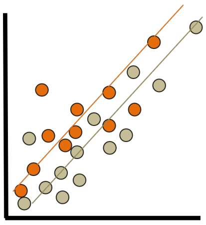
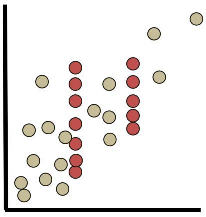
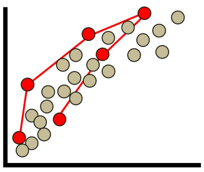
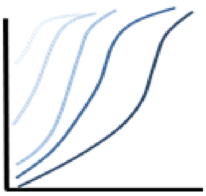
Sediment data are noisy. They tend to include a lot of uncertainty, measurement error, and natural variability. But sediment models require modelers to summarize these data into more concrete inputs and trends that the model can use. The two most common data analysis tasks users encounter include summarizing the flow-load data with a sediment rating curve and evaluate sediment load gradation trends.

The Sediment Transport User Guide includes an extensive discussion of common data challenges encountered in the process of developing a sediment rating curve and analyses that modelers should do with their data before settling on a sediment relationship for their boundary conditions. These are also summarized in this video:

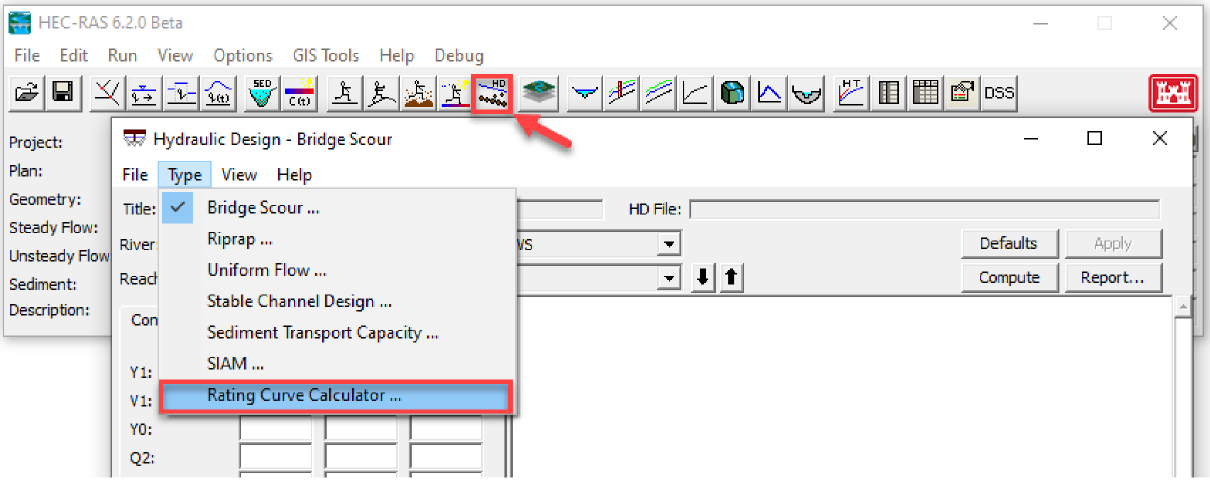
Sorry, the widget is not supported in this export.
But you can reach it using the following URL:

http://youtube.com/watch?v=cBr3KkLTW1Y

But the latest version of HEC-RAS includes a Sediment Rating Curve Analysis Tool that standardizes these analyses and provides simple tools to help sediment modelers and analysts think carefully about their data and develop quality relationships for model boundaries or sediment budgets. The tool includes the following capabilities:

Import Sediment Data		The Rating Curve Analysis Tool can import data directly from the USGS website (for US users) or from standard csv formats.
Bias Correction		The tool provides two methods to rectify bias implicit to the log-transform regression used to develop sediment rating curves
Piecewise Linear		The tool includes new methods to fit "bent" rating curves to sediment data (e.g. for supply limited scenarios)
Stationarity		These are visualization methods to explore how sediment data change over time and fit rating curves to temporal sub-sets of the observations
Temporal Averaging and Autocorrelation		Groups observations collected within a specified time window to avoid over-representing them and violating the independence assumption.
Hysteresis		Traces the temporal path of flow-load/concentration data over a water year
Rating Curve Results		These tools allow users to build their rating curve power function or populate their flow-load table for HEC-RAS.
Load-Gradation Trends		These tools help users visualize the load-gradation data and determine if there is a fining or coarsening trend with flow.

Opening the Sediment Rating Curve Analysis Tool



Funding and Support

The Rating Curve Analysis Calculator development was funded by the Mississippi River Geomorphology and Potomology Program (MRG&P). Additional features and documentation were funded by the Hydrology, Hydraulics and Coastal Community of Practice, Science and Engineering Technology program (HH&C- SET).

Importing Sediment Data

The Rating Curve Analysis Tool includes several methods to import and input data. Most of these methods follow US Geological Survey data formats because most US users will get sediment data directly from the USGS data portals (and most will use the automatic download tools described below).

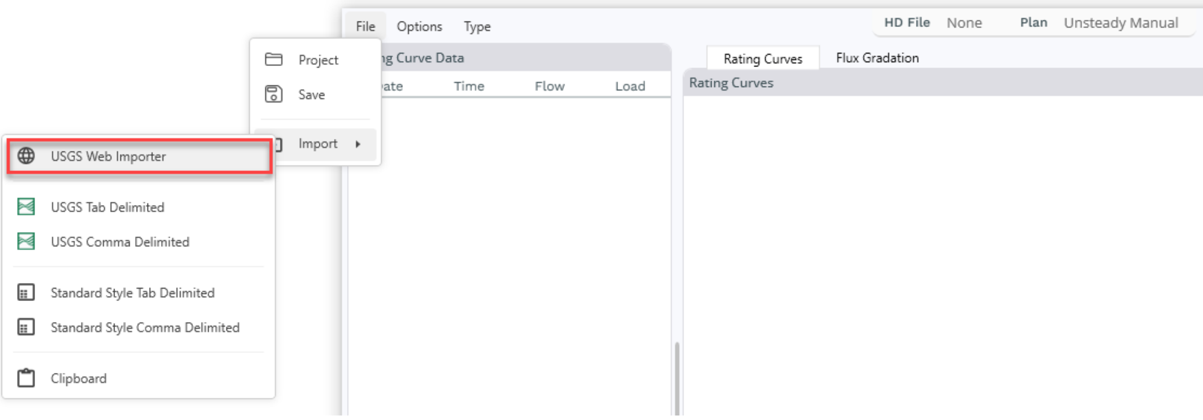
HEC-RAS requires paired flow-load/concentration data to use the sediment rating curve tool. It can only display load or concentration, but it can import either (or both formats) and convert between them. It is also helpful to include dates and times for these flow-load/concertation pairs. USGS data should include these dates and times automatically. If you are entering flow-load/concertation data manually or creating an import file in one of the supported formats, and do not have dates and times, you can still import dateless flow-load/concentration and gradation information. But several analyses with temporal components (e.g. stationarity, autocorrelation, and hysteresis) will not work without dates and times.

In the United States, the most common approach to retrieve sediment data will be to request it directly from the USGS website. The next section describes that process in detail. Go to the section on other file formats for information on formatting and importing other data or to the clipboard section for information on how to copy and paste data directly from Excel.

Downloading Data From USGS

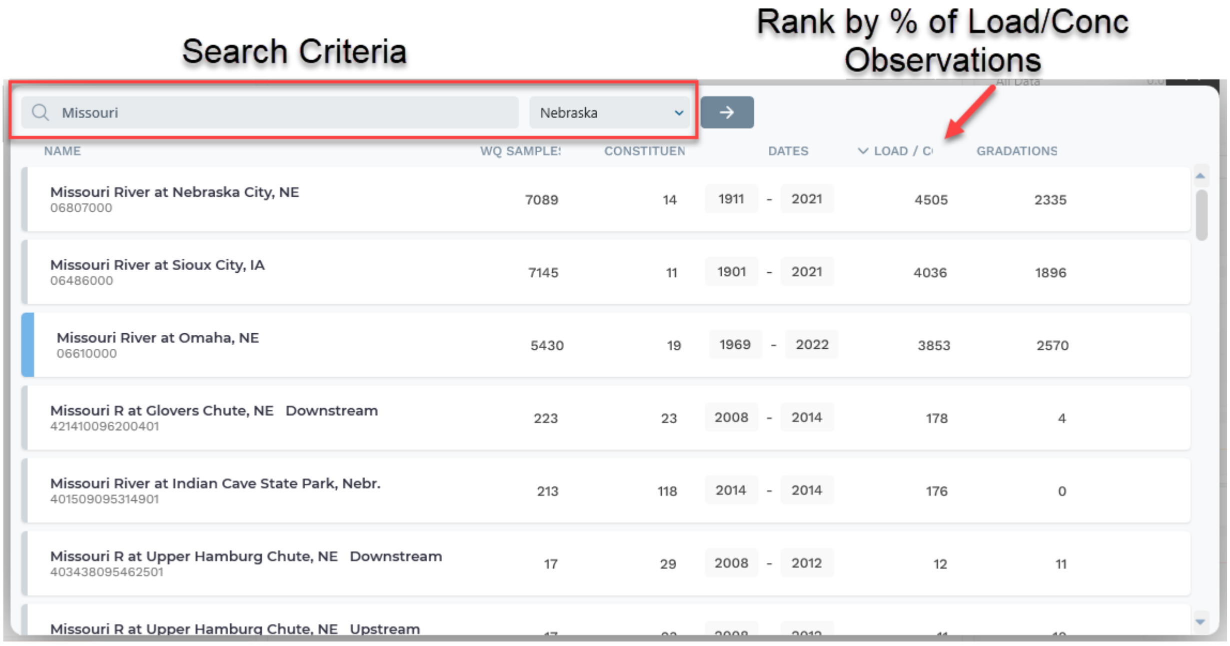
Most practitioners in the United States get their data directly from USGS data portals. Historically, sediment scientists and modelers have downloaded data-dense text-based files to retrieve these data and post processed them in spreadsheets. More recently , the USGS has provided access through R packages. The Rating Curve Analysis Tool bypasses these processes and imports sediment load, concentration, and load-gradation data directly into HEC-RAS.

To download data, go to **File** → **Import** → **USGS Web Importer**.

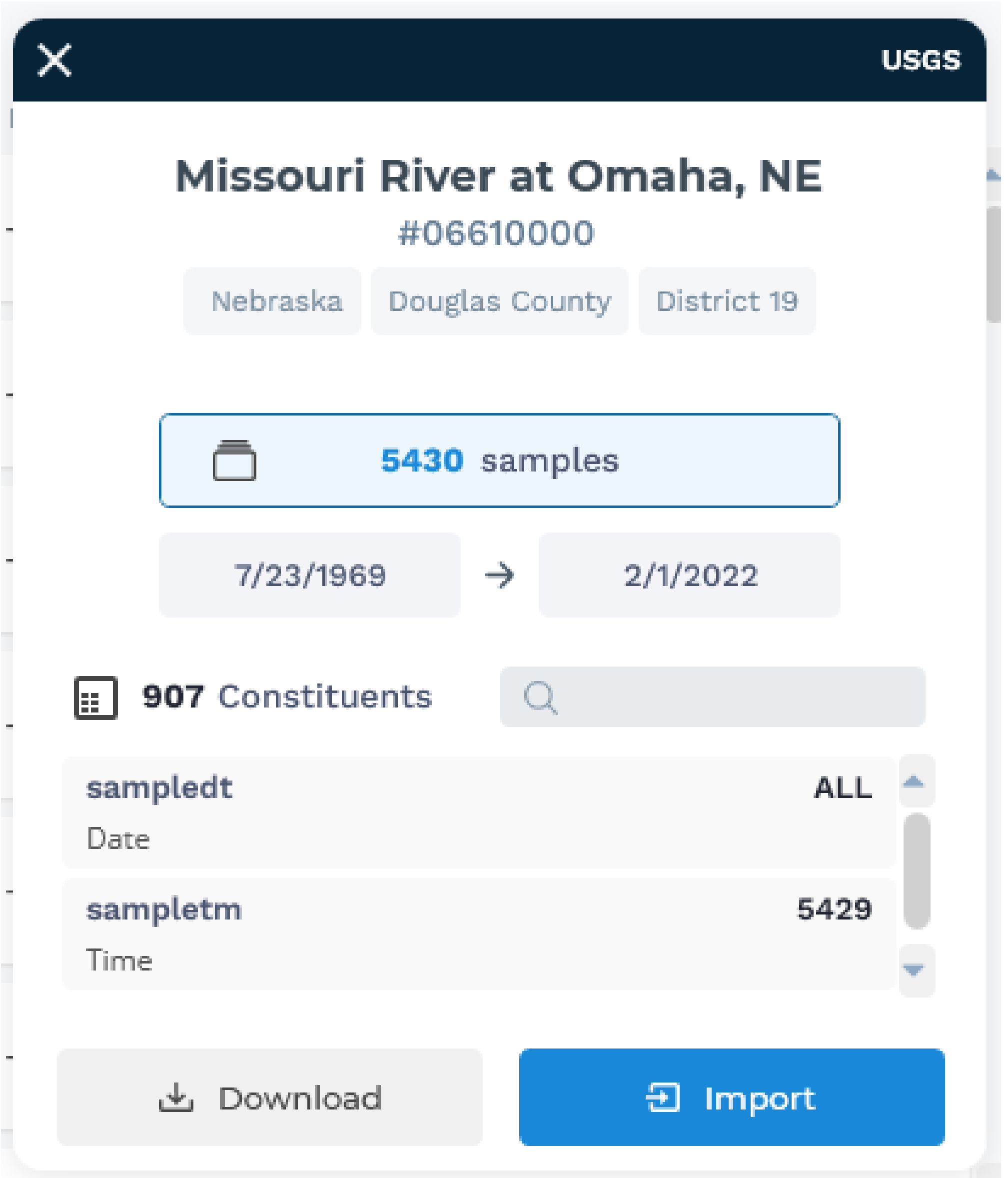


The automatic web import tool requires two search parameters to narrow the list of gages to provide: the state and a text string (see red box below). The text string will recognize the gage number if you know the exact gage you are looking for, but if you input the river name it can also populate summary statistics for all the gages on the river to help decide which gages to work with. If the search returns a long list of gages, the importer can take a few seconds to populate the statistics for all the gages.

To find the gages with the most data, sort by any of the headings. In the following figure, ordered the Missouri River data from Nebraska by the number of sediment load or concentration measurements. But users can also sort by the total number of samples, the number of different water quality constituents measured, or the load-gradation samples available.

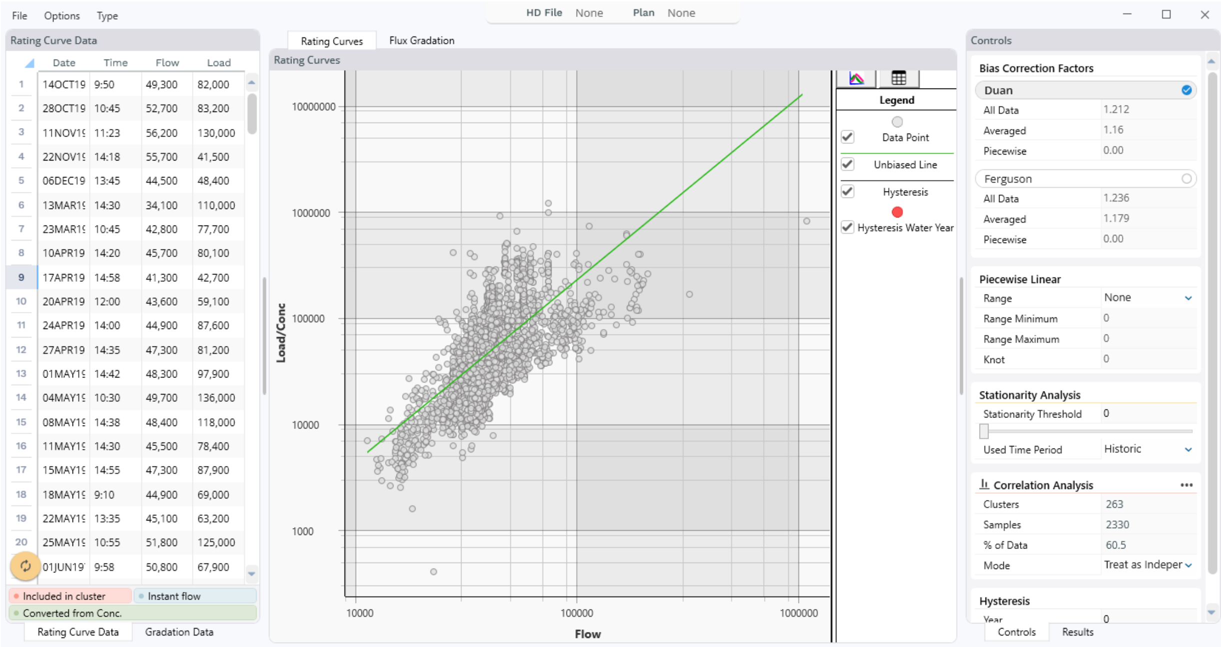


Selecting a gage will provide more information about the gage, including searchable meta-data and information on each available constituent (using the USGS codes). HEC-RAS can only import sediment data for now, but provides information on the other data available.

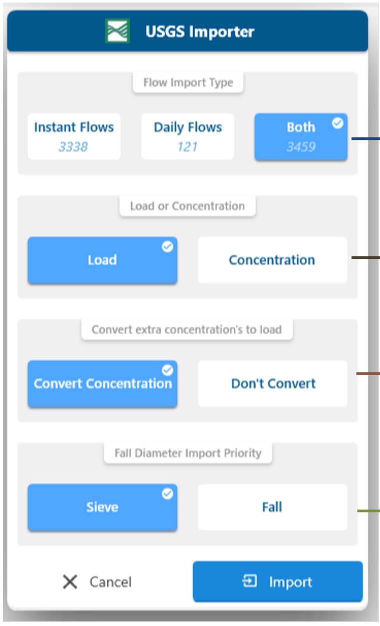


Press the **Import** button to download the sediment data into the Rating Curve Analysis Tool.

Some water quality measurements are stored with paired flow data but many of them are not. All of the capabilities of the Rating Curve Analysis Tool use paired sediment-flow data, so the tool will only import sediment data if it has paired flow data. If the water quality record has a measured flow (daily or instantaneous) associated with it, the Rating Curve Calculator will import both. But if the gage has sediment measurements without flows, the tool will show the option below. The top button just imports the sediment measurements paired with flows in the water quality data. But the bottom button reports how many sediment measurements do not have paired flows, and offers to reach out to the gage flow data and select the closest flow from the gage to pair with the sediment observation. This second option is recomended.



Before the data download, HEC-RAS will launch another download tool to guide users through some common decisions about which data they want and how the model should handle it:



Sediment samples are can be paired with average daily flows or flows measurements collected at the same time as the sediment sample. This tool tells you how many of each, and lets you choose either or both.

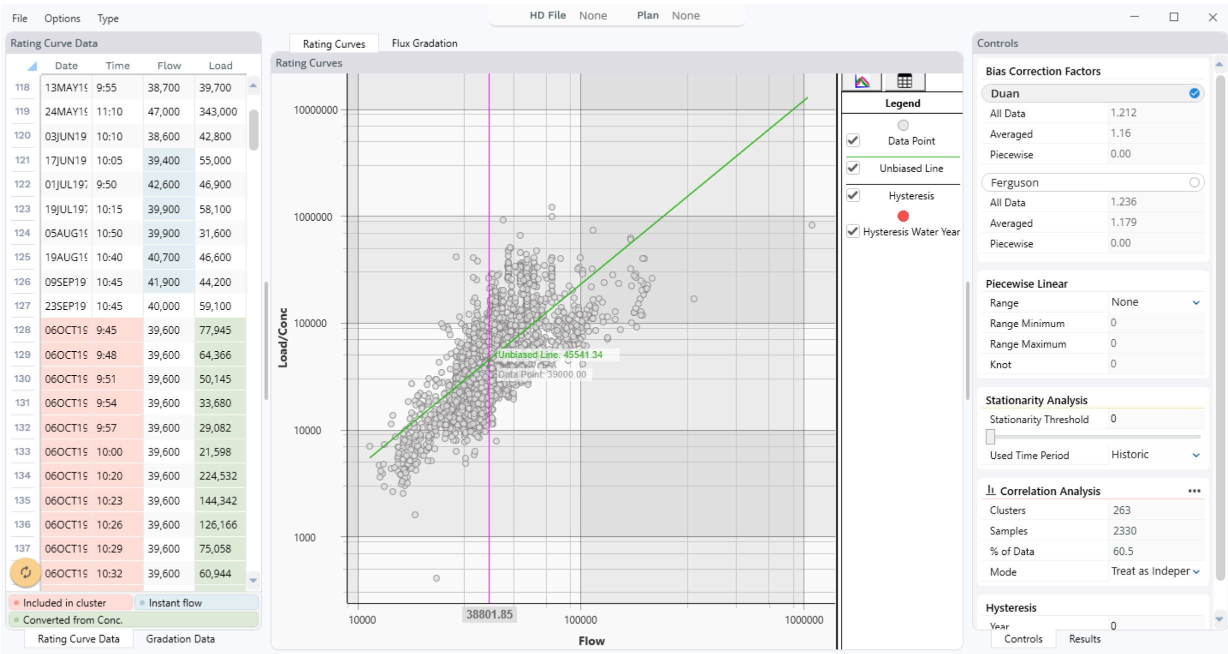
Choose if you want sediment data to come into the tool as load (tons/day) or Concentation (mg/L).

This tells the tool what to do with the data type NOT selected above. If Load is selected, the tool can convert Concentrations to Load (if both are not Reported and add them to the data set – or ignore and exclude them. If you select Concentration above, this will apply to records that only have Loads.

Load-Gradation data sometimes have multiple analyses for one sample, sieve analysis for coarse grain classes and fall analysis (hydrometer or laser) for fines. But sometimes, these analyses overlap, so the same grain class has two, different, results. This option tells the tool which to prioritize if a sample has conflicting measurements.

Even if you decide to import and/or convert all data , regardless of native type (instantaneous/daily, load/concertation) HEC-RAS color codes the imported data in the data grid to classify them by their native format.

This will bring the data into the Sediment Rating Curve Analysis tool. The tool will plot the flow-load/ concentration data in the main **Rating Curve** plot and populate the tabular data in the table on the left. However, it will also import the load-gradation data and plot them in the secondary tabs. By default, the tool will calculate a bias-corrected rating curve through the data with the Duan bias-corrector.



Converting Between Flow and Concertation

The Flow-Load Conversion tool is the orange button  on the bottom-left corner of the Rating Curve Data grid. It is common to collapse the data grid to provide more room for the plot (and less for a table of numbers). But you can only access the Load-Concertation conversion tool if the data are visible. If you hover over this button, it will expand to tell you what action it will perform (based on what state the data are in).

Clipboard Import

Sorry, the widget is not supported in this export.
But you can reach it using the following URL:

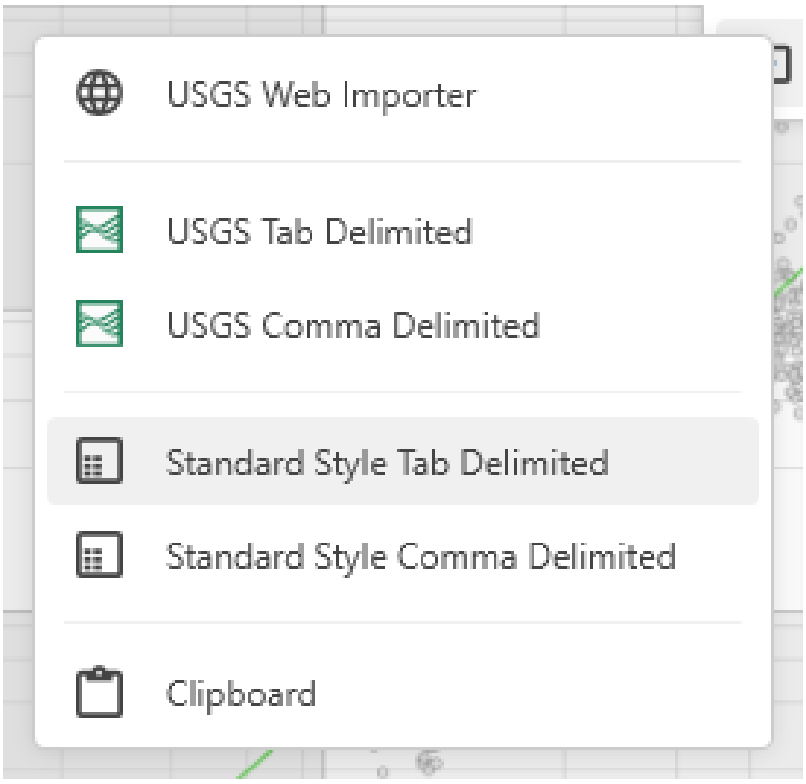
http://youtube.com/watch?v=lLuhxrTbE0g

Users can also simply copy data from excel and paste it into the editor. The data must have the same four headings (Date, Time, Flow, Load), though not all the data are required. Copy the four columns from Excel. The select File→ Import → Clipboard. The tool will check if the clipboard data are in the correct format. If they are, it will provide the editor pictured above, allowing users to identify their sediment data type. If not, it will return an error, explaining that the format is not correct. An example of a good excel format is below:

	A	B	C	D
1	Date	Time	Flow	Load
2	14-Oct-71	9:50	49300	82000
3	21-Sep-72	10:35	49600	92900
4	27-Feb-74	14:30	23200	27900
5	3-Jul-75	9:50	49700	53500
6	17-Jul-78	12:55	52700	135000
7	29-Aug-83	11:40	45000	46000
8			60200	249000
9			40300	19900
10			34200	24500
11	14-Oct-87	10:50	34500	47900
12	20-Apr-88	12:23	33300	20900
13	1-Jun-88	12:23	34200	17000
14	13-Jul-88	13:15	32600	14700
15	6-Oct-88	10:25	31500	29300

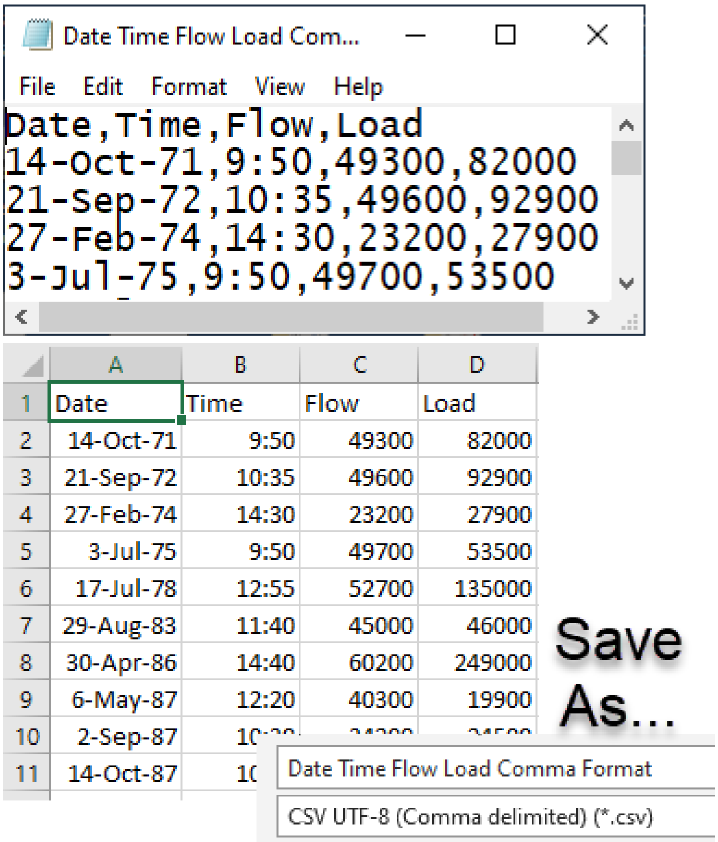
Importing Data Files

The import tool can also import four data file formats.



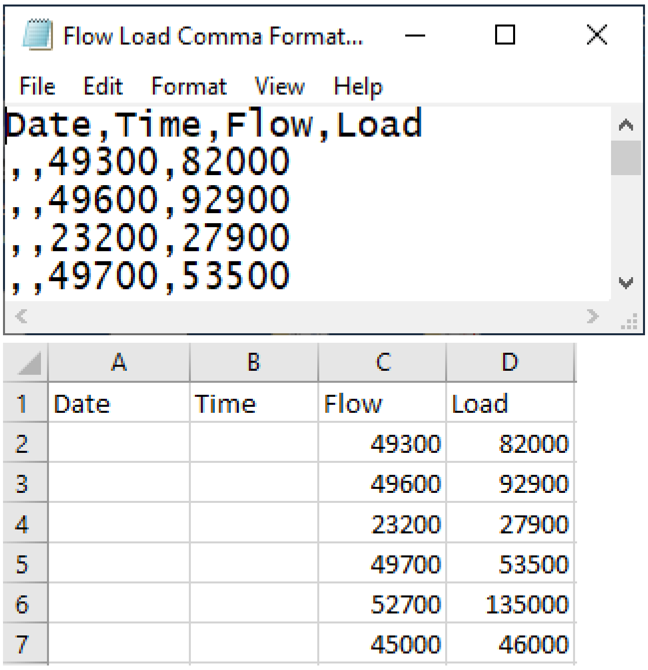
The first two data formats are just extensions of the USGS Web importer. These are USGS data formats that can be downloaded from their website. These are useful if users already have USGS data downloads they want to use, but will mostly be replaced by the automatic web importer.

But the Rating Curve Analysis Tool does include two generic file formats that the model can import. These generic formats currently only support flow-load/concentration data, not load-gradation data. Sample files of each format are included below. You can download these and replace the data with your data to import data into the tool.



	A	B	C	D
1	Date	Time	Flow	Load
2	14-Oct-71	9:50	49300	82000
3	21-Sep-72	10:35	49600	92900
4	27-Feb-74	14:30	23200	27900
5	3-Jul-75	9:50	49700	53500
6	17-Jul-78	12:55	52700	135000
7	29-Aug-83	11:40	45000	46000
8	30-Apr-86	14:40	60200	249000
9	6-May-87	12:20	40300	19900
10	2-Sep-87	[illegible]	[illegible]	[illegible]
11	14-Oct-87	[illegible]		

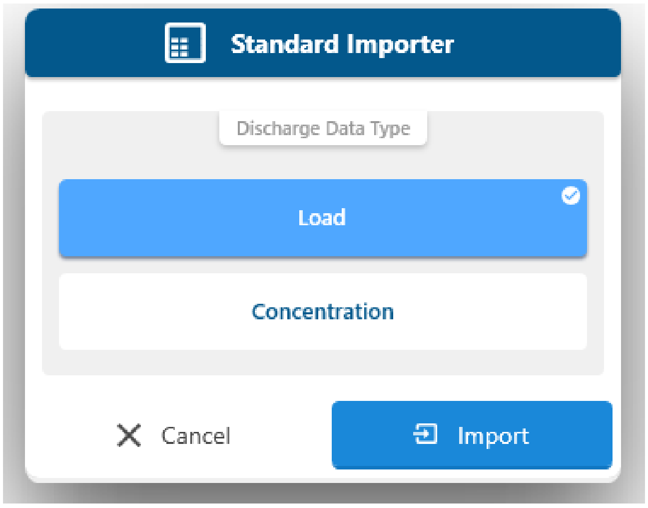
If you want to include data with just flow and load/concentration data, the file will still need the Date and Time columns, but they can be blank.



	A	B	C	D
1	Date	Time	Flow	Load
2			49300	82000
3			49600	92900
4			23200	27900
5			49700	53500
6			52700	135000
7			45000	46000

File Format	
Comma Delimited with Date/Time	
Comma Delimited w/o Date/Time	

This importer will also allow users to specify whether the data they are importing are load or concentration before they import.



Warning - Remove Commas from Numbers for Comma Delimited Files

If you are creating a comma delimited file to import into the Rating Curve tool, be careful to format the numbers **without** commas.

Wish List - Other Water Quality Constituents

Now that HEC-RAS can download data directly from the USGS Water Quality sites, it will not be a major effort to expand the functionality to other constituents. We are looking to partner with water quality modelers who use these other constituents to understand how these methods transfer to other constituents.

Bias Correction

Sediment transport is non-linear. Therefore, a flow-load or flow-concentration rating curve is almost always non-linear.

We usually represent a flow-sediment relationship with a power function, such that:

$Qs=aQ^b$

Where Qs is the sediment load, Q is the flow, a is a small coefficient, and b is a power (usually between 1.5 and 2.5).

But the most common method to fit a power function to data like these **includes an intrinsic bias**. The log-transform, Least Mean Square Error, that a program like Excel uses to fit a power function includes an implicit bias, making the rating curve it produces systematically low.

It is important to correct for this bias when you create a power function rating curve through sediment data.

The Rating Curve Analysis Tool applies a bias correction by default. But it also has two options for this bias correction and it is useful to understand what the software is doing.

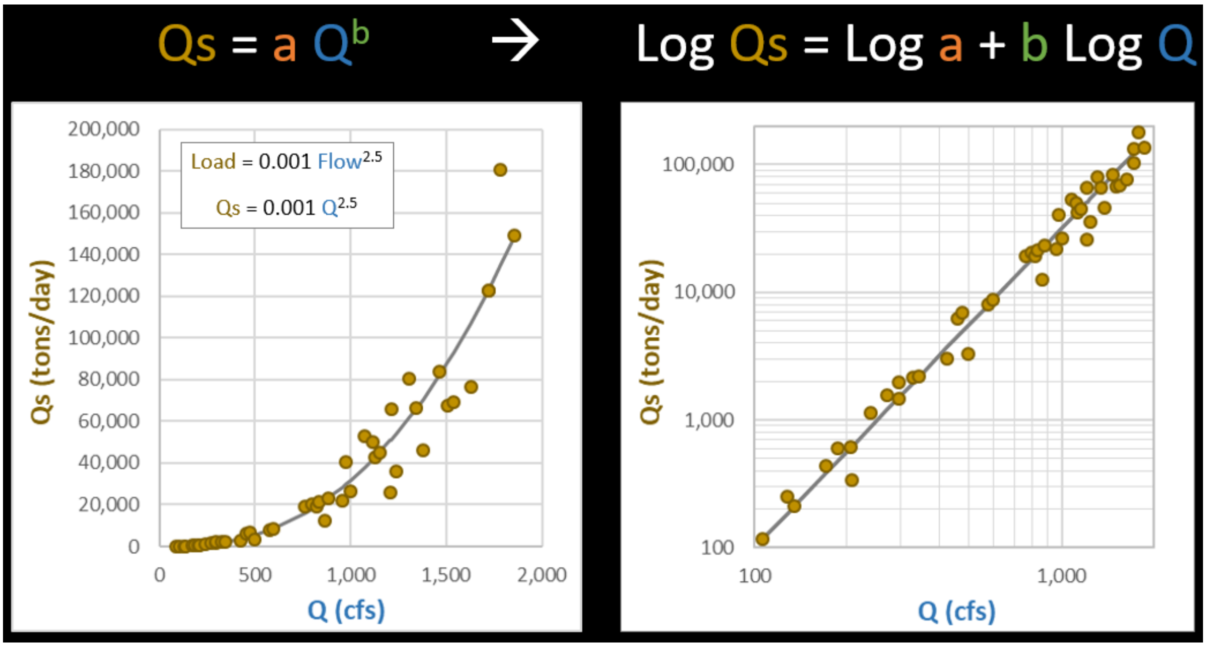
This section describes these bias corrections.

Where Does The Bias Come From?

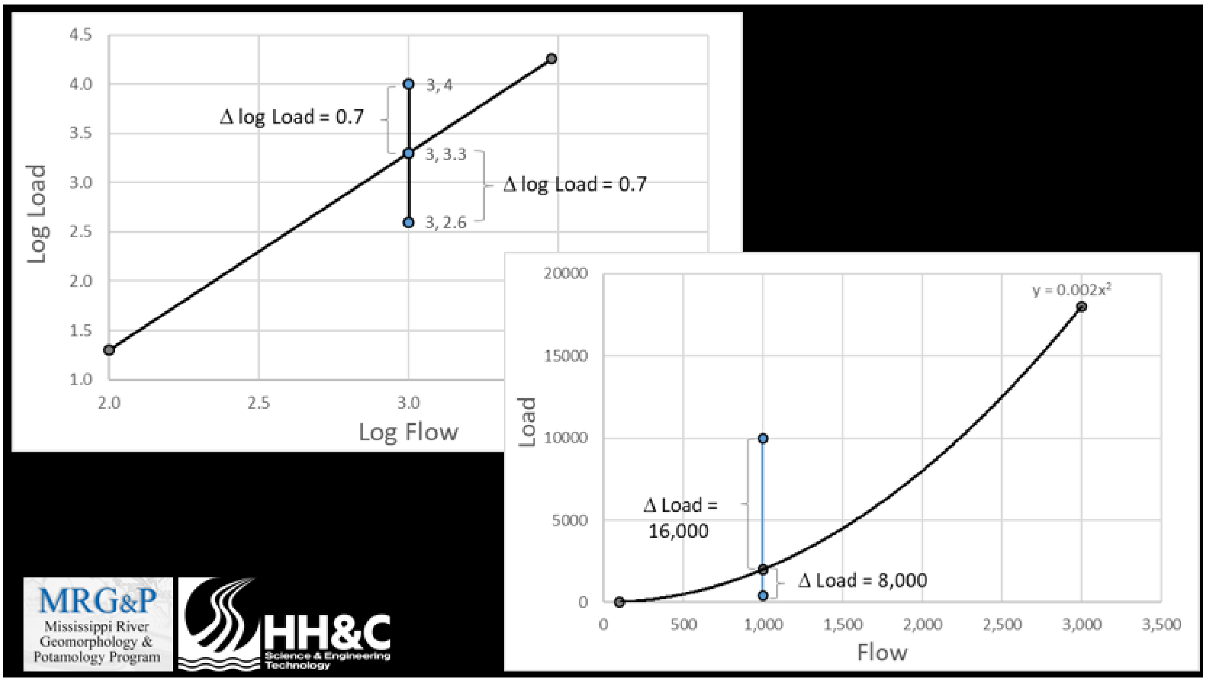
Before describing the bias correction, it is helpful to understand where the bias comes from.

The Least Mean Square Error (LMSE) approach to linear regression measures the residuals between the regression and each observation and computes the line (slope and intercept) that minimizes those errors.

Fitting a power function to log-distributed data usually uses a log-transform approach. The figure below includes a synthetic power function and data sampled from it with random residuals. The power function is non-linear in arithmetic space. But in log-log space the power function becomes linear. This is because a log-transform of the power function takes a linear form (see below). So, by log-transforming the data, the form of y = b + mx and we can apply the tools of simple linear regression to the log residuals.



Log-transforming the regression makes it relatively easy to fit a power function to log-distributed data. However, it also introduces a bias when the data are untransformed. For example, the observations in the figure below have equal and opposite residuals in the logarithmic transformation (0.7). However, when these residuals untransform, the positive residual is larger than the negative residual. Therefore, the log-transformed linear regression ends up with larger positive residuals than negative, making the fit power function systematically low. This rating curve will under-predict sediment load for a given flow.



Bias Correction Functions

There are several bias correction functions (sometimes called "predictor correctors"). The Duan Smearing Estimate is widely used, but USACE practitioners have also used Ferguson. The Sediment Rating Curve Analysis Tool uses Duan by default, but also reports Furguson, and allows users to toggle between them. These methods all tend to quantify the variability of the residuals and backs out the asymmetry in the residuals to come up with a linear correction coefficient. For example, the Duan Smearing Estimate *(E)* is a linear coefficient in front of the power function, such that:

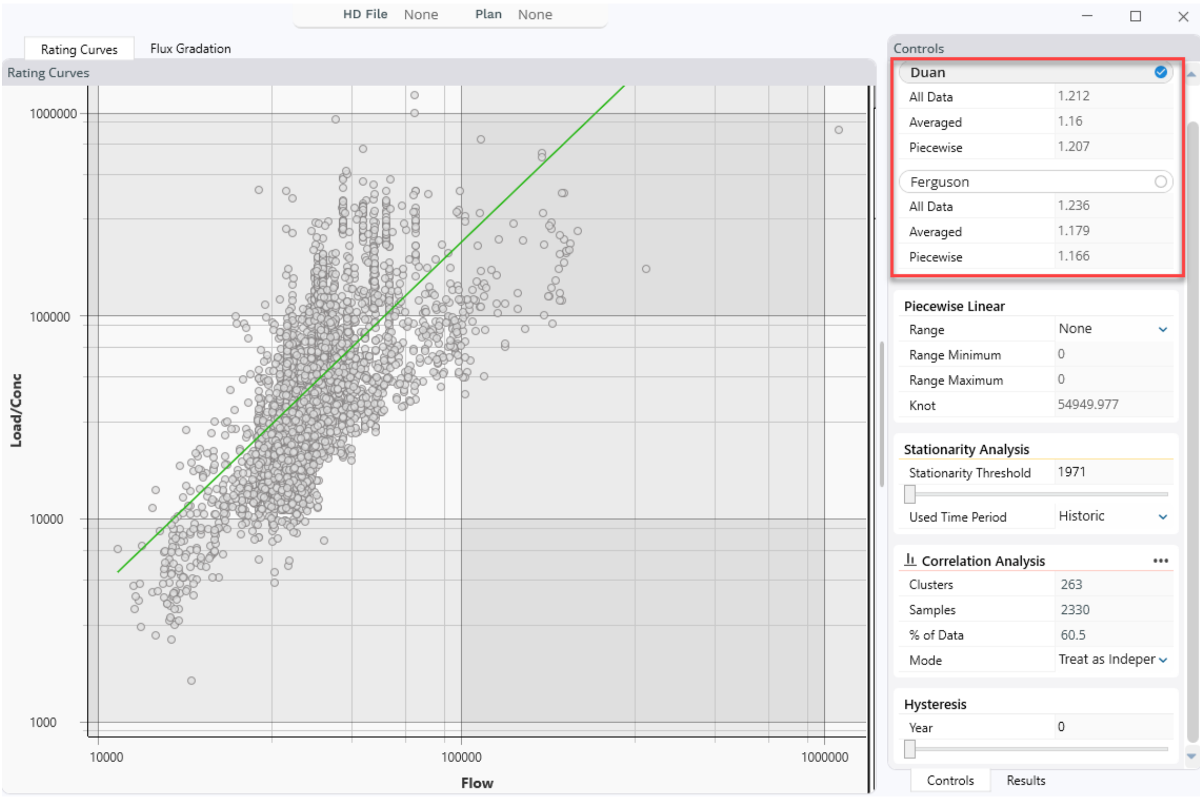
$$Qs = E\ a\ Q^b$$

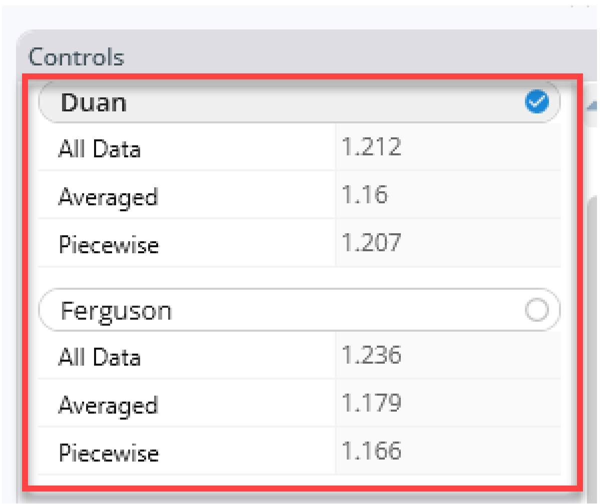
$$E = \frac{1}{N}\sum_{i=1}^{N} exp(ln(Qs_i(obs) - ln(aQ^b))$$

On the whole, the more spread the sediment data have, the higher the bias correction.

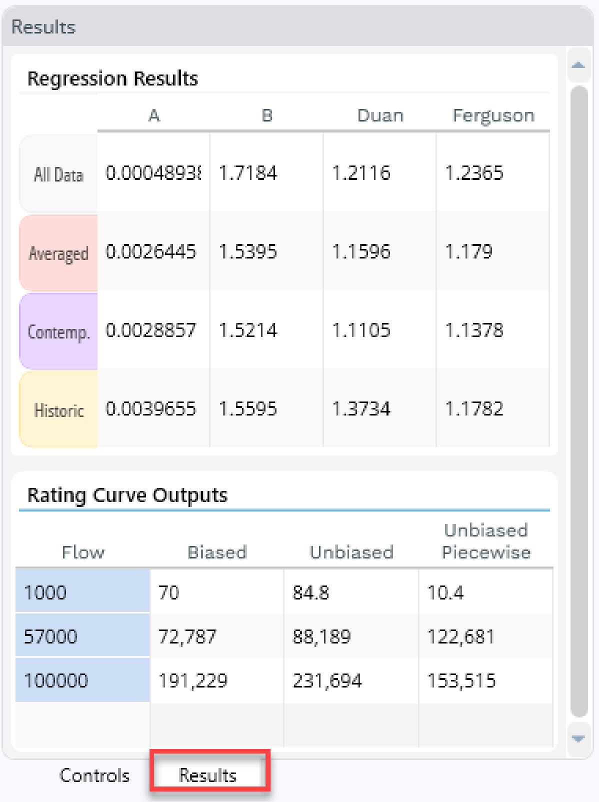
Bias Correction Results

The Rating Curve Analysis tool automatically reports the Duan and Ferguson bias corrections, including factors for all of the data, the results after same-day (or a user-specified temporal grouping) data are averaged, and then the bias correction associated with the piecewise-linear model if one is (or was) selected. In the example below, the averaged data have a Duan Factor of *E*=1.16 which means that the rating curve increases the load 16% to account for the regression bias. The rating curve (green line in figure below) automatically increases the selected bias-correction. Users can select which bias correction to plot by toggling between Duan and Ferguson.





These correction factors also show up in the tabular data.



Results

Regression Results

	A	B	Duan	Ferguson
All Data	0.0004893[illegible]	1.7184	1.2116	1.2365
Averaged	0.0026445	1.5395	1.1596	1.179
Contemp.	0.0028857	1.5214	1.1105	1.1378
Historic	0.0039655	1.5595	1.3734	1.1782

Rating Curve Outputs

Flow	Biased	Unbiased	Unbiased Piecewise
1000	70	84.8	10.4
57000	72,787	88,189	122,681
100000	191,229	231,694	153,515

Controls Results

The coefficients are reported (with the a and b coefficients for the power function) in the Regression Results, and included in any rating curve output described as **Unbiased** (based on the approach selected in the Bias Correction control window)**.**

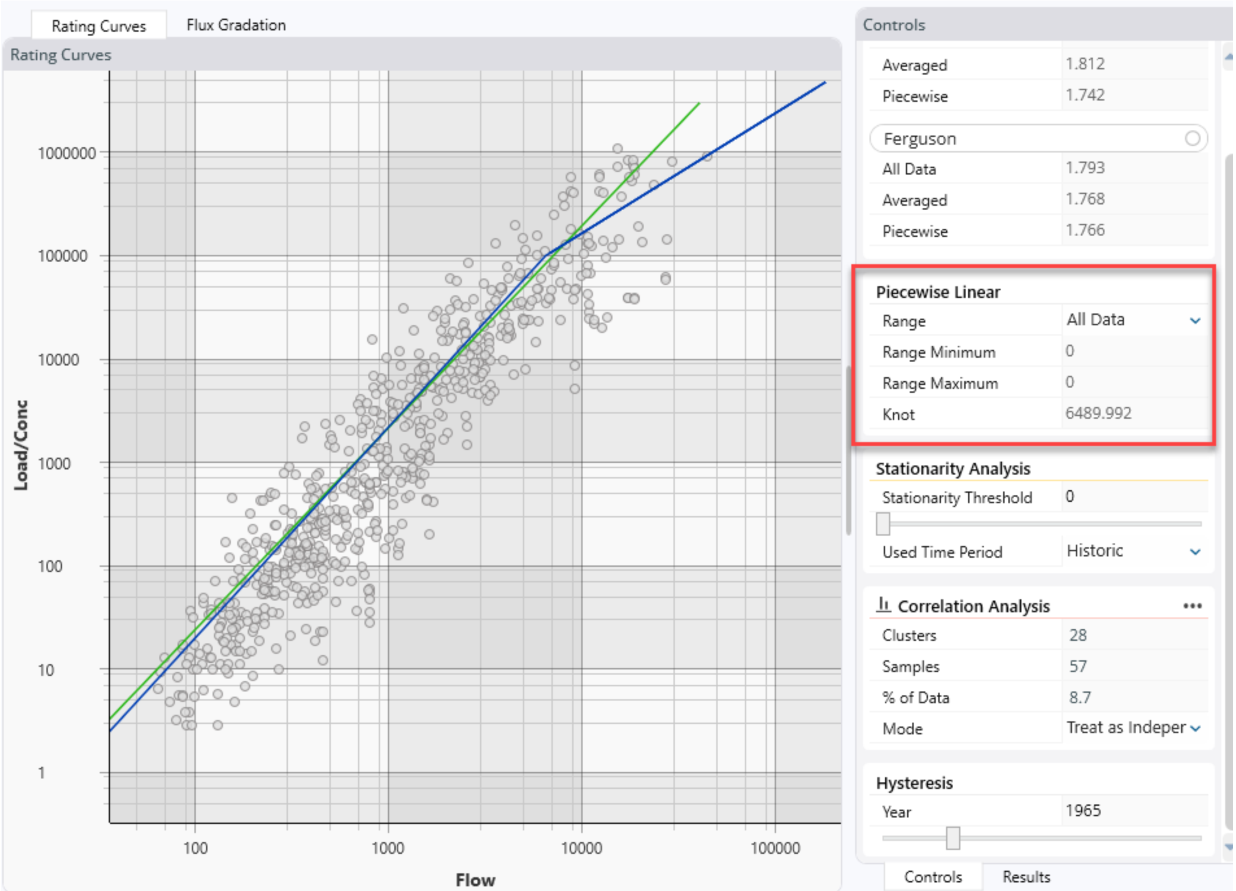
References

Duan, N. (1983). “Smearing estimate: A nonparametric retransformation method.” *Journal of the American Statistical Association*, 78(383), 605–610.

Piecewise Linear Regression

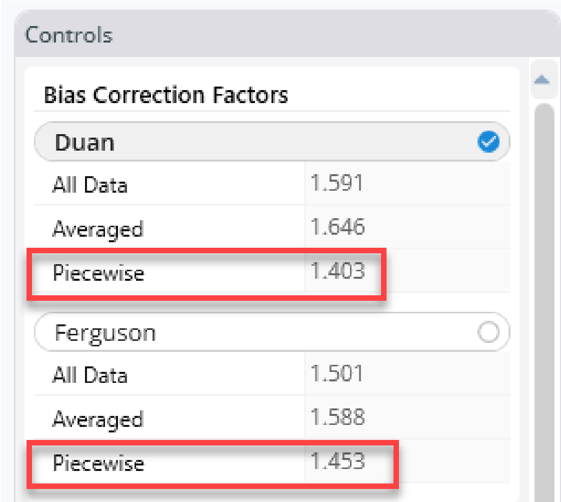
Often, a single power function does not capture the complexity of the data. Sediment data tend to over-represent low flows, which can dominate the regression in the moderate-to-large flow range that is most morphologically active. Additionally, "bent" or "inflected" rating curves are relatively common, particularly in supply limited systems. Future version of this tool will include local regression methods, that will allow users to develop more sophisticated rating curves. But a two-slope, piece-wise linear, regression can capture some of this complexity. HEC worked with UC Davis () to develop a piecewise linear algorithm that identifies the inflection point in an inflected or bent rating curve and fits a continuous model to the upper and lower halves of the data.

Piecewise Regression Approach



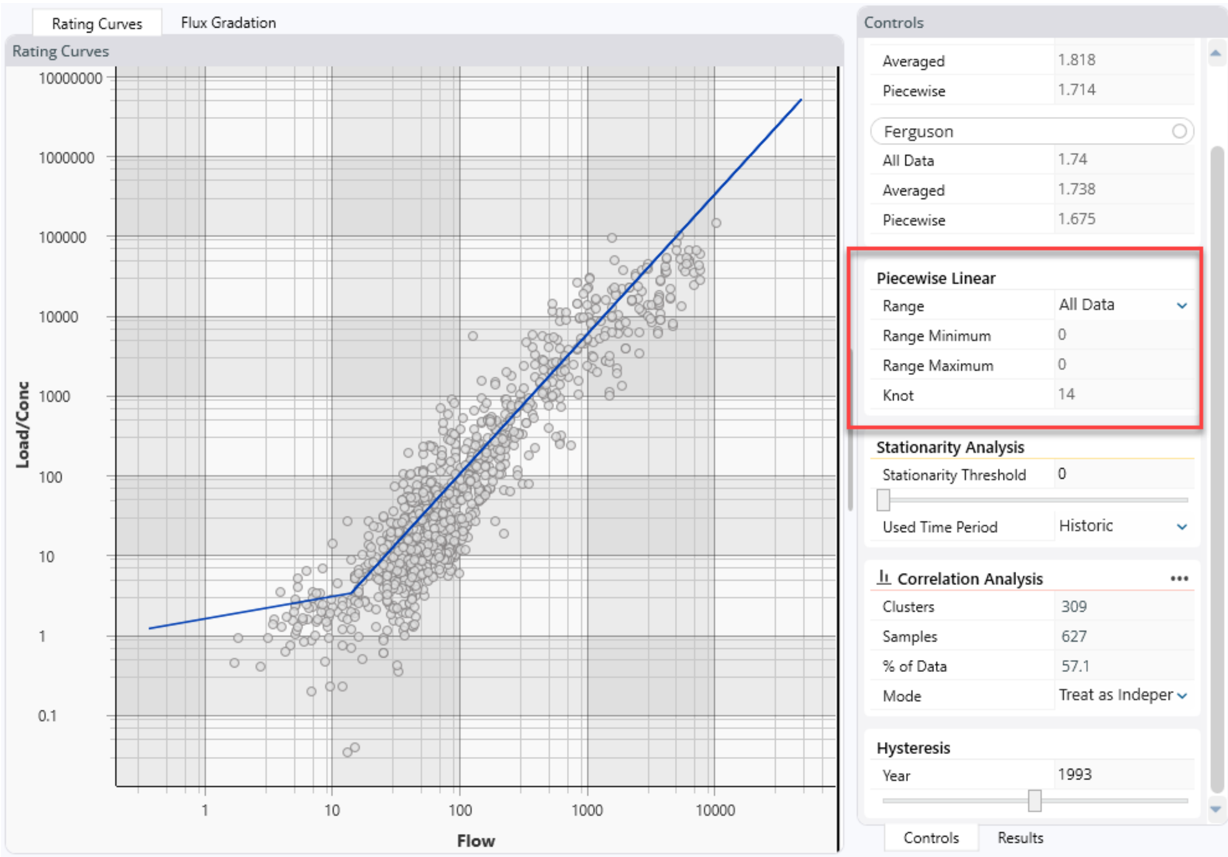
The simplest form of the piecewise linear model is included in the figure above. Change the **Range** from **None** to **All Data**. The calculator evaluates every data point as a potential inflection point (i.e. "knot" in the statistical terminology) and fits separate-but-continuous power functions to the upstream and downstream data. The algorithm selects the inflection point with the lowest Root Mean Square Error (RMSE). In the case pictured above, the model computed an inflection point at 6,490 cfs, and fit a steeper slope to the lower flows than the higher flows (which is typical of rivers in this region). Because most of the sediment moves in the moderate-to-large flow range, fitting a separate slope to these larger flows can affect the sediment budget and model dramatically.

The piecewise linear model also computes biased and unbiased regressions. If you select this option, it will update the **Piecewise** correction factors for both Duan and Furguson (below) and will plot and report the unbiased result by default. Users can request the biased result, but this is not recommended.

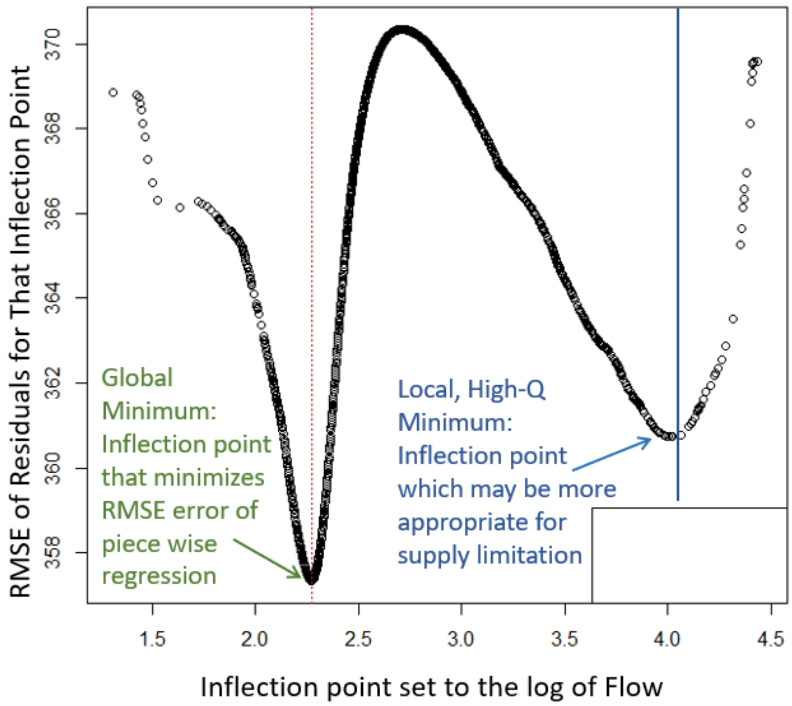


Constraining the Inflection Point Range

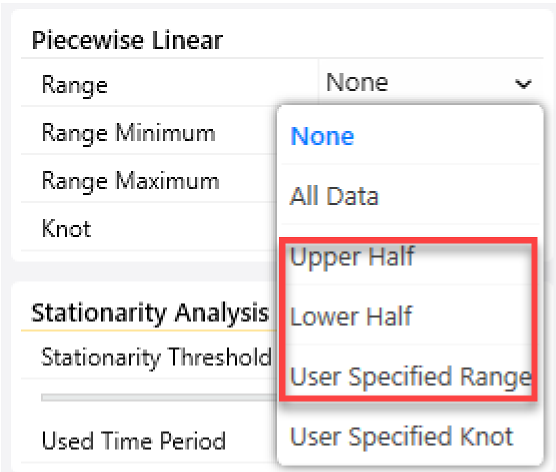
Because sediment data often over-represent the low flows, the flow-load inflection point that minimizes the RMSE can turn up in the lower flows (see Figure below). But because these flows do not deliver much sediment, the total sediment load will not be very sensitive to this constraint.



In some cases, the data can have multiple, local, minimums, in the RMSE, including a potential inflection point in the higher flow data that is not the global RMSE minimum. For example, the following figure includes the RMSE computed from each candidate inflection point. The global minimum is associated with a low flow, but there is a much higher flow inflection point that improves the overall fit substantially.



By constraining the inflection-point candidates to a particular flow range, users can force the model to select a local minimum and specify an inflection point that is more morphologically meaningful. The tool includes three options to constrain the search range:

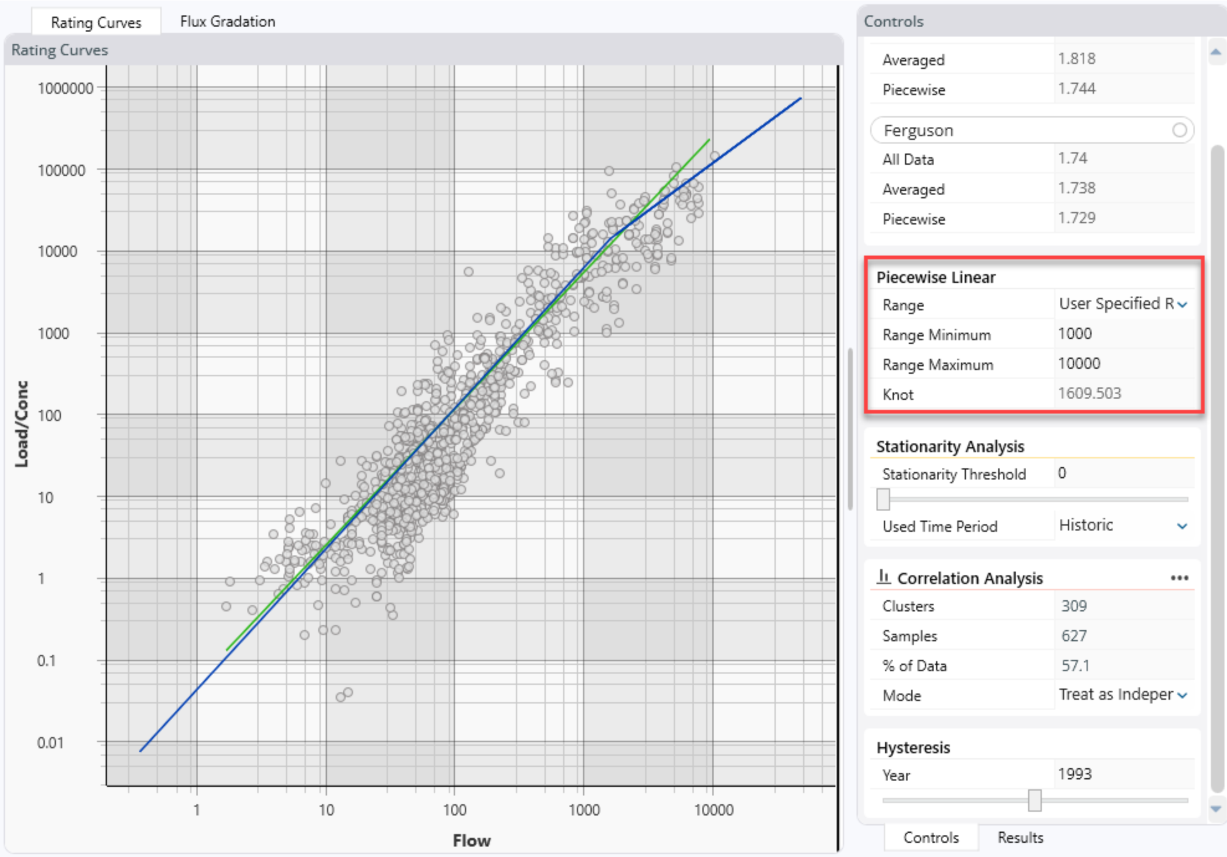


The **Upper Half** and **Lower Half** methods split the data and search the specified half for a local minimum, or users can specify a range over which the algorithm will search for a minimum.

Piecewise Linear

Range	User Specified R
Range Minimum	1000
Range Maximum	10000
Knot	1609.503

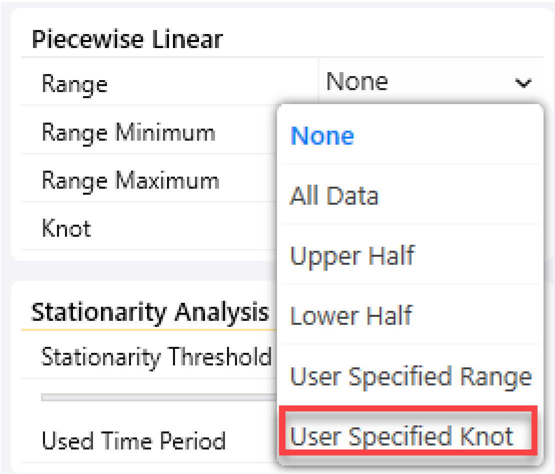
The following figure fits a piecewise linear model to the same data that set the inflection point at 14cfs above, but searches for an inflection point above 1,000 cfs. The rating curve below the inflection point is very similar to the simple power function, but the piecewise linear model fits those higher flows better.



Do Not Use Inflection Points on the Edge of the Range

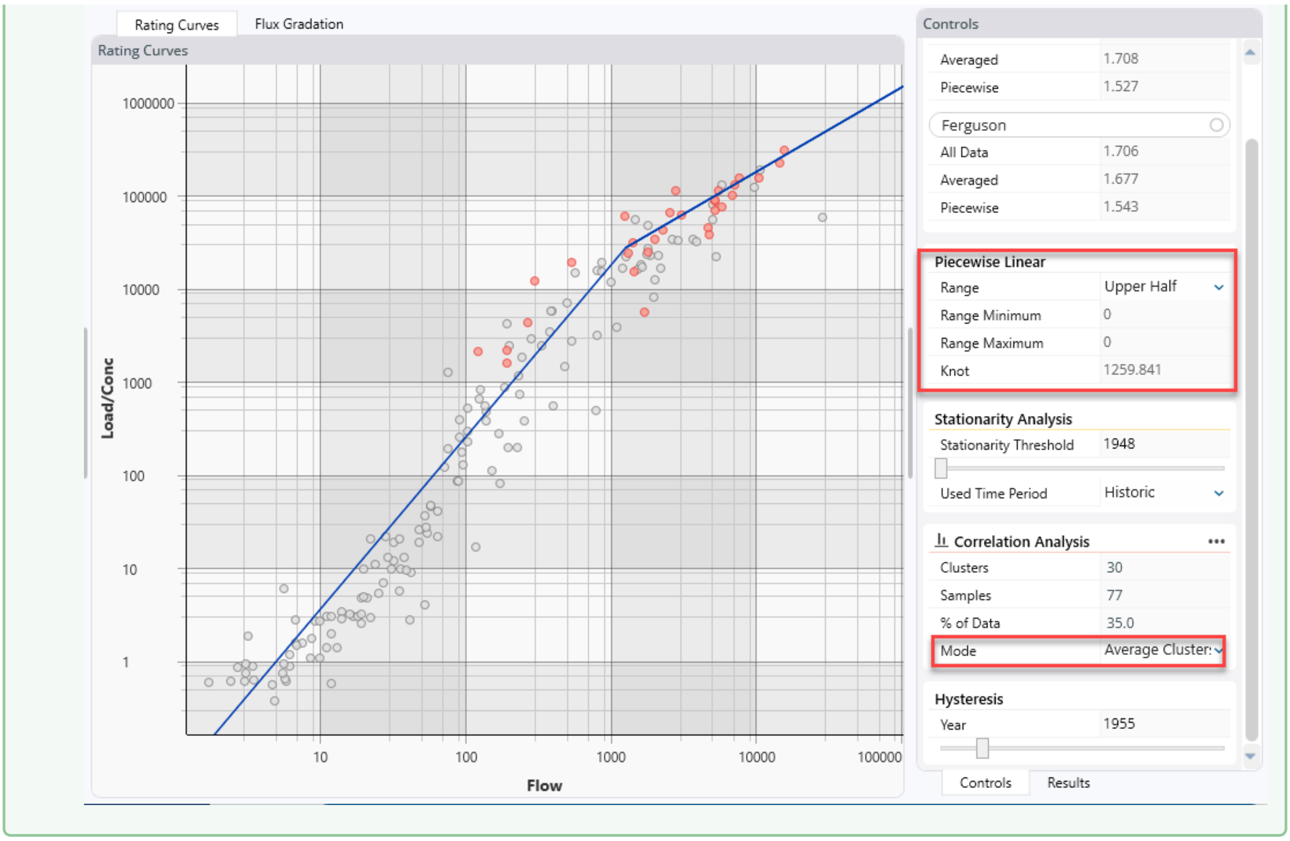
Be careful of inflection points on the edge of the range. If you constrain the range to half the data, and the algorithm computes the median flow as the inflection point, it did not find a local minimum in the specified half of the data. Both the local and global minimum are outside the range, and a larger range should be used. This is also the case if the inflection point corresponds to either end of the user-specified range.

Finally, if the analyst has a physical justification for specifying an inflection point at a particular flow, the tool includes a **User Specified** option. In this option, the algorithm will assume the specified inflection point and minimize the slopes above and below it for the lowest error regression.



Use Temporal Averaging with Piecewise Linear Regression

Like all of the statistical tools, the piecewise linear model assumes data points are independent. Analyze the data for autocorrelation and apply any temporal averaging before selecting a final rating curve.



Stationarity

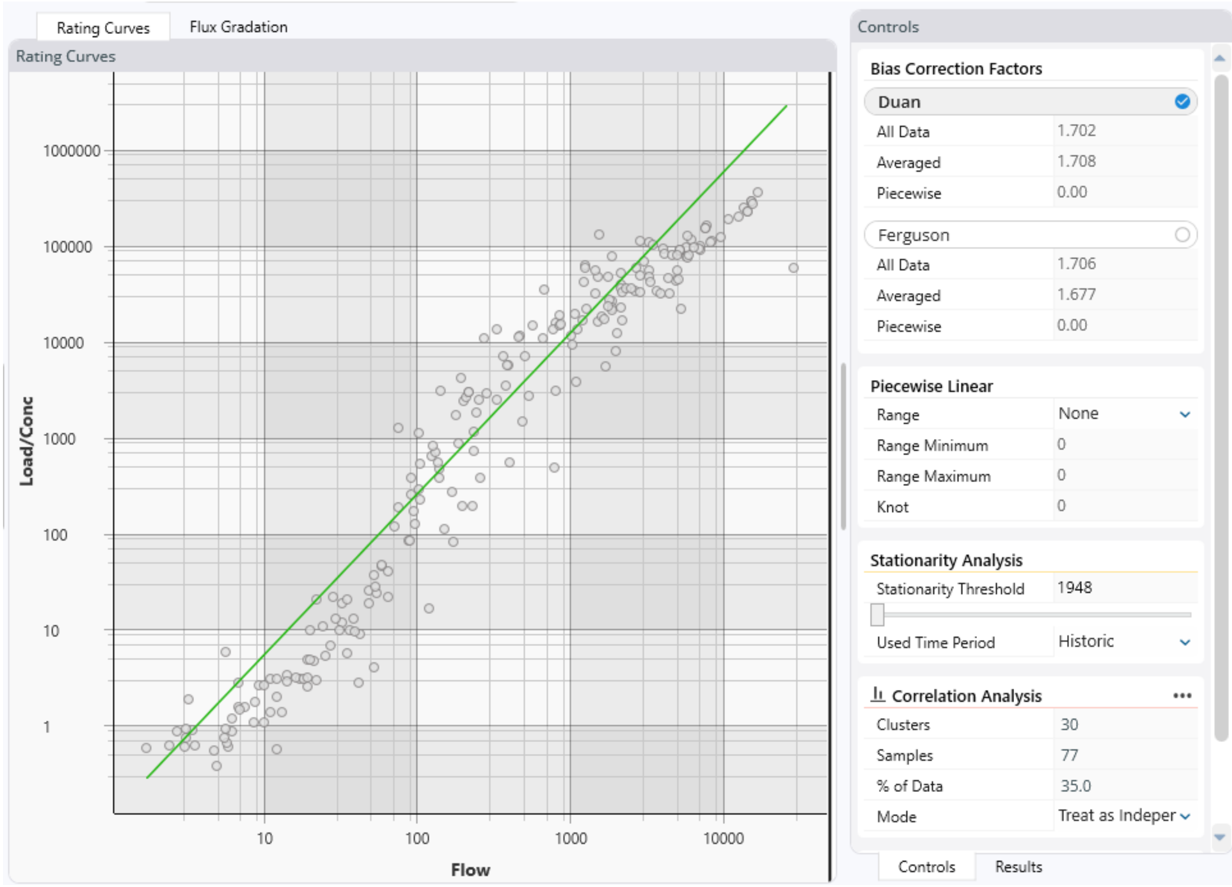
The relationship between flow and load can change systematically over time. If you cannot assume that the relationship between flow and load is "stationary" (constant over time), it may not be appropriate to use all the data for an analysis or model. For, example, when calibrating a model in a system with a non-stationary sediment data, it is appropriate to use the historic rating curve that reflects the data over the calibration period. Alternately, when forecasting, it is appropriate to use a rating curve based on the most recent relationship. Scientists and modelers should always - at a minimum - evaluate their data stationarity. But if sediment data are non-stationary, they must partition their data to develop a rating curve appropriate for the time period under consideration.

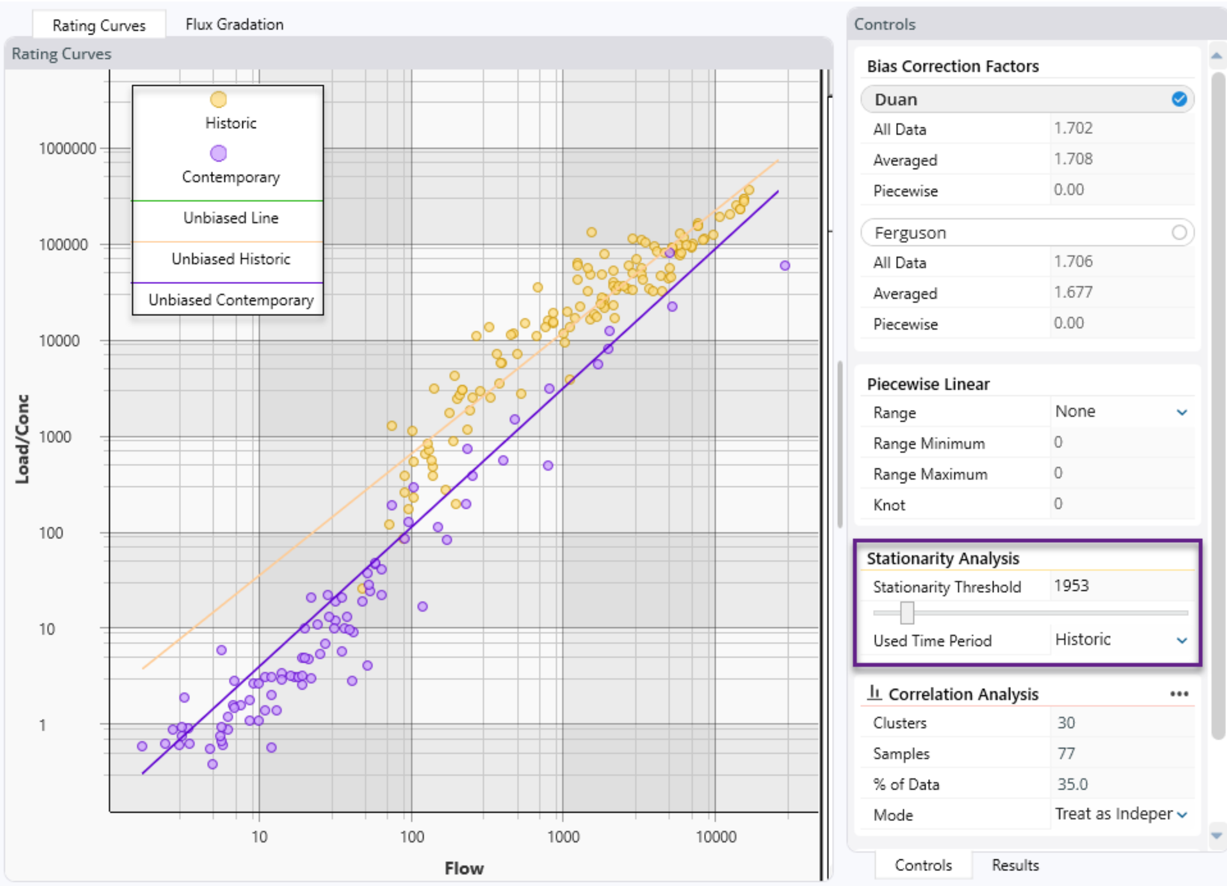
The rating curve calculator includes stationarity tools that allows users to visualize stationarity by plotting the data before and after a selected year in different colors, and reports separate rating curves for those before and after data.

The Stationarity Slide Bar

By default the rating curve data uses all the data available. For example, in the first image below, the tool fits a single, bias-corrected, power function through a data set. The Stationarity tool partitions the data by date to visualize and quantify temporal trends. The Stationary tool provides a scroll bar that spans the time between the earliest and latest measurement. Users can then move the bar to evaluate stationarity across different dates. The date before and after the selected year will plot in different colors to help visualize non-stationarity. For example, the second figure below uses the same data as the first, but plots the measurements prior to 1953 in yellow and those after in purple.

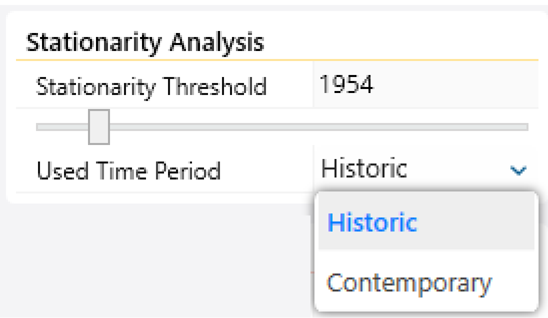
The older data trend higher, but were also collected over a larger range of flows. This is typical of changes observed after dam constrcution.





Warning - Stationarity Analysis Requires Temporal Data

The rating curve calculator can fit a bias corrected rating curve (or a piecewise linear model) to sediment data without any temporal data. Users can input simple, paired, flow-load/concertation information without dates or times and use these features. But stationarity is a temporal analysis. The stationary options will only be available if the data include dates and times.

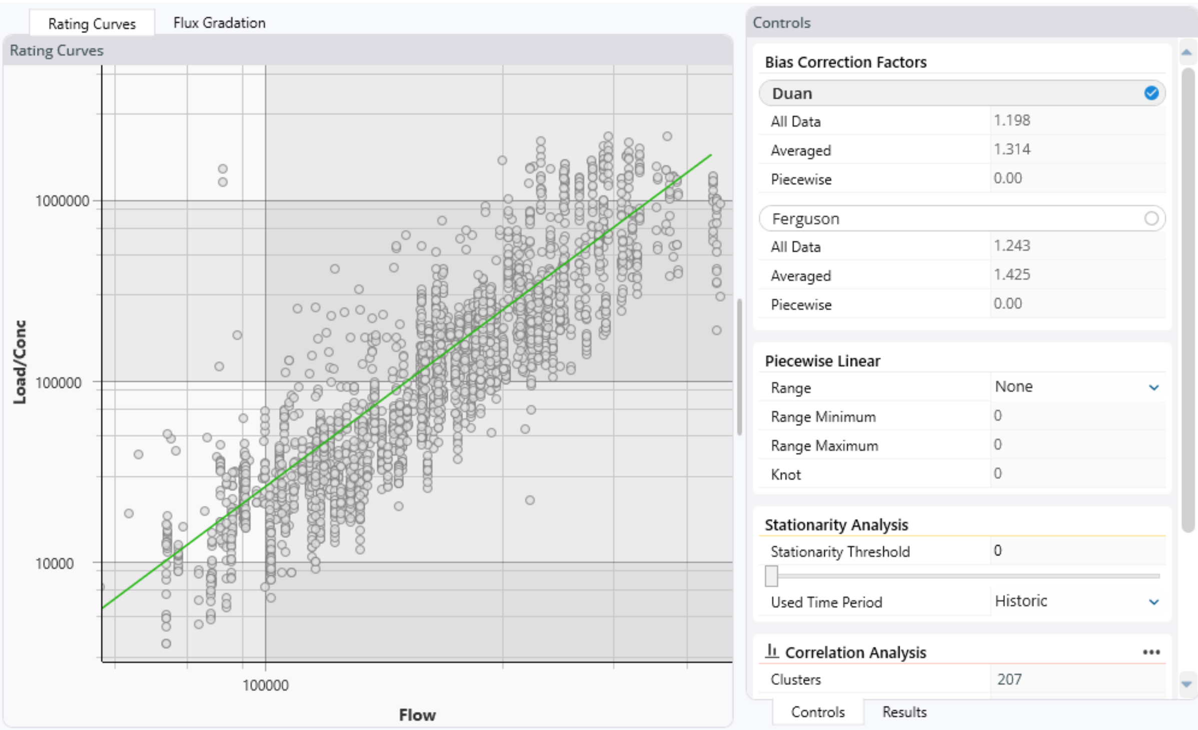


Wish List - Additional Stationarity Methods

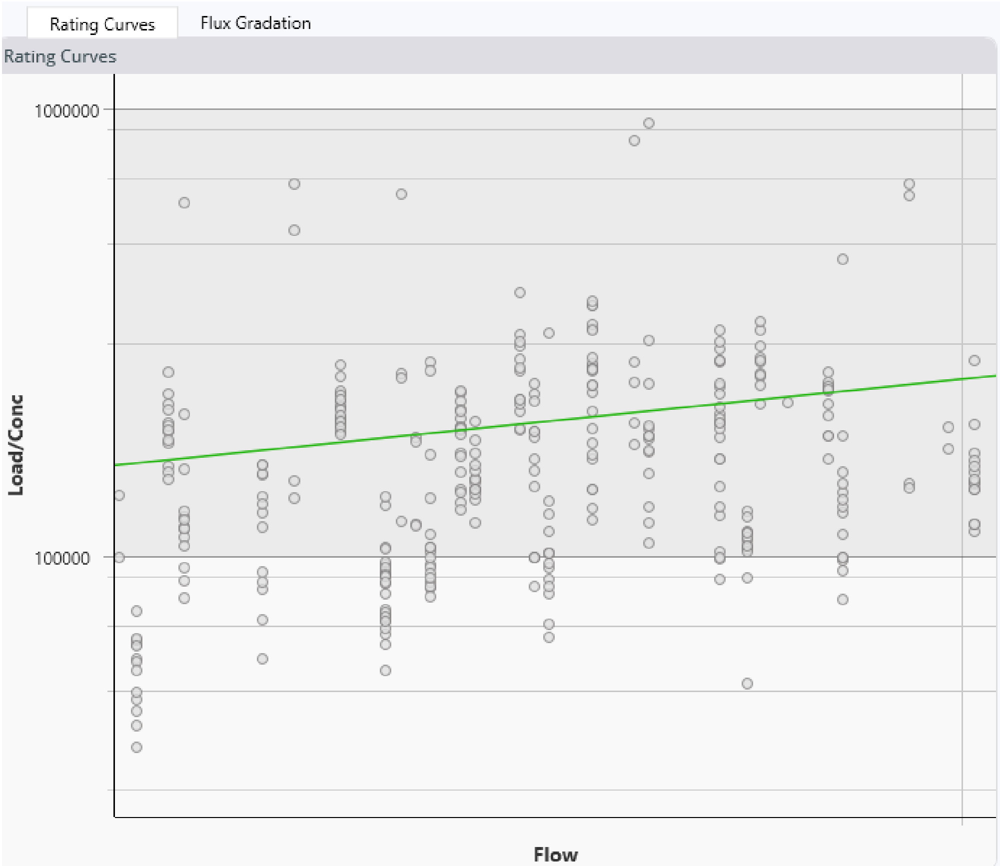
We would like to add several additional stationarity analysis methods, including color coding data by date (e.g. monochrome plotting with the lightest tone earliest and the darkest latest) or color coding the data by temporal bins (e.g. decades). We would also like to compute load for a given flow(s) with the before and after rating curves for the entire date range to explore how the rating curves evolve over time.

Temporal Averaging and Autocorrelation

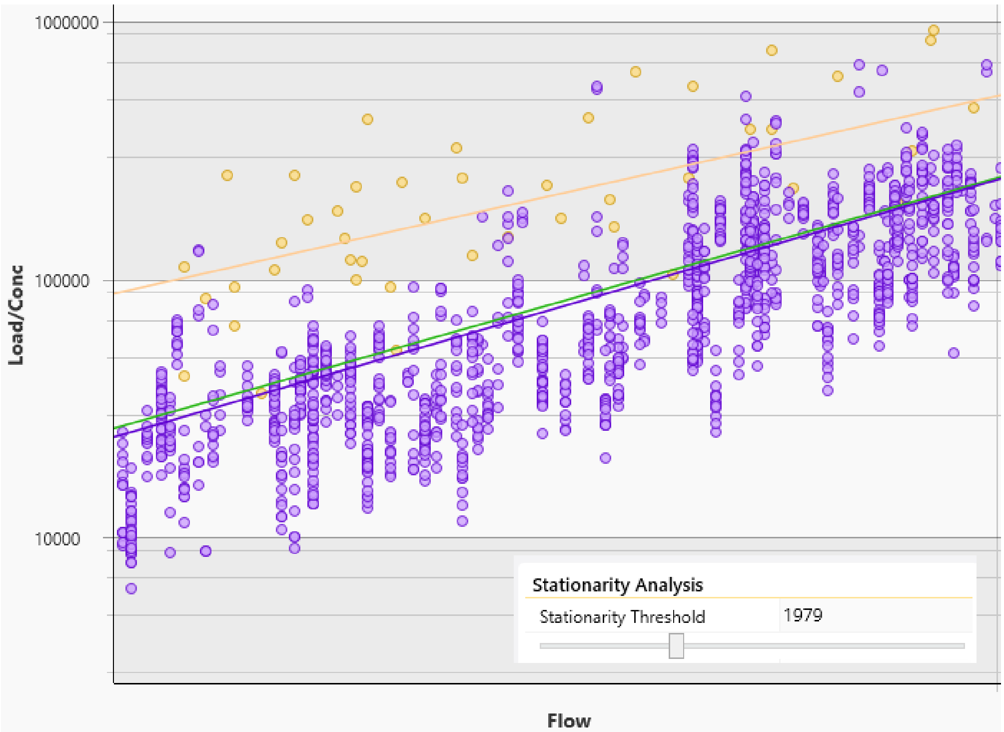
Sampling programs sometimes take multiple sediment measurements in a single sampling event. Because of sediment's natural variability, these sediment loads can vary dramatically, even though they were collected a few minutes or hours from each other and at about the same flow. The gage below includes a number of these multi-measurement, same-day replicates.



The vertical "striations" in the data often indicate these kinds of same-day replicates.

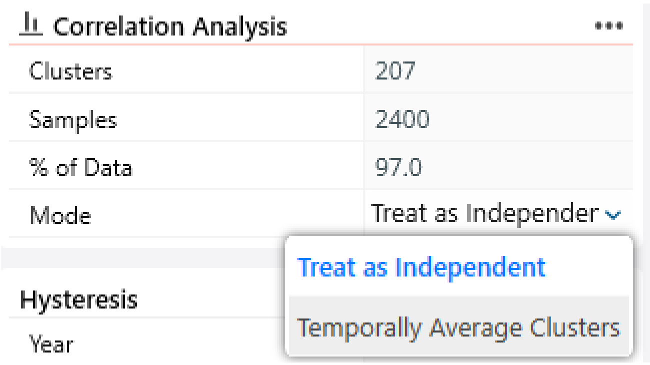


Regression analysis assumes each observation is independent. But these same-day replicates often are not. In this gage, the historical data mostly include single sample measurements. Therefore, if the regression analysis considered each contemporary replicate as an independent sample, it would overrepresent these data.



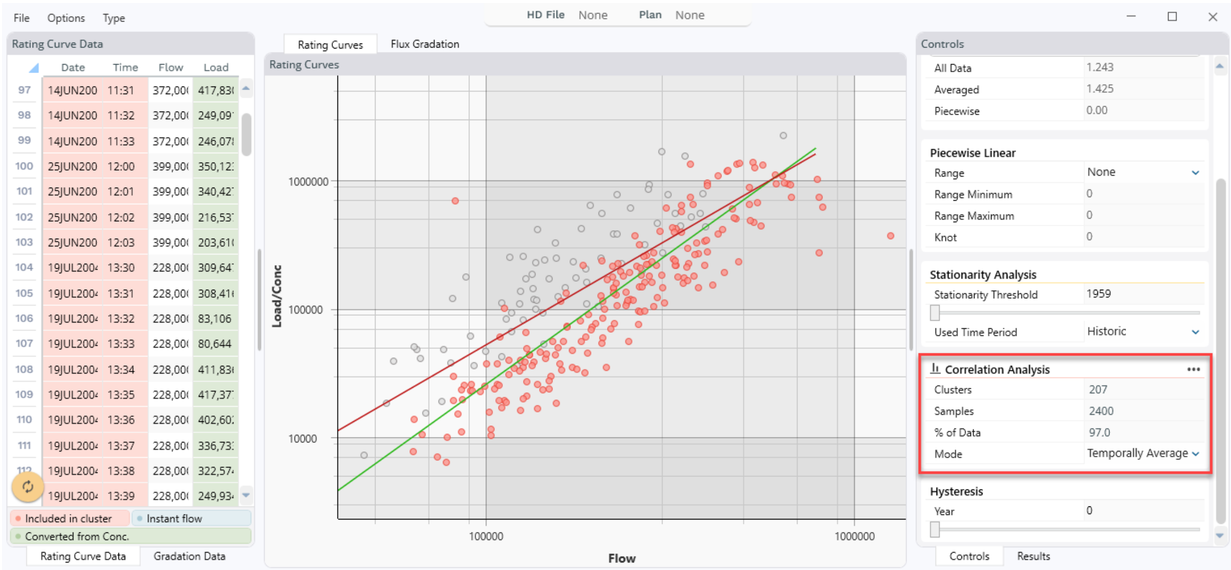
Temporal Averaging

The temporal averaging/autocorrelation tool allows users to automatically average replicates collected within a specified time frame. This control reports the number of "clusters" which are the collections of replicates that fall within the specified time threshold of each other (12 hours by default). At this gage, 2400 measurements fall within 12 hours of another measurement, and they group into 207 12 hour clusters. 97% of these data were collected as multi-measurement replicates within a single sampling event.



The **Mode** provides two options. The tool plots all the data and computes the regression as if they are independent by default. This can be appropriate for small rivers with flashy hydrographs, where samples collected in close succession have very different flows. But for large rivers, it is almost always appropriate to average these temporal clusters.

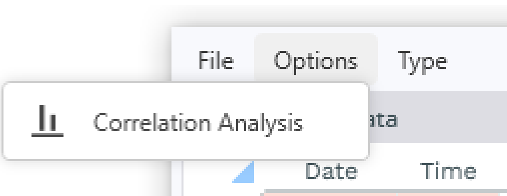
At this gage, averaging the clusters reduces the power of the contemporary measurements and generates a higher rating curve (though the analyst should also note the non-stationarity and decide if it is appropriate to use all of the data). The plot replaces the replicates with the cluster-average loads or concentrations (red). The Sediment Rating Curve Analysis tool also marks the measurements that fall within the time tolerance of other measuremnts in the data grid.



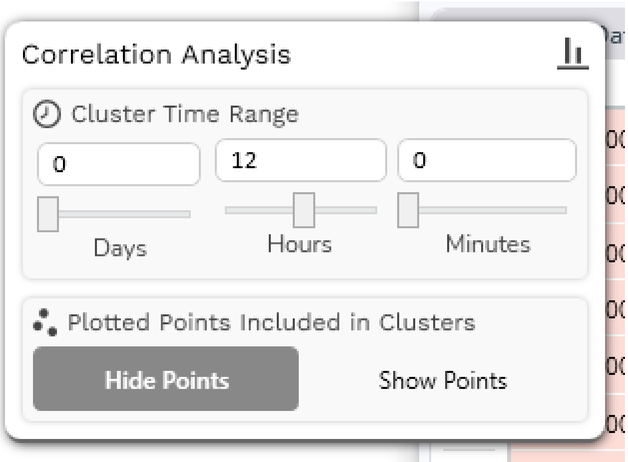
Setting the Temporal Averaging Threshold

By default, the temporal averaging tool averages observations collected within 12 hours of each other. But that time threshold is variable.

To change it, go to **Options** → **Correlation Analysis**.

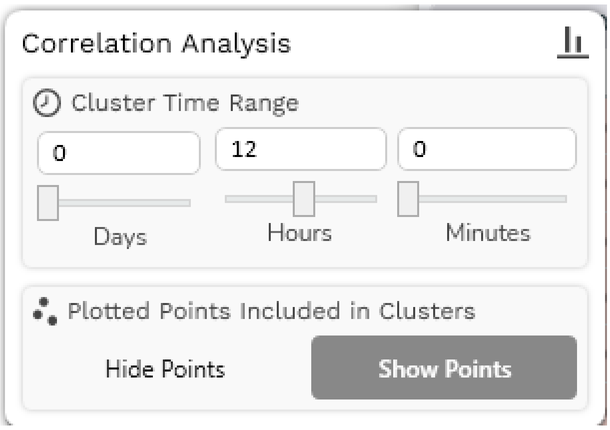


This opens an editor that allows users to set the temporal averaging threshold.



Plotting Original and Averaged Points

By default, the temporal averaging tool only plots the average measurements. However, under **Options** → **Correlation Analysis** users can select Show Points. This plots both the average and the averaged data so users can see the original measurements.



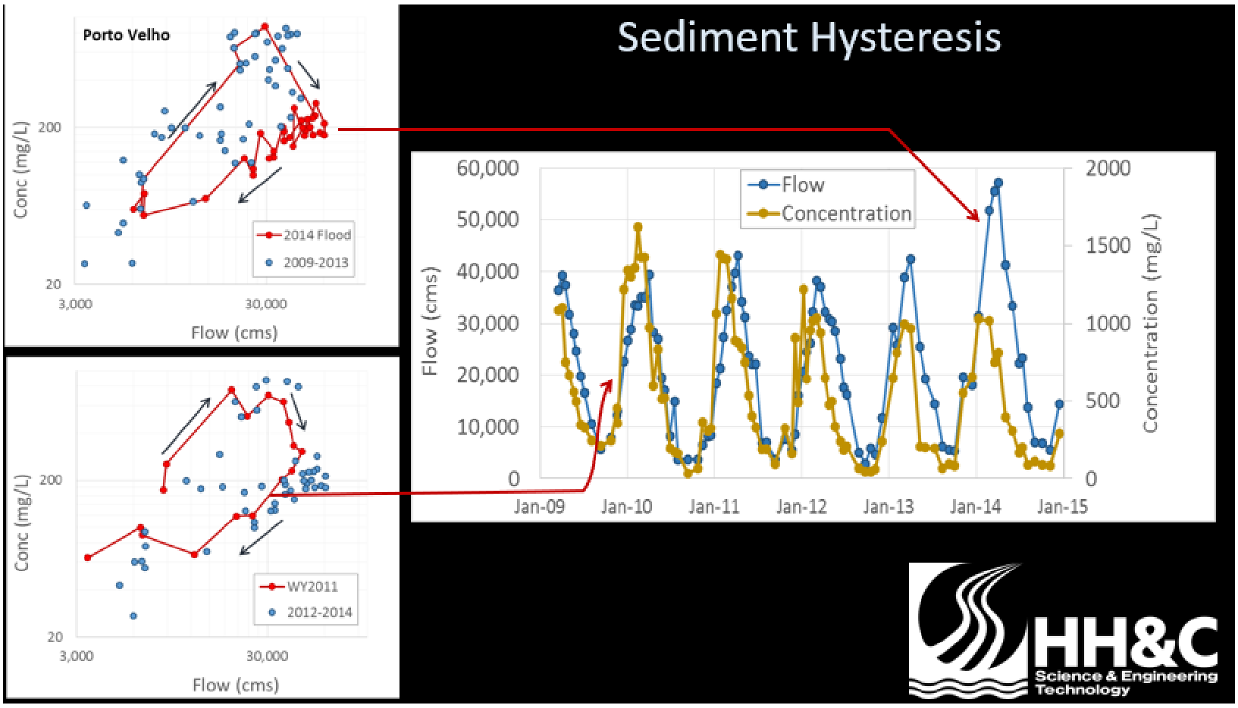
The plot below includes single-measurement observations (grey), replicates (green) and replicate cluster averages (red). The green line is the unbiased regression for all of the measurements. The red is the unbiased regression of the single-measurement observations and the temporal averages.

Hysteresis Visualization

A process that is path dependent, that takes a different path on the way up than it does on the way down, has *hysteresis*.

Sediment load data often has hysteresis. Loads are often higher on the rising limb of the hydrograph than they are on the falling limb of the hydrograph.

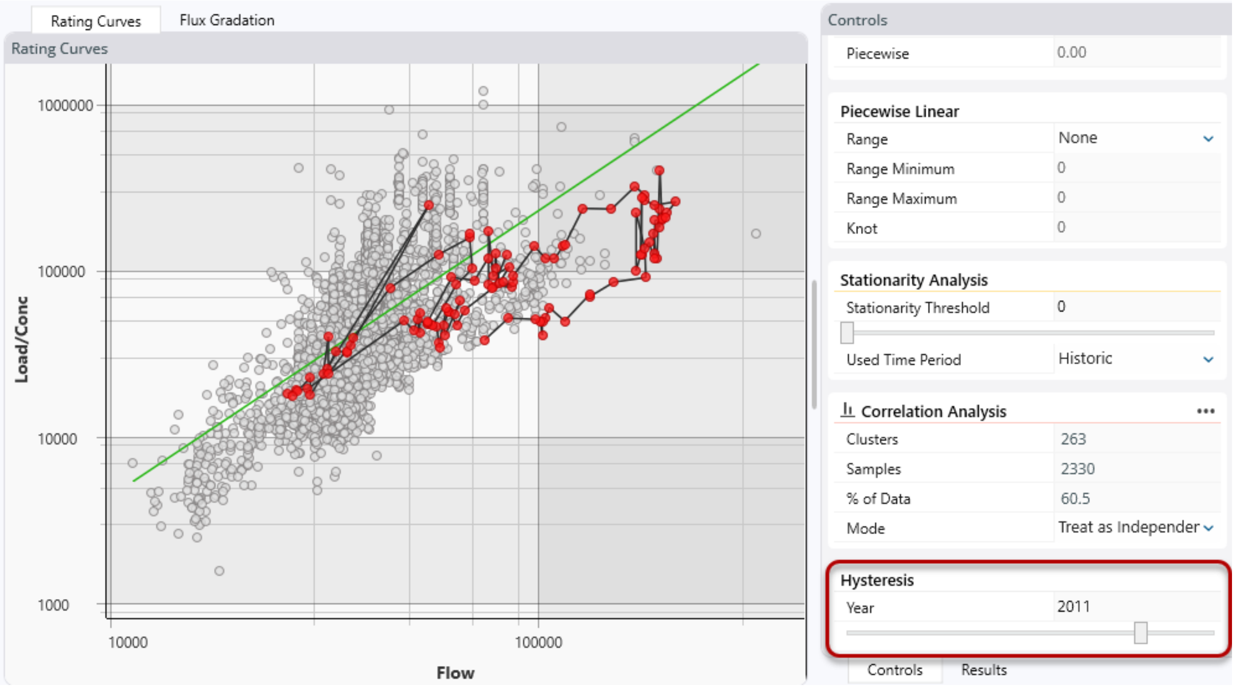
The data below include the flow hydrograph and sediment time series measured at the Porto Velho gage on the Madeira River (right). The plots on the left show the sediment measurements from water years 2011 and 2014 connected in time. This system has strong clockwise hysteresis (sediment loads are much higher on the rising limb of the hydrograph than the falling limb).



Sediment modelers and scientists often lose track of hysteresis effects when we simply plot flow vs load or concentration as temporally naïve paired data.

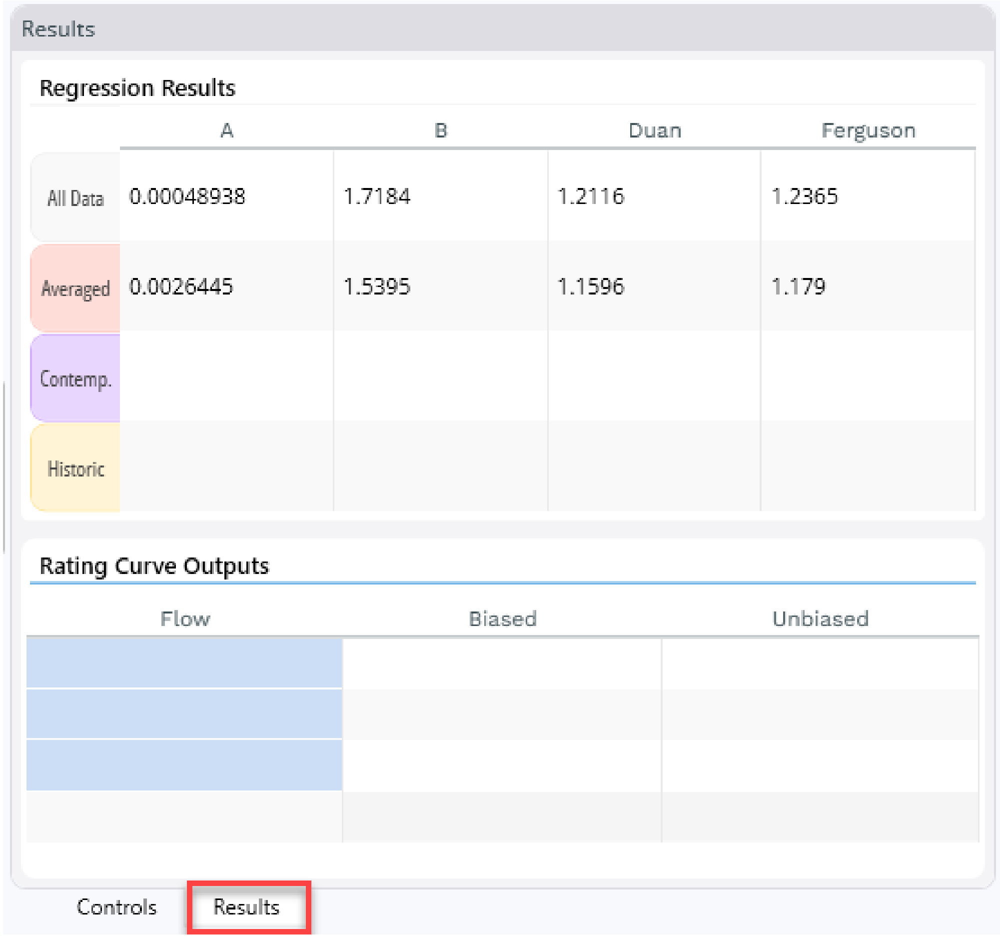
Because a rating curve does not distinguish between the rising and falling limb of a hydrograph, but make a 1-to-1 relationship between flow and load, the hysteresis tools in this software do not affect the rating curve or calculations. However, it can be very useful to visualize hysteresis. In some cases, this may motivate modelers to use a sediment time series for a model boundary condition instead of a rating curve).

The Rating Curve Analysis Tool connects sediment measurements collected in the same water year. Type in a water year or move the scroll bar to track the temporal path of the observations in that year. The gage below is plotting the hysteresis associated with a 2011 event, which delivered much more sediment on the rising limb than the falling limb.



Analytical and Tabular Rating Curve Results

After the analyses and visualization, modelers and analysts eventually will want to reproduce the rating curve. To get the rating curve results, go to the **Results** tab (that is grouped with the **Controls** in the standard layout).



This tab provides two types of results:

- Regression Results that will help reconstruct an analytical power function and
- Rating Curve Output, which computes the loads for user specified flows in a tabular format

Regression Results (Analytical Results)

The Regression Results provide the ingredients to reconstruct the

By default, the tool computes the unbiased regression (with both correctors) for all the data and the temporally averaged data. The tool offers these regressions by default because averaging replicates and bias correction are best practices for most applications. The parameters fit the equation

$$Qs = E\ a\ Q^{b}$$

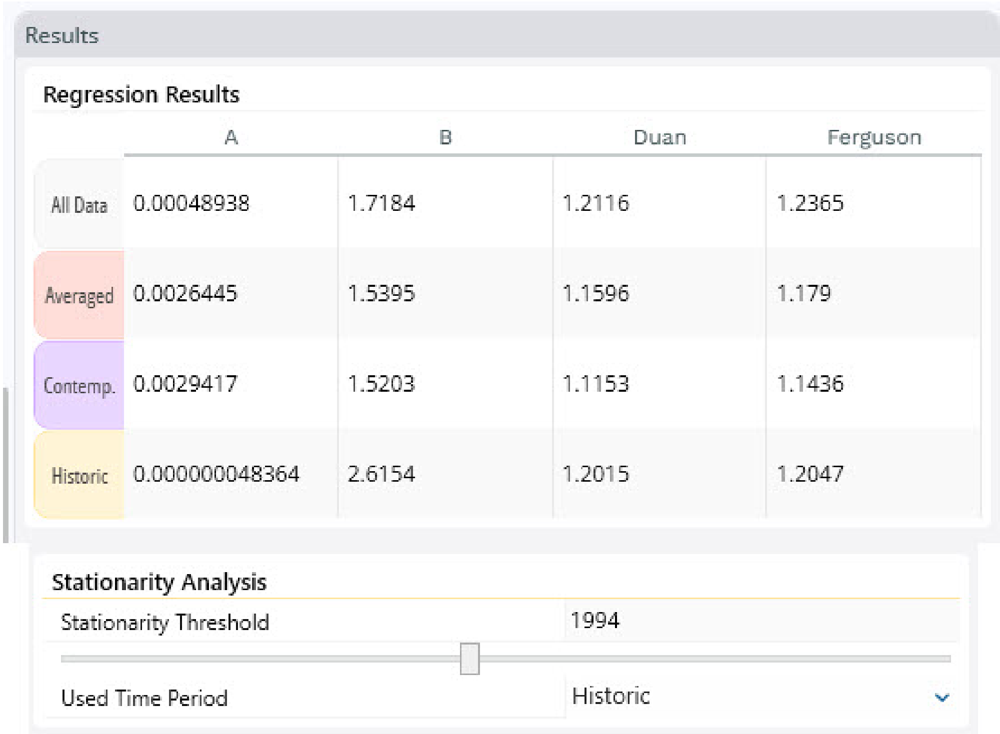
where Qs is the sediment load (or concentration if the analysis used concentration), a and b are the coefficient and the power, and E is the bias corrector (Duan or Ferguson). So, the results in the figure above translate into an analytical rating curve of:

$$Qs = (1.1596)\ 0.0026445\ Q^{1.5395}$$

with the Duan correction of the temporally averaged data.

Regression Results from Stationarity Analysis

If you use the Stationarity Control (e.g. the results below are associated with the stationarity control bar also pictured below) the analytical rating curve results will also populate the coefficients for the "historic" and "contemporary" regressions. The historic regression includes the data before the split-year selected in the stationarity scroll bar and the "Contemporary" coefficients reproduce the power function fit to the data points more recent than the stationarity threshold.


Results

Regression Results

	A	B	Duan	Ferguson
All Data	0.00048938	1.7184	1.2116	1.2365
Averaged	0.0026445	1.5395	1.1596	1.179
Contemp.	0.0029417	1.5203	1.1153	1.1436
Historic	0.000000048364	2.6154	1.2015	1.2047

For example, in this analysis, the measurements before 1994 (with the Duan correction) yield a rating curve of:

$Qs = (1.2015)\ 4.836E\text{-}8\ Q^{2.6154}$

while the data after 1994 (with Duan) yield:

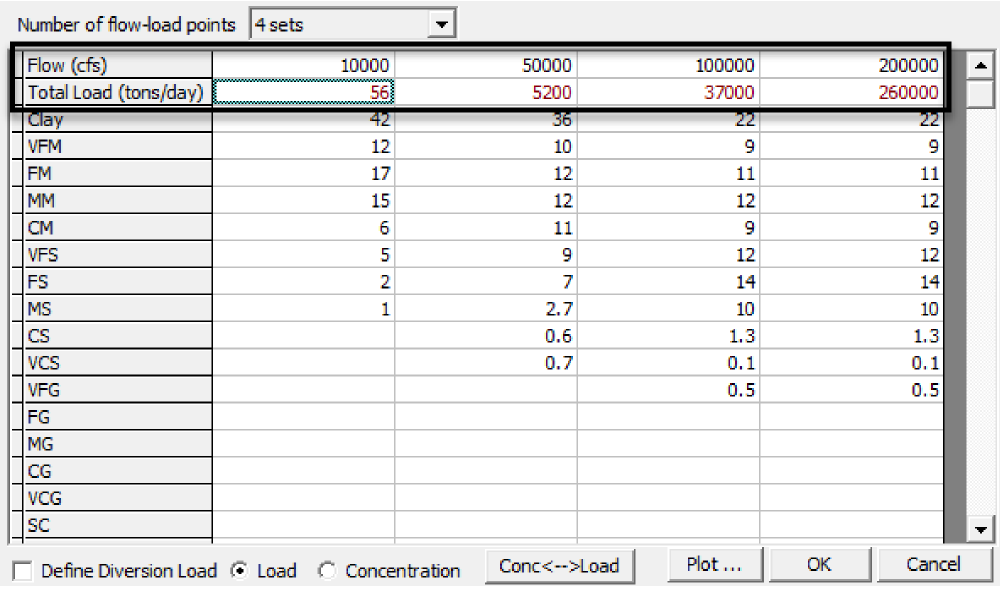
$Qs = (1.2015)\ 0.002941\ Q^{1.5203}$

Piecewise Linear Regression Does Not Have an Analytical Result

Because the piecewise linear regression is actually two power functions forced to connect within the data domain, it cannot be characterized by a single set of power-function coefficients. Use the below feature (the tabular rating curve) to generate a piecewise rating curve (and make sure you select one point at or very close to the inflection point).

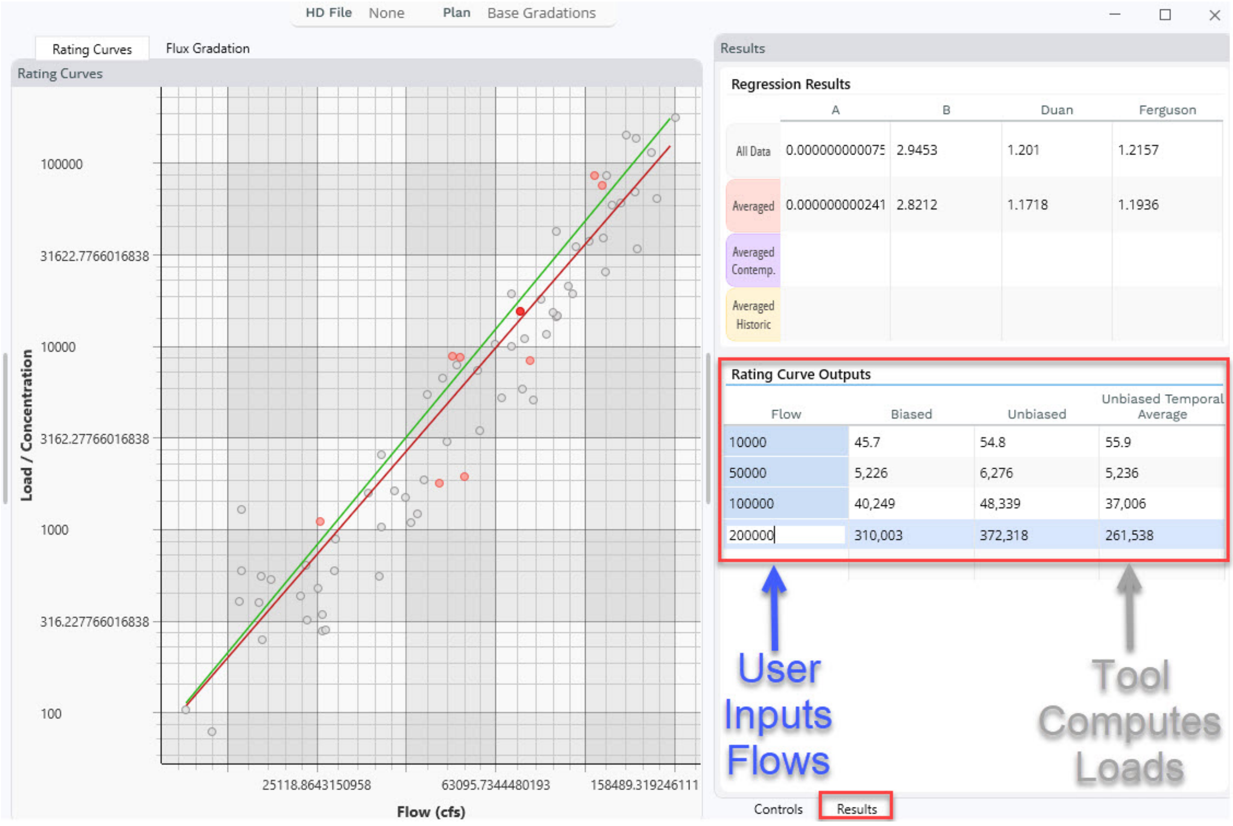
Generating a Tabular Rating Curve (Tabular Results)

HEC-RAS sediment, rating-curve boundary conditions require a tabular flow-load or flow-concentration rating curve. An example of a flow-load rating curve boundary condition in the HEC-RAS sediment model is included below.



Flow (cfs)	10000	50000	100000	200000
Total Load (tons/day)	56	5200	37000	260000
Clay	42	36	22	22
VFM	12	10	9	9
FM	17	12	11	11
MM	15	12	12	12
CM	6	11	9	9
VFS	5	9	12	12
FS	2	7	14	14
MS	1	2.7	10	10
CS		0.6	1.3	1.3
VCS		0.7	0.1	0.1
VFG			0.5	0.5
FG				
MG				
CG				
VCG				
SC				

The tabular data requires user input. It is blank by default. The user must input flows (see figure below). When the user inputs flows, the tool will compute loads with the active methods (the methods used in the **Control** menu). In the example below, the user input four flows and the tool returned the biased and unbiased results, assuming all measurements were independent and the unbiased results (with the method selected in the **Controls** menu - Duan in this case) with temporal averaging. The tool returns the **Unbiased, Temporally Averaged** results by default, because these are considered best-practice for most systems. These results were transposed into the HEC-RAS sediment boundary condition above.

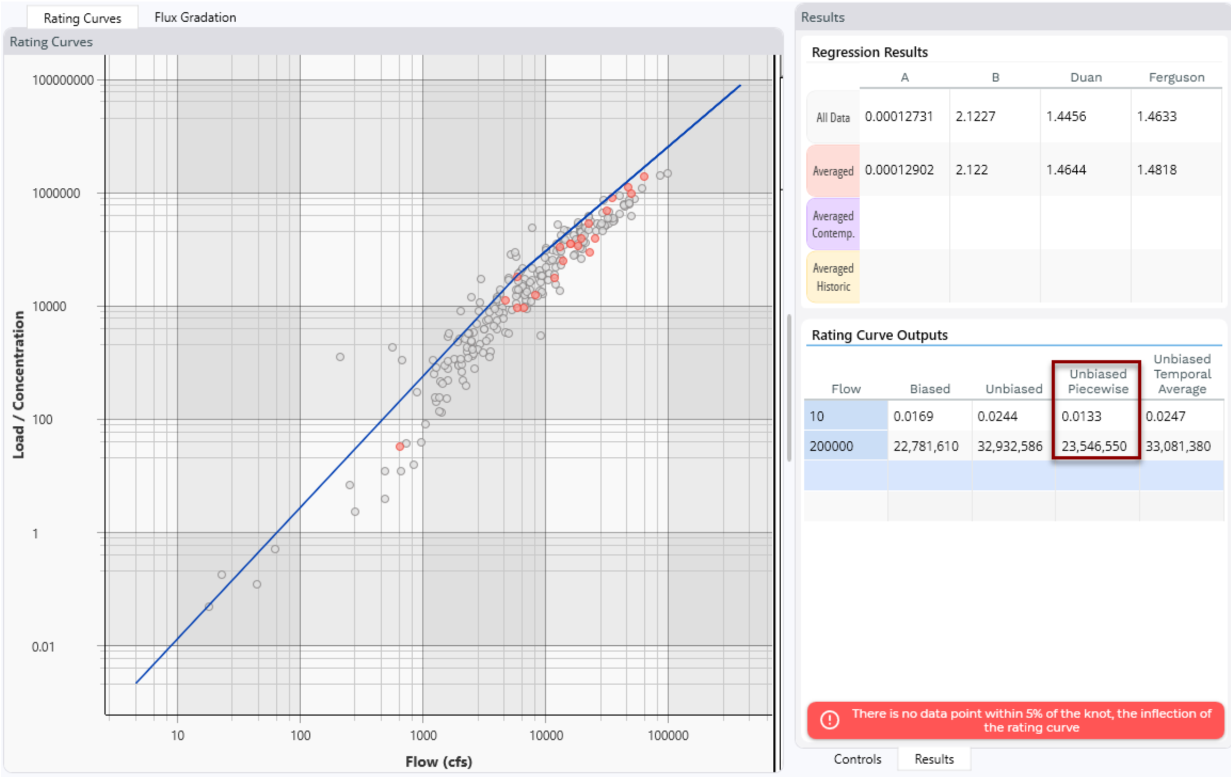


Logarithmically Interpolate Between Tabular Results

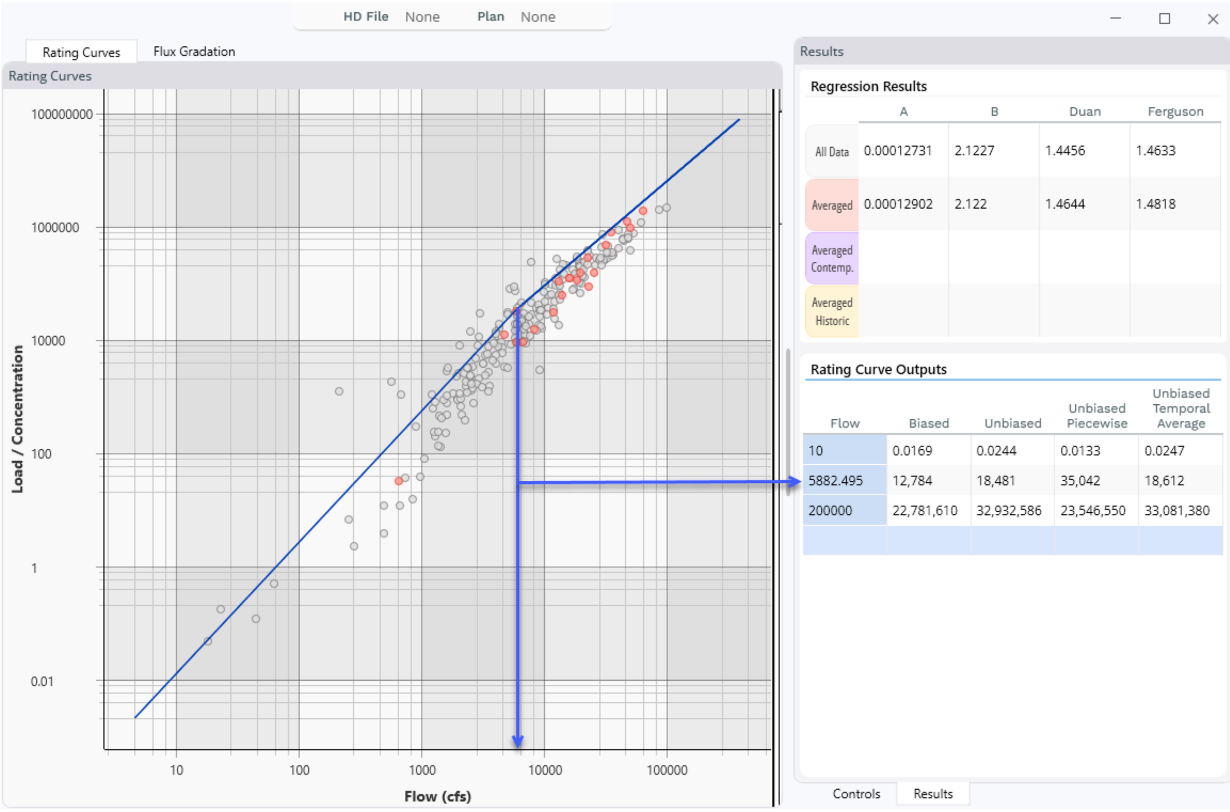
The tabular results reproduce the rating curve with two or more points. To compute loads for other flows, modelers and scientists will have to interpolate between these flow-load pairs. But these are logarithmically distributed data that fall along a power function (log transformed linear relationship). A simple linear interpolation is not appropriate. HEC-RAS log-interpolates between these data. Other applications should as well.

Piecewise Linear Result

Flow-load power functions can be defined with two points (these points should bound the highest and lowest flows expected, not the highest and lowest flows observed in the data). But a piecewise linear result requires at least three, and should include a point at or very close to the inflection point (i.e. the "knot"). For example, in the result below, the user has only entered bounding flows (high and low) in the tool. The tool is providing an error message, that to get good results from the piecewise linear tool, they must include a flow close to the inflection point (or knot).



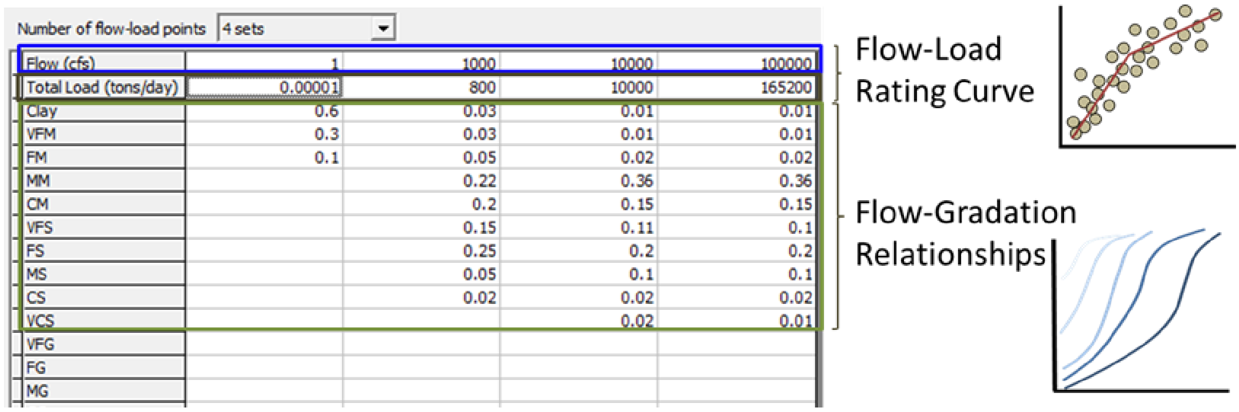
When the user copies the inflection point for the piecewise linear analysis into the flow data, the tool generates a three-point curve and the error goes away.



> ⚠ **Wish List - Local Regression**
>
> We would like to add LOESS local regression analysis to fit independent but continuous non-linear relationships to different portions of the curve. These approaches do not devleop simple analytical equations, but could generate tabular results that could feed a model.

Gradation Trend Analysis

Multiple grain class sediment models not only require flow-load or flow-concentration rating curves, they also require users to partition those loads by grain class. Sediment transport is very sensitive to the size distribution of the transporting sediment. HEC-RAS requires not-only a flow-load/ concentration relationship but also requires users to specify the fraction of each grain class associated with each load.



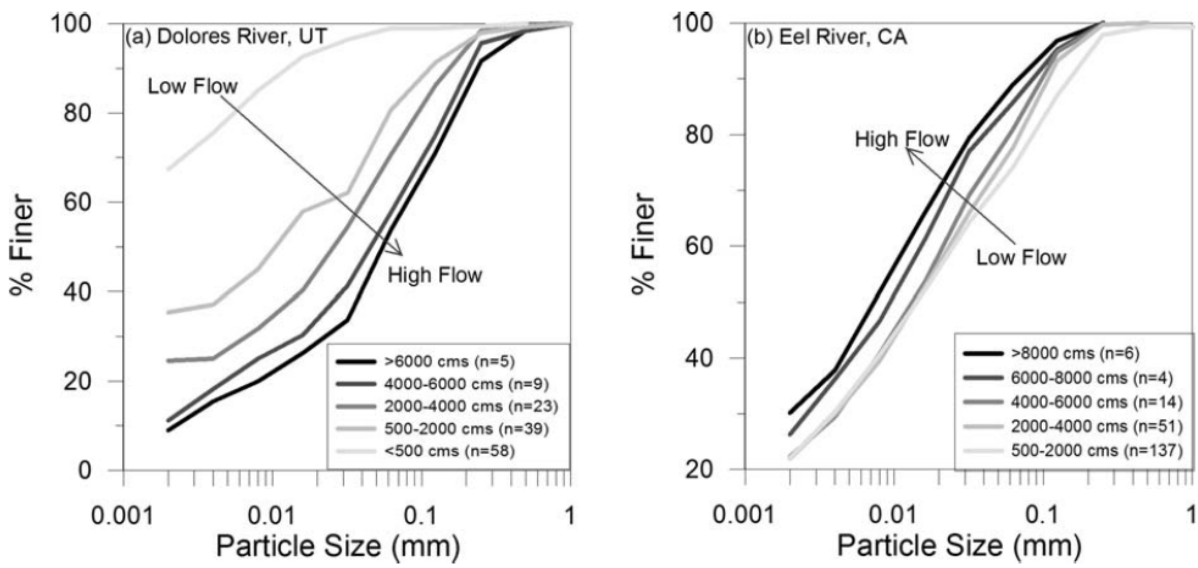
Number of flow-load points: 4 sets

Flow (cfs)	1	1000	10000	100000
Total Load (tons/day)	0.00001	800	10000	165200
Clay	0.6	0.03	0.01	0.01
VFM	0.3	0.03	0.01	0.01
FM	0.1	0.05	0.02	0.02
MM		0.22	0.36	0.36
CM		0.2	0.15	0.15
VFS		0.15	0.11	0.1
FS		0.25	0.2	0.2
MS		0.05	0.1	0.1
CS		0.02	0.02	0.02
VCS			0.02	0.01
VFG				
FG				
MG				

Estimating the grain-class partition of each load is often the most difficult boundary condition to estimate in a sediment model. The data are often scarce, and when the exist, they are usually noisy. HEC added a gradation analysis tool to the Sediment Rating Curve Calculator to help modelers and scientists to visualize and quantify these trends.

Suspended Load Gradation Trends

Suspended load can fine or coarsen with flow, or remain approximately the same. This process diversity complicates gradational trend analysis. The figure below includes data from a gage that coarsens with higher flows and another that fines. Gibson and Cai (2017) describes these trends and provides some context for these trends.



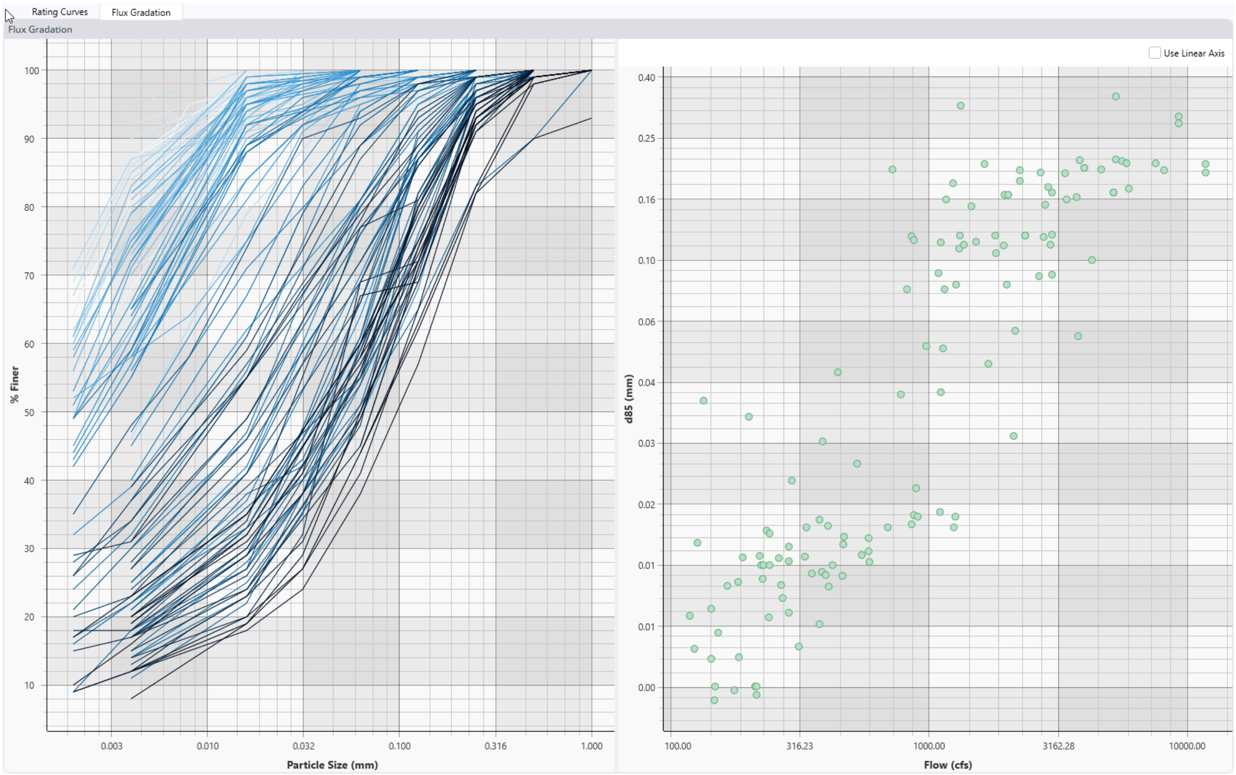
Load Gradations Must Include Bedload

Most of the sediment load and gradation data downloaded from the USGS are suspended load measurements. But river morphology is disproportionately sensitive to the bed load gradations. Therefore, even thought bed load might be a small percentage of the load, augmenting the suspended load gradations with bed load grain classes is often essential to get a sediment model to reproduce prototype behavior. Some gages have bedload data and future versions of this tool may import and integrate those measurements. But bed load data are rare and bed load gradations are more rare. Modelers must use scientific intuition to add bed load gradations based on the bed material and often adjust these fractions during calibration.

Viewing Suspended Load Gradations

If a gage has gradation data associated with flows, the Sediment Rating Curve analysis tool will automatically import them. The importer groups gradation data assigned to the same sample, builds a geotechnical (% finer) curve and computes gradation statistics for each sample.

To view the gradations, select the **Flux Gradation** tab on the main plot of the tool. This provides two different visualizations of the gradation data.



The plot on the left is a monochromatic plot of the gradation curves. The monochromatic color scheme plots by flow, so gradations associated with lower flows are light blue and those associated with higher flows are darker. For the gage pictured above, the lighter colors plot to the upper left, and the darker lines plot to the left, which means the higher flows are coarser.

The visualization on the right plots summary statistics against flow. The gage pictured above depicts the d85 tending up with flow, also indicating flow-coarsening.

Wish List: Binning, Bed Load, and Statistics

There are several statistical and visualization strategies that can help users understand the trends in these data, which can be very noisy, and are not always monotonic. We would like to add binning, regression, and other visualization and summary tools, including several included in Gibson and Cai (2017). We would also like to import bed load data and gradations where available and find intuitive ways to plot those with the suspended data and integrate them into the summary results.