R2Cross Model

User's Manual & Technical Guide

CIVIL AND ENVIRONMENTAL ENGINEERING
COLORADO STATE UNIVERSITY

ONE WATER SOLUTIONS INSTITUTE

COLORADO
Department of Natural Resources

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DISCLAIMER

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DOCUMENT STRUCTURE

The purpose of this document is to provide a guidance in running the R2Cross model. The first section (User's Guide) describes the components, capabilities, inputs, and outputs of the R2Cross program. This section is intended to help users navigate the eRAMS platform. The second section (Technical Guide) describes the underlying equations used in the R2Cross program, including the hydraulic equation, sediment distribution equations, and other relevant technical details. A companion document, R2Cross Field Manual, provides guidance on how to collect field data necessary for the R2Cross method.

INTRODUCTION

PURPOSE OF R2CROSS

Colorado's General Assembly created the Instream Flow and Natural Lake Level Program in 1973, recognizing "the need to correlate the activities of mankind with some reasonable preservation of the natural environment" (see 37-92-102 (3), C.R.S.). The statute vests the Colorado Water Conservation Board (CWCB) with the exclusive authority to appropriate and acquire instream flow (ISF) and natural lake level water rights (NLL). ISF water rights are held by the CWCB on behalf of the people of the State of Colorado to "preserve the natural environment to a reasonable degree". These water rights are non-consumptive, in-channel or in-lake uses of water made exclusively by the CWCB for minimum flows between specific points on a stream or at specific levels in natural lakes. ISF and NLL rights are administered within the state's water right priority system to preserve or improve the natural environment.

Any entity can make a recommendation to the CWCB to appropriate ISF or NLL water rights including State and Federal agencies, local communities, cities, local environmental groups, water users, and other interested parties. Recommending entities document the natural environment, determine the amount of water necessary to protect the natural environment, and support their recommendations through the CWCB process. CWCB staff reviews all data submitted and conducts water availability assessments and outreach. The CWCB makes decisions on all ISF and NLL appropriations following the procedures in the ISF Rules.

R2Cross is one of the techniques used to determine ISF flow rates in order to develop an ISF recommendation. The R2Cross method is based on a hydraulic model and uses field data collected in a representative riffle (Espegren, 1996). Riffles are generally the shallowest locations in a stream and are the stream habitat type most sensitive to changes in hydraulic parameters with variations in discharge. The field data consists of streamflow measurements, surveys of channel geometry at a cross-section, and of the longitudinal slope of the water surface, and optional pebble counts to determine the grainsize distribution (please see the R2Cross Field Manual for more information).

The field data is used to model three hydraulic parameters: average depth, average velocity, and percent wetted perimeter. Maintaining these hydraulic parameters at adequate levels across riffle habitat types also will maintain aquatic habitat in pools and runs for most life stages of fish and aquatic macro-invertebrates (Nehring, 1979). The summer flow recommendation is based on meeting three of three hydraulic criteria. The winter flow recommendation is based on meeting two of three hydraulic criteria.

R2CROSS UPDATE

The purpose of this update is to provide a user-friendly, open-access interface for the CWCB, recommending entities, and stakeholders to use the R2Cross program. The updated R2Cross program is hosted in eRAMS, an open platform supporting development of geospatially-enabled web applications for sustainable management of land, water, and energy resources. eRAMS uses open source technologies to provide geospatial data analysis, presentation, processing, and visualization to build custom analytical tools that incorporate model and data services. The following program features are included in R2Cross on the eRAMS platform:

1) Standard data entry templates to import field data for the R2Cross model, discharge measurements, and pebble counts.

2) Dynamically generated figures and graphs illustrating cross-section information, R2Cross calculations, and habitat criteria selection.

3) A tool for calculating stream discharge using standard cross-section and velocity data.

4) A tool to calculate standard metrics for particle-size analysis using pebble count data.

6) Mapping capabilities to display data collection sites, National Hydrography Dataset streamlines, streamflow gages, water right structures and other relevant coverages.

7) Export tools for pdf reports and Excel files of model output.

USER'S GUIDE

R2CROSS ONLINE PROGRAM

The updated R2Cross program (https://r2cross.erams.com) is hosted in the eRAMS platform. The R2Cross program can be accessed without registering for an eRAMS account. The R2Cross program includes five components:

1. Getting Started - provides an overview of the purpose of R2Cross and brief instructions on each tool that is part of the program. It also provides blank templates and examples templates for each tool.
2. R2Cross Tool - used to compute stream flows that meet habitat criteria based on user-input field measurements.
3. Discharge Calculator - can be used separately to determine the discharge measured at a cross-section.
4. Particle Size Calculator - can be used separately to determine statistical distributions of sediment sizes based on size classifications.
5. Data layers and Mapping Tool - can be used to locate the cross-section and display information related to hydrography, stream gages, water right structures and other coverages.

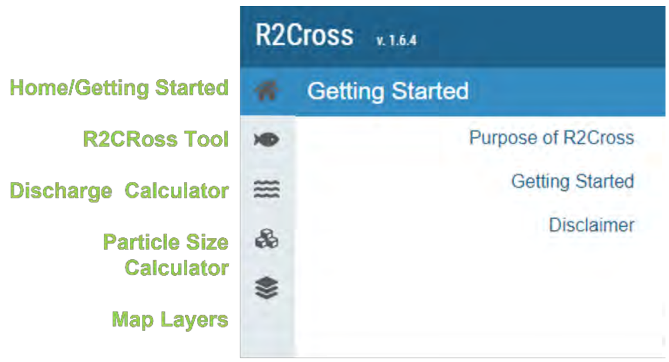


Figure 1. R2Cross program overview.

The following sections describe the user interface and details of each of these tools.

R2CROSS TOOL

With the R2Cross program interface open, click the R2Cross tool icon (R2Cross tool icon) on the left dashboard (Figure 2). Each step in the R2Cross tool is numbered to guide the user through the tool. The steps include 1) uploading the R2Cross data using a standard Excel file template; 2) running the model; and 3) downloading a report of the results in either a pdf or Excel format.

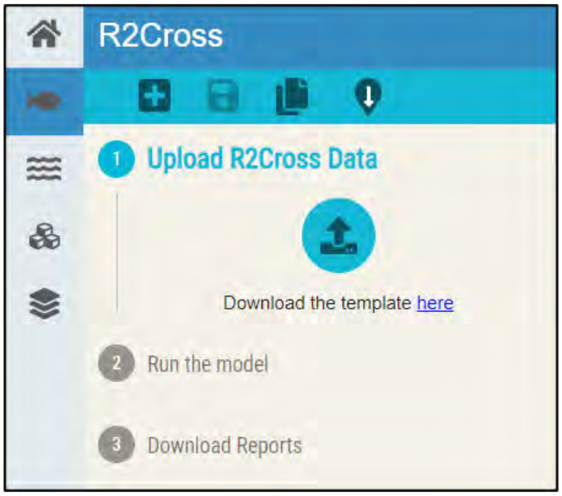


Figure 2. Accessing the R2Cross Tool

The main screen/window, to the right of the steps used to run the model, has two modes. Initially it shows a map centered on Colorado. When R2Cross data is uploaded, the window changes to display the cross-section data in the model view. The user can toggle between the map view and the model view by selecting the button.

R2Cross project files are saved as tokens or URLs on the eRAMS server using the toolbar icons located above the model steps. When R2Cross opens, a New Project is automatically created, the user does not need to create a New Project before uploading data. New Project will create a new project or token and clear any previously data and model runs. Save Project will save the uploaded data, model settings, and results. Copy Project Link can be used to make a copy of the URL in order to reopen the project later.

Upload R2Cross Data

With the R2Cross tool open, the user uploads the R2Cross Data file by clicking the icon (upload icon) on the left dashboard under Step 1 (Figure 2). The upload icon opens a file selection window to select the R2Cross data file for upload. If the data is not formatted correctly, the upload will not work and an error message will display at the top of the screen. A blank R2Cross data file is also available for download below the upload icon. R2Cross field data is entered into the data file using Microsoft Excel. All of the fields are mandatory and the file will not load properly unless they are filled. The blank R2Cross data file provides basic instructions for the user to enter their data in the appropriate format (Figure 3). An example R2Cross data file filled with data that is correctly formatted is included on the Home page under the Getting Started section.

COLORADO Department of Natural Resources				
			Observer	JB and JS
			Cross-section#	1
			Coordinate	UTM Zone 13
			X (easting)	501243
			Y (northing)	4398584
R2CROSS CROSS-SECTION NOTES				
Stream Name	Stream Location			Slope
Example Creek	Approx .5 mi upstream from bridge			0.011
Feature	Distance From Initial Point (ft)	Rod Height (ft)	Water Depth (ft)	Velocity (ft/s)
	0	1.68		
Bankfull	5.8	2.02		
	8	3.1		
	11	3.84		
	12.5	4.32		
Waterline	13.7	4.8	0	0
	16	5.05	0.25	0
	18	5.3	0.6	1.56
	20	5.6	0.9	0.85
	22	5.6	0.8	1.16
	24	5.9	1.1	1.04
	26	5.9	1.1	0.42
	28	5.45	0.65	2.42

Figure 3. R2Cross example data.

Once the R2Cross data has been uploaded, the cross-section will be processed and displayed (Figure 5). A new tab will be created at the top of the tool labeled "Cross-Section", which includes a table of survey data, a graphical representation of the cross-section, and descriptive information about the stream name, location, and other field data.

Mapping Display

After R2Cross data is uploaded, the location of the cross-section is displayed on the map using the icon (position icon). The user can modify the base layer in the R2CROSS interface by clicking the icon (map icon) on the right side of the dashboard and select the arrow buttons to toggle between available base layers (Figure 4). Options include: OpenStreetMap, OpenStreetMap Humanitarian, USGS Imagery, USGS Imagery Topo, USGS Hydro-NHD, USGS Shaded Relief, Bing Aerial, Bing Aerial/Labels, Bing Road, and None. Settings under map icon include changing the opacity, map scale, and aspects of the map toolbar. Additional mapping

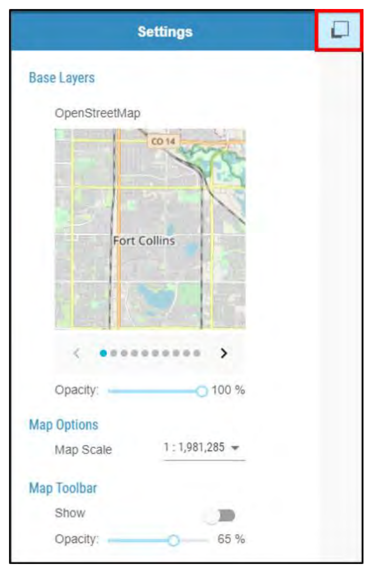


Figure 4. Map layers

features are available using the Data Layers tool (see Data Layers section).

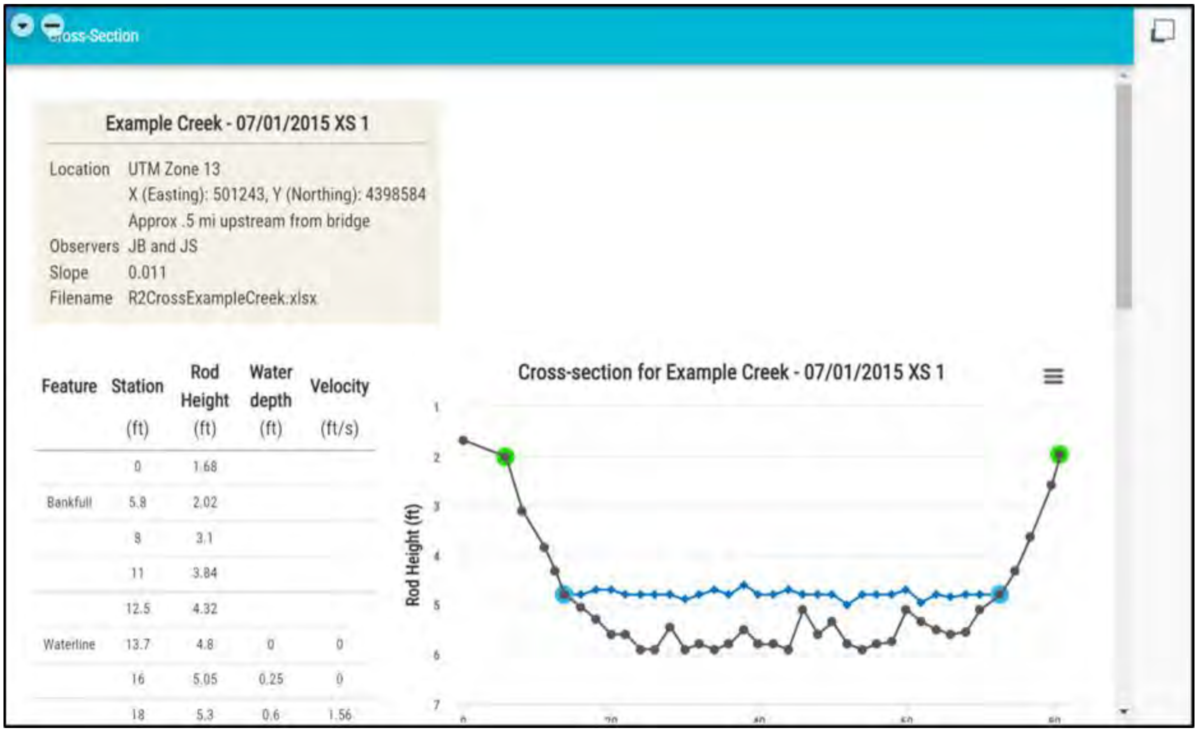


Figure 5. Cross-section tab showing example information.

Cross-section Graph

The graph of the uploaded cross-section is interactive; the user can hover over points on the graph to highlight them and display their X/Y coordinates and feature type. The user can also click and drag on the graph to zoom in on an area of interest. The ≡ icon (menu) in the top right corner of the graph provides options to download the graph as an image (png, jpeg, pdf, and svg formats) or as a spreadsheet of the data (csv and xls formats).

Carefully inspect the graph to make sure the data is reasonable. Once the user has reviewed the cross-section tab, click the NEXT button to move to the second step.

Run the Model

The R2Cross model uses Ferguson's Variable-Power Equation (VPE) to estimate hydraulic conditions (Ferguson 2007, 2021). The VPE is an empirical formula which accounts for the relative difference in channel roughness and water stage to estimate velocity or discharge. This equation is discussed in more detail in the Technical Guide at the end of this document.

Select Discharge Calculation Method

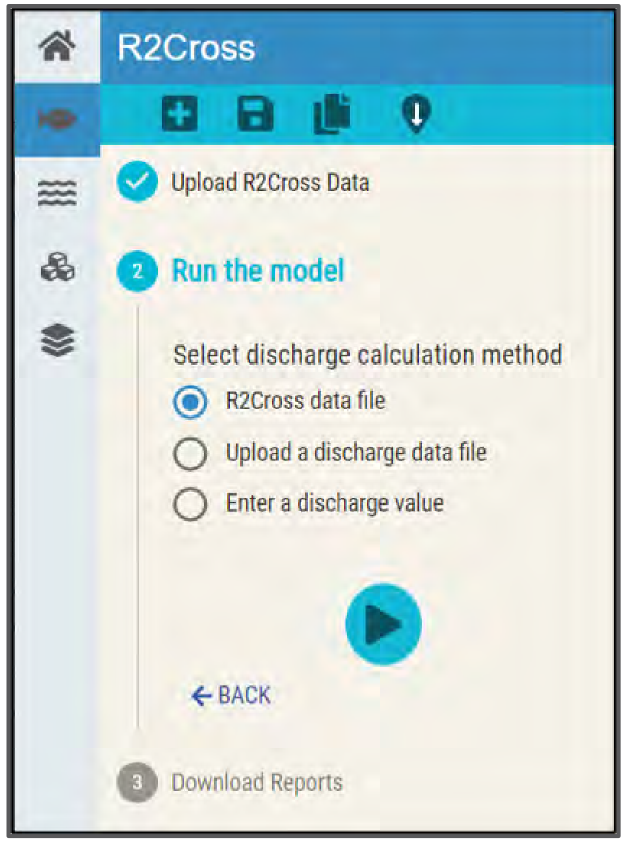


Figure 6. Running the R2Cross model.

Once the cross-sectional data has been uploaded, the user must select which discharge calculation method should be used in running the model (**Error! Reference source not found.**6). As a default, the model will calculate the discharge based on the velocity and depth data provided in the R2Cross Data file. However, measuring the discharge at a nearby location more suitable for a discharge measurement (such as a cross-section with more uniform velocity) may provide a more accurate measurement (See the R2Cross Field Manual for additional information). In this case, the user can choose to use a different discharge either by uploading a discharge data file measured in a nearby cross-section or by manually entering a discharge value (for example, a discharge value obtained from a nearby gage or FlowTracker). Selecting these options will result in R2Cross calculating an average velocity for the measured cross-section. R2Cross makes all calculations for staging table computations based on the total cross-section area and the total discharge. R2Cross does not use the cell-by-cell water velocity data in any of the staging table computations. A blank discharge data file with basic instructions is available to download when the “Upload a discharge data file” option has been selected. An example discharge file filled with data is included on the Home page under the Getting Started section. This file format is the same as the Discharge Calculator Tool file.

Model Output Tabs

Once the model inputs are specified, the model can be run by clicking on the  icon (run model icon). When the run is completed, a number of tabs are generated which are described below. Each tab should be carefully reviewed before looking at the final results.

R2Cross Summary Tab

The R2Cross Summary tab compares measured and model calculated values (Figure 7). Measured variables refer to the characteristics measured in the field at the time the cross-section data was collected. Calculated variables are determined by the model using Ferguson's VPE.

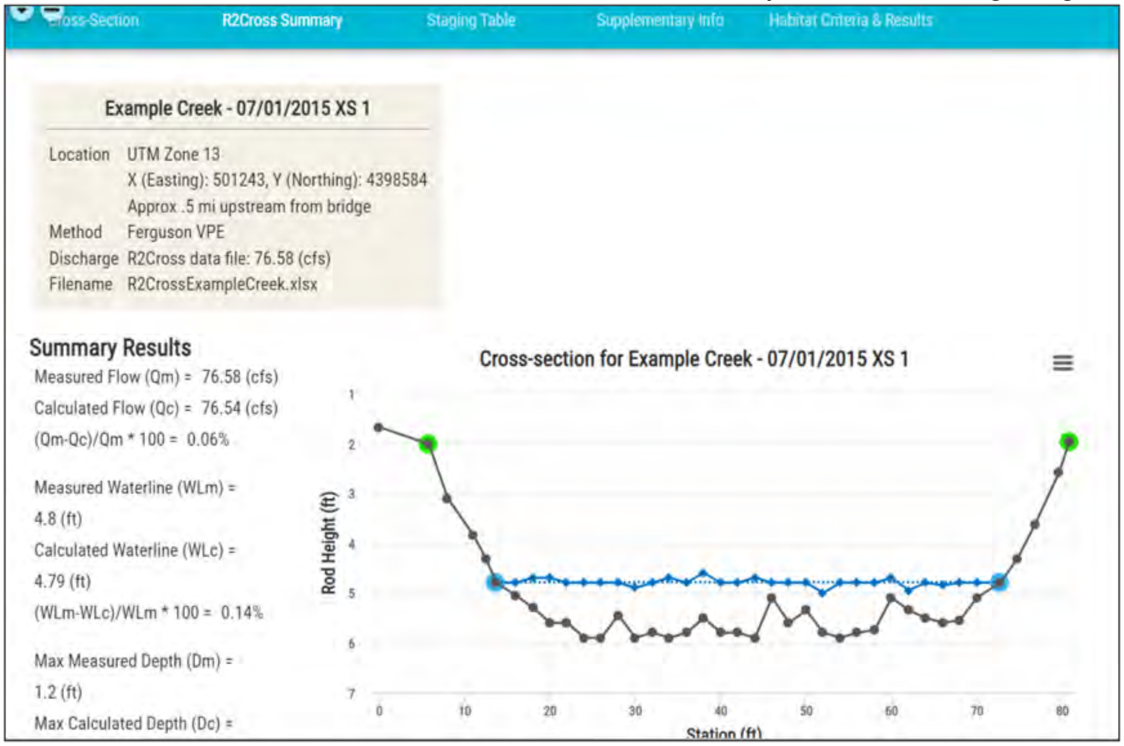


Figure 7. R2Cross Summary tab showing example information.

Table 1 provides an explanation of the variables given on the R2Cross Summary Tab.

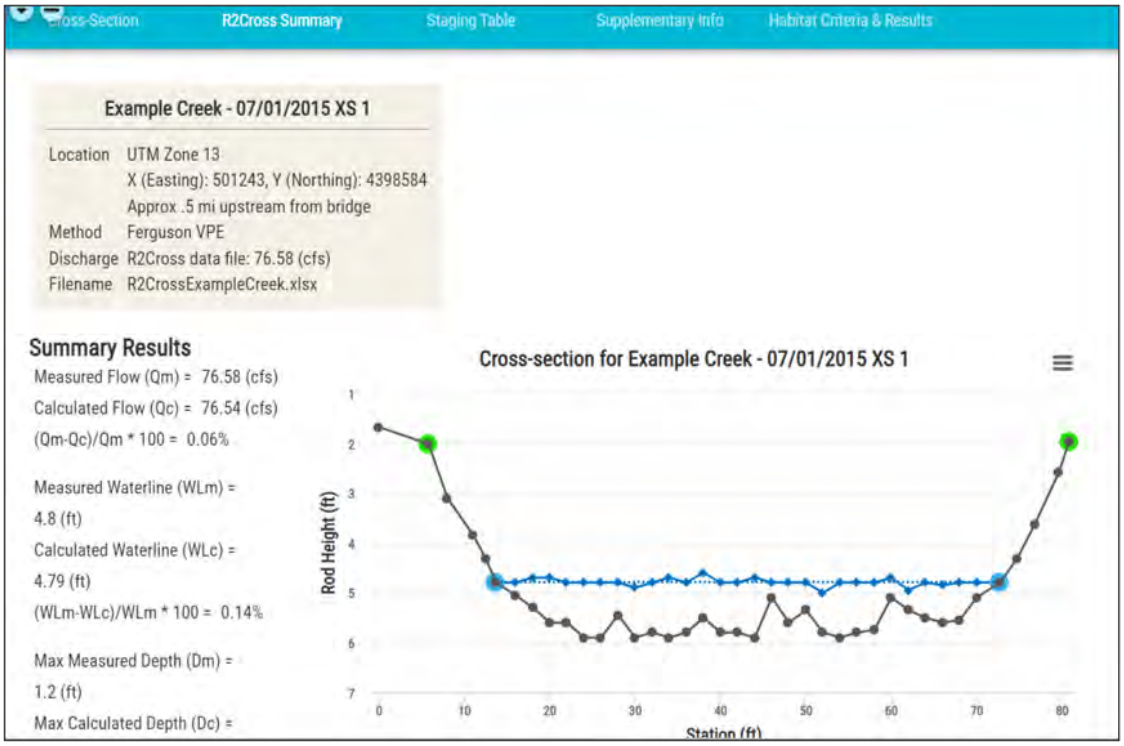


Figure 7. R2Cross Summary tab showing example information.

Table 1. Information presented in the Summary Results Tab

Hydraulic Variable	Description
Measured Flow (Qm)	Flow measured in the field using standard field methods
Calculated Flow (Qc)	Discharge calculated at the optimized waterline using the Ferguson VPE.
Measured Waterline (WLm)	The mean of the two waterline values indicated in the field
Calculated Waterline (WLc)	Model determined waterline based on minimizing the difference in area between the calculated and measured values
Max Measured Depth (Dm)	Maximum depth in the cross-section based on field measurements
Max Calculated Depth (Dc)	Calculated maximum depth based on the calculated waterline
Mean Velocity	Calculated as the total discharge divided by the total flow area using data collected from field measurements
Slope	The field measured slope used by the model

The differences in the measured and calculated flows, waterlines, and depths is provided as a check of the model run. The height of the water surface at each point is determined by adding the bed elevation and the measured depth. This may result in small variations in the measured waterline at each point. These variations could have multiple causes (e.g. surface waves, small differences in the surveyed bed and the measured depth location, etc.). In order to determine a single stage for the calculated waterline, the model determines the waterline elevation that minimizes the difference between the cross-sectional area based on depth measurements and the cross-sectional area based on bed measurements. There may be a slight difference in the discharge and maximum flow depth calculated using the measured and single waterlines, which are shown in the R2Cross Summary Tab. Large differences in the measured and modeled values should be examined closely to determine if there was a survey error or typo in the input file.

Staging Table Tab

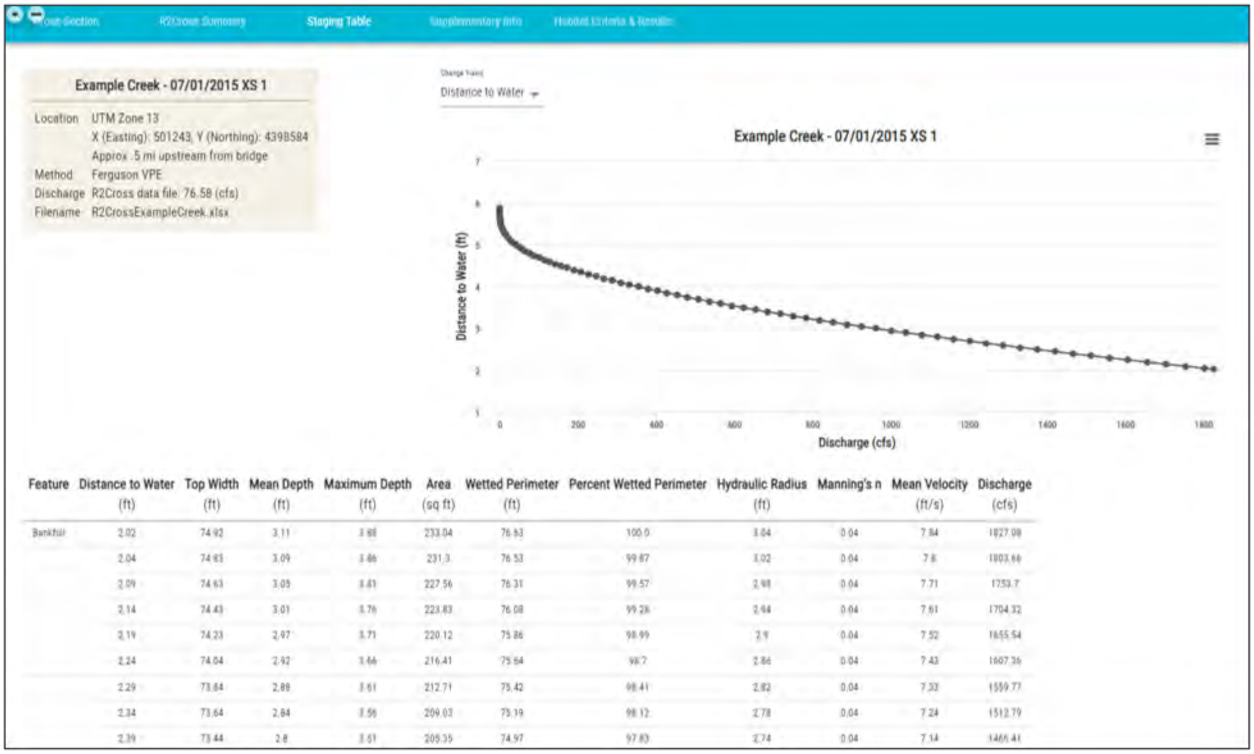


Figure 8. R2Cross Staging Table tab showing example information

The Staging Table tab includes a table of hydraulic variables for incremental stream stages (**Error! Reference source not found.**8). The hydraulic variables are calculated based on channel geometry and the roughness equation (Ferguson's VPE) for each stage between zero flow and bankfull. The staging table includes the following columns:

- Feature: Identifies the stage attributed to either the bankfull elevation or waterline elevation
- Distance to Water (ft): the measured or calculated distance from the survey instrument to the water surface. The Distance to Water is displayed in 0.05 foot increments above or below the waterline stage.
- Top Width (ft): calculated top width of flow in the channel based on the surveyed cross-section geometry
- Mean Depth (ft): calculated as the average depth of flow by dividing the total flow area by the top width at each stage
- Maximum Depth (ft): calculated as the maximum depth of flow based on the surveyed cross-section geometry
- Area (sq. ft): calculated as the total flow area based on the surveyed cross-section geometry
- Wetted Perimeter (ft): calculated as the total wetted perimeter of flow based on the surveyed cross-section geometry
- Percent Wetted Perimeter: calculated by dividing the wetted perimeter at that stage by the bankfull wetted perimeter

- Hydraulic Radius (ft): calculated as the area divided by the wetted perimeter
- Mean Velocity (ft/s): calculated based on Ferguson's VPE
- Discharge (cfs): calculated as the product of mean velocity and area

In addition to the staging table, a dynamic graph is also included in the Staging Table tab. The graph allows the user to plot various rating curves by changing the variable represented on the y-axis. The y-axis options include any of the columns shown in the staging table.

NOTE: Any cross-sections that have measured topography below the elevation of the measured waterline, but beyond the surveyed edge of water, may have non-uniform changes in the roughness for stages near the measured water surface. In this situation, the user will need to carefully review the results.

Supplementary Info

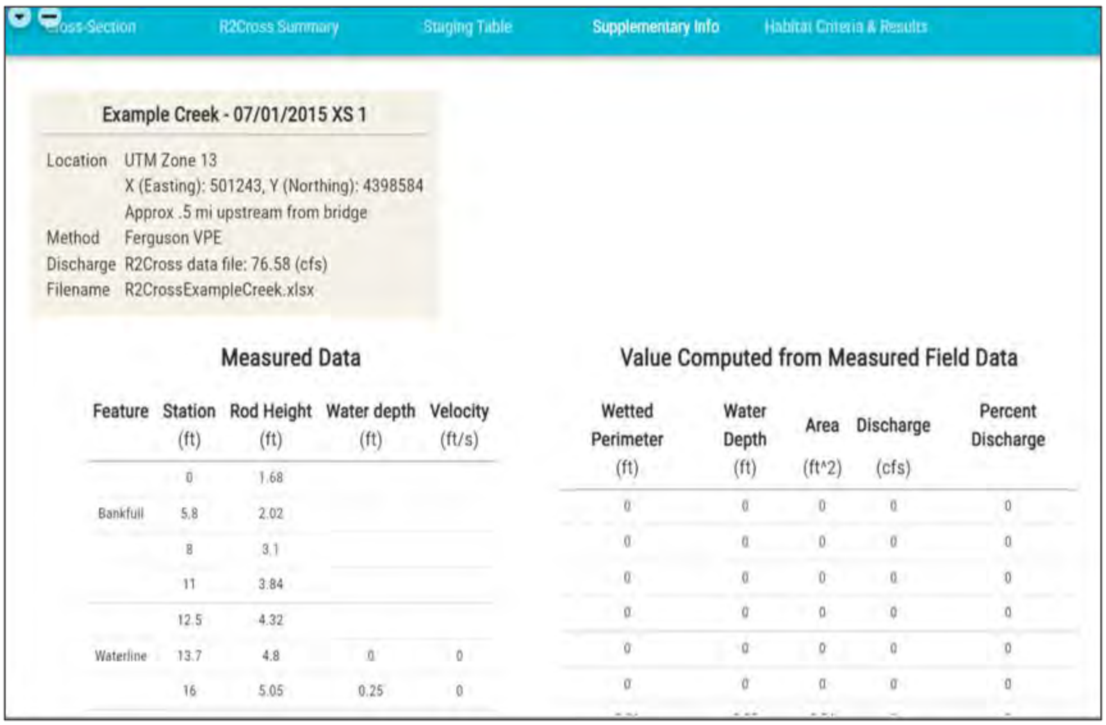


Figure 9. Supplementary Results tab showing example information.

The Supplementary Info tab (**Error! Reference source not found.**9) contains two tables that display: 1) measured data collected in the field; feature, station (called distance from the initial point in the input file), rod height, water depth, and velocity, and 2) accompanying hydraulic variables calculated using the field surveyed data (wetted perimeter, water depth, flow area, discharge, percent of total discharge). Summaries of hydraulic variables are shown at the bottom of the table.

Habitat Criteria & Results Tab

The Habitat Criteria & Results tab contains a summary table of results and three dynamic graphs that show the relationship between hydraulic criteria and discharge (Figure 9).

The R2Cross method is based on maintaining three principle hydraulic criteria related to average depth, average velocity and percent wetted perimeter, as established in Nehring, 1979 (

Table 2). Nehring determined that maintaining these parameters in a riffle cross-section indicates flow-related stream habitat quality that generally supports a cold-water fishery (see the R2Cross Field Manual for additional information).

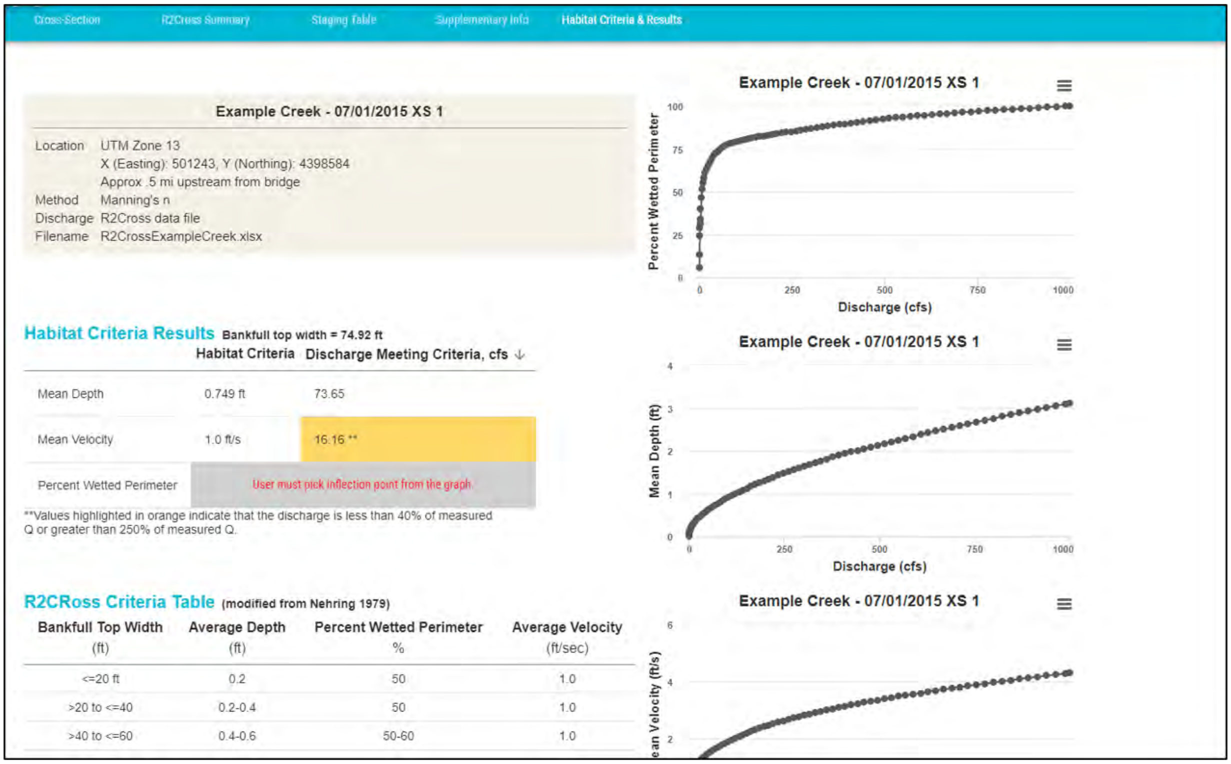


Figure 10. Habitat Criteria & Results tab showing example information.

Table 2: Criteria used to determine minimum flow requirements (modified from Nehring, 1979)

Bankfull Top Width[1] (ft)	Average Depth (ft)	Percent Wetted Perimeter (%)	Average Velocity (ft/sec)
≤20	0.2	50	1.0
>20 to ≤40	0.2-0.4	50	1.0
>40 to ≤60	0.4-0.6	50-60	1.0
>60 to ≤100	0.6-1.0	≥70[2]	1.0

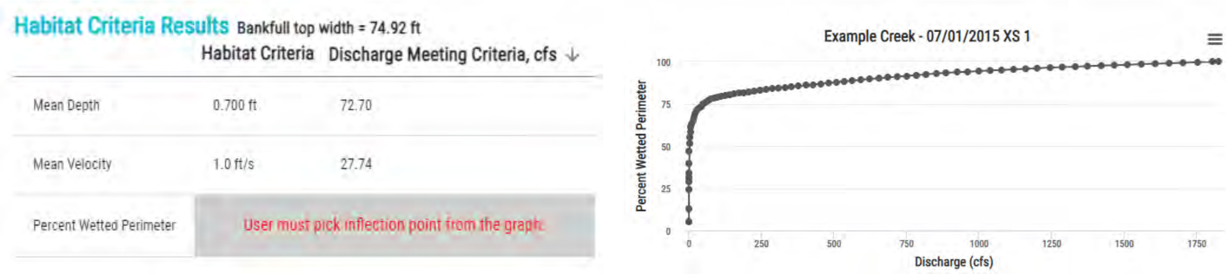
The Habitat Criteria Results table displays the appropriate hydraulic criteria based on the cross-sections' bankfull width. The R2Cross program calculates these criteria by smoothly interpolating between the criteria shown in Table 2. The lowest discharge that meets the hydraulic criteria is displayed and is automatically calculated by linearly interpolating the results shown in the staging table.

When the bankfull top width is greater than 60 feet, the appropriate percent wetted perimeter criteria must be determined by the user. This is done by evaluating the inflection point in the percent wetted perimeter-discharge curve, which typically occurs at or above a 70% wetted perimeter. Generally, wetted perimeter increases rapidly with small increases in discharge until water reaches the sides of the channel at which point only small changes in wetted perimeter occur with large changes in discharge. If more than one inflection point is present, the inflection point that corresponds to the flow that fully wets the bottom of the channel should be selected. In larger streams and rivers, that area of the channel is important for production of macroinvertebrates in the riffle, maintains important riffle habitat used for spawning and rearing of young fish, and corresponds with overhead vegetative cover (Leathe and Nelson, 1986). Selection of the wetted perimeter criteria when bankfull top width is greater than 60 feet should be based on professional judgment relative to the needs of the fish present in the specific stream or river.

If the bankfull top width is greater than 60 feet, the R2Cross program will display a message in the Habitat Criteria Results Tab to notify the user. To select the appropriate percent wetted perimeter for channels wider than 60 feet, the user clicks on the inflection point from the dynamic percent wetted perimeter-discharge graph (

[1] When the bankfull top width is greater than 100 feet, please contact staff at CWCB and CPW for more information.

[2] User should select an inflection point on the wetted perimeter-discharge curve that corresponds with a flow that fully wets the bottom of the riffle. The inflection point can occur at a value greater than 70%. Beyond this inflection point, the water starts to move up the sides of the active channel and the slope of the wetted perimeter-discharge curve begins to decline.



Figure, located at the top right). The user can click and drag on the graph to zoom in to the area of interest, and then select the inflection point on the curve where the rate of change (or slope) between discharge and wetted perimeter decreases noticeably. Once the user selects the inflection point from the graph, that value will automatically be populated into the Habitat Criteria Results table and the discharge meeting that value will be calculated.

The R2Cross program will provide a warning message at the top of the screen if a specific habitat criteria is not met at any point in the stage table. In this situation, the user will need to evaluate the cause and may need to discuss options with CWCB or CPW staff.

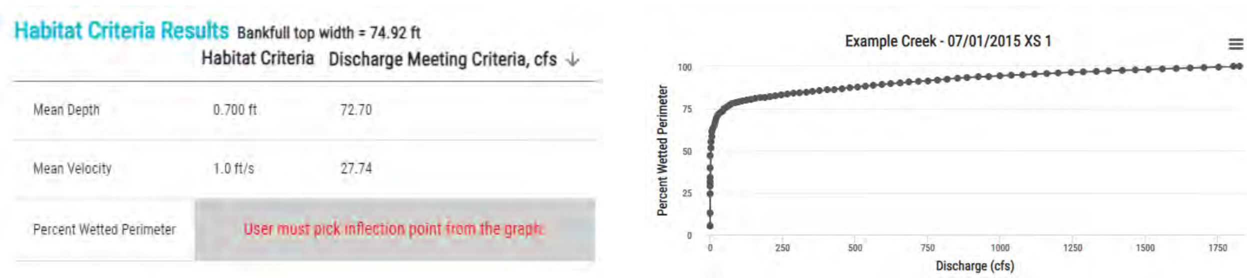


Figure 11. Example showing when bankfull top width is greater than 60 feet, requiring the user to select an appropriate percent wetted perimeter from the figure.

Download Reports

After running the model and reviewing the results, click the next button to move to step 3. The final step of the tool allows users to download information contained in all the result tabs into a pdf report format or as Excel tables (**Error! Reference source not found.**). Please note that all model outputs displayed in the web interface have been rounded to three or less significant digits. However, data contained in the exported Excel tables is not truncated so that the user can verify any of the input data or calculations. It is also advisable to copy the URL which contains a unique token so the model run can easily be reopened.

Use of R2Cross Results

Please see the R2Cross Field Manual for more information about using R2Cross results to determine ISF flow rates. The CWCB website also contains additional information on developing recommendations, guidelines for recommendation letters, and Board processes.

Figure 12. Downloading results in PDF or Excel format.

DISCHARGE CALCULATOR

The Discharge Calculator is a separate tool that allows the user to calculate discharge at a cross-section that is different than the cross-section surveyed for the R2Cross tool. Running the discharge calculator is not a required step in the R2Cross tool, it is provided as a simple means to accurately calculate discharge. The results from the discharge calculator can be used as a substitute discharge in the R2Cross tool in the Select a Discharge Calculation Method step of the R2Cross Tool or can be used completely independent of the R2Cross tool.

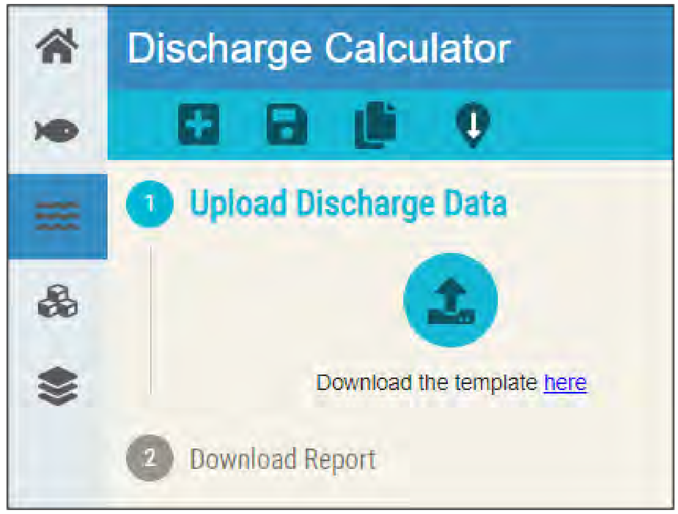


Figure 13. Discharge calculator.

To begin using the Discharge Calculator, click the icon (Discharge Calculator icon) on the left dashboard (**Error! Reference source not found.**).

Upload Discharge Data

With the Discharge Calculator interface open, the user can click the icon (upload icon) on the left dashboard. The upload icon will open a file selection window to select the Discharge Data file for upload. If the data is not formatted correctly, the upload will not work and an error message will display at the top of the screen. The option to download a blank Discharge Data file (Figure) is also provided. This file contains basic instructions for the user to enter data in the appropriate format using Excel. An example discharge file filled with data is included on the Home page under the Getting Started section.

Once discharge data has been uploaded, the cross-section will be processed, and two tables will be displayed to the user. One table contains the field measured data (feature, station, water depth, velocity), and a second table displays the calculated hydraulic variables (flow area, discharge, and percent discharge) at each vertical. The total calculated discharge (Q) is displayed in the yellow box in the top left corner.

COLORADO Department of Natural Resources		
	Date	7/1/2015
	Observer	JB and JS
	Cross Section #	1
	Coordinate	UTM Zone 13
	X (easting)	501243
	Y (northing)	4398584

FIELD MEASUREMENTS FOR DISCHARGE CALCULATOR

Stream Name	Stream Location
Example Creek	~0.5 miles upstream from bridge

Feature	Station (ft)	Water Depth (ft)	Velocity (ft/s)
	0	0	
	2.2	0.32	0
	5.2	0.7	0.94
	8.2	1.2	2.39
	11.2	1.1	3.1
	14.2	0.7	4.07
	17.2	1.05	4.35
	20.2	1.1	4
	23.2	1.15	1.9
	26.2	0.8	3.57
	29.2	0.8	3.04
	32.2	1	2.68
	35.2	0.55	3.77
	38.2	0.8	4.19
	41.2	0.75	2.02
	44.2	0.7	3.44
	47.2	1	3.42
	50.2	1.25	3.11
	53.2	1.1	1.16
	56.2	1.15	1.21
	59.2	1.1	0.42
	62.2	0	

Figure 14. Discharge Calculator example data.

Download Report

Similar to the R2Cross tool, the user can export a report as an Excel file or pdf file showing the results of the Discharge Calculator.

PARTICLE SIZE CALCULATOR

The Particle Size Calculator allows the users to calculate sediment size distributions using pebble count information collected in the field. To begin using the Particle Size Calculator, click the icon (Particle Size Calculator icon) on the left dashboard (**Error! Reference source not found.**).

Upload Sediment Data

With the Particle Size Calculator interface open, the user can click the icon (upload icon) on the left dashboard to open a file selection window and select the Pebble Count Data file for upload. If the data is not formatted correctly, the upload will not work and an error message will display at the top of the screen. The option to download a blank Pebble Count data template (**Error! Reference source not found.**), which includes basic instruction for the user to enter their data in the appropriate format, is also provided. An example particle size file filled with data is included on the Home page under the Getting Started section.

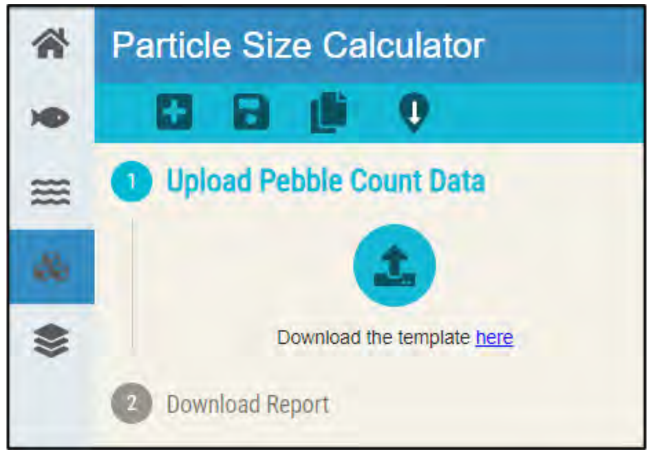


Figure 15. Particle size calculator.

Once particle size data has been uploaded, the information will be processed and displayed to the user (**Error! Reference source not found.**). Results from the particle size calculations include a cumulative yield curve and sediment size histogram as well as summary table by particle size type (i.e. sand and silts, fine gravel, etc.). Summary metrics of the sediment distribution is located at the top of the page, including percent finer sizes (D50, D84), geometric mean, standard deviation, and gradation coefficient.

COLORADO Department of Natural Resources	
Date	7/1/2015
Observer	JB and JS
Coordinate	UTM Zone 13
X (easting)	501243
Y (northing)	4398584

PEBBLE COUNT OBSERVATIONS

Stream Name	Stream Location	Cross-Section No.
Example Creek	~0.5 upstream	1

Description of Particle Size	Size (mm)	Count
Sand and Silts	<2	54
Very Fine Gravel	2 - 4	6
Fine Gravel	4 - 5.7	16
Fine Gravel	5.7 - 8	14
Medium Gravel	8 - 11.3	13
Medium Gravel	11.3 - 16	15
Coarse Gravel	16 - 22.6	21
Coarse Gravel	22.6 - 32	50
Very Course Gravel	32 - 45	57
Very Course Gravel	45 - 64	90
Small Cobble	64 - 90	71
Small Cobble	90 - 128	62
Large Cobble	128 - 180	29
Large Cobble	180 - 256	7
Small Boulder	256 - 362	8
Small Boulder	362 - 512	0
Medium Boulder	512 - 1024	0
Large Boulder	1024 - 2048	0
Very Large Boulder	2048 - 4096	0
Bedrock	>4096	0

Figure 16. Particle Size Calculator example data.

Download Report

Similar to the R2Cross tool, the user can export a report as an Excel file showing the results of the Particle Size Calculator.

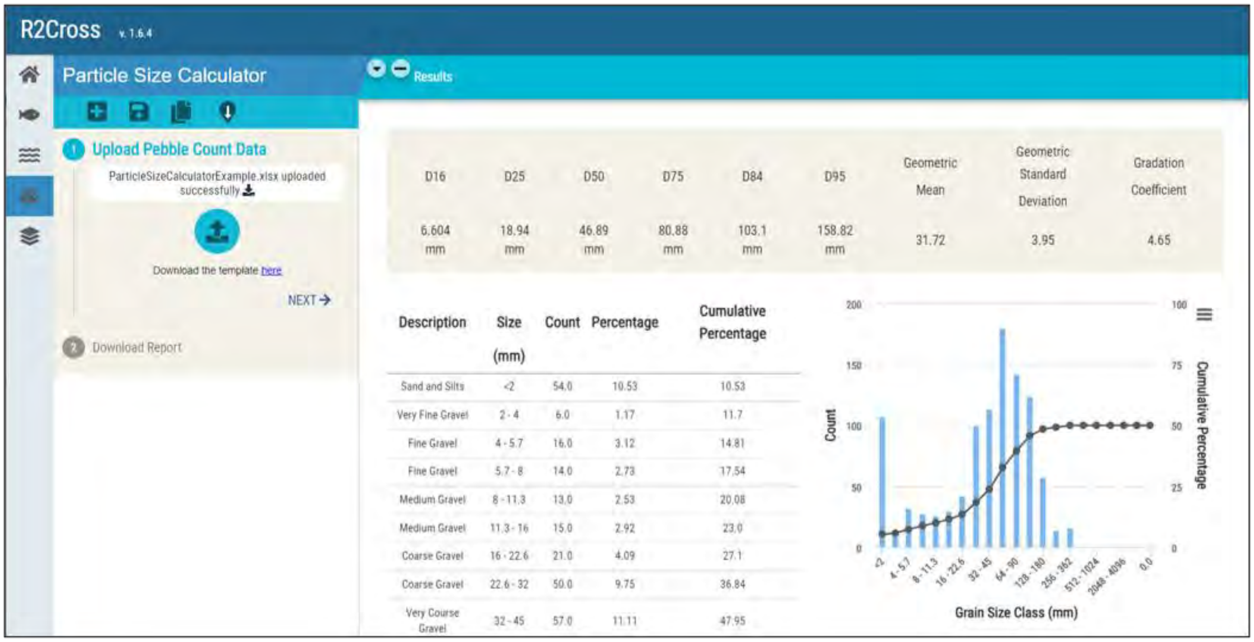


Figure 17. Particle Size Calculator results summary.

DATA LAYERS AND MAPPING

The Data Layers feature allows the users to add additional geospatial information to the map. To access this additional geospatial information, click the icon (Data Layers icon) on the left dashboard. This will open the map and provide the user a list of data sources (Figure). Some of these options are not available at high spatial scales and will be greyed out. To enable these layers, zoom in closer on the map. Multiple data layers can be displayed simultaneously.

Figure 18. Data layer options

Flowlines

Checking the "Flowlines" option will display NHD+ Flowline data for the current map extent. A legend for this map will be included on the left-hand side of the interface and is collapsible with the arrow icon shown in Figure Figure . Each of the data types in this data set have their own legend as shown in Figure Figure .

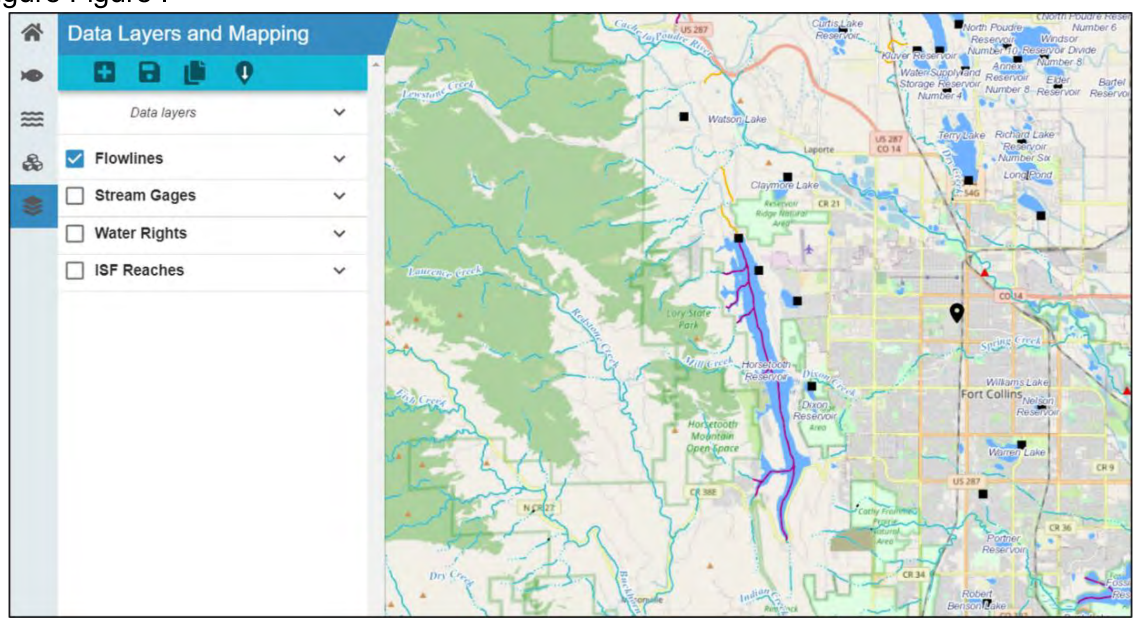


Figure 19. Flowlines Map

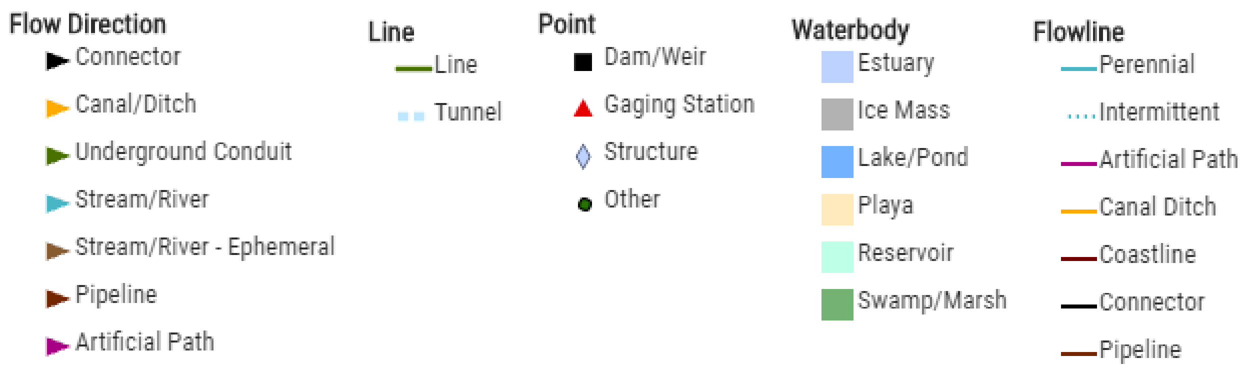


Figure 20. Legend options for NHD+ data

Stream Gages

The Stream Gage option displays stream discharge monitoring locations from USGS National Water Information System (NWIS) and the Colorado Division of Water Resources (CDWR). Checking this data layer will show all of the stream/river and ditch gages locations for the current map extent (Figure 20.). Currently operating gages and discontinued historical gages are shown with differing symbols.

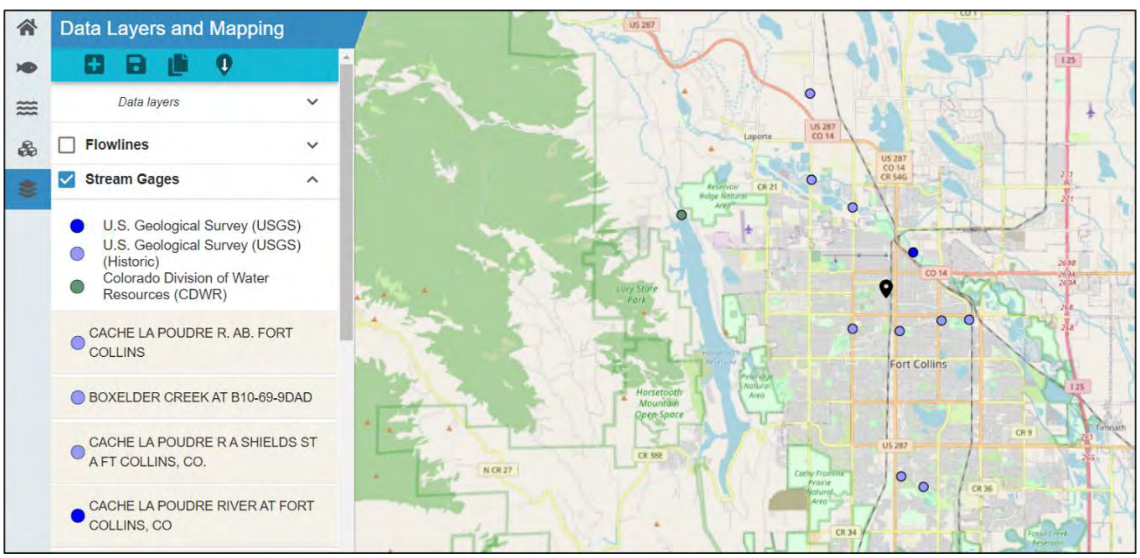


Figure 21. Stream Gage layer

Clicking any of the gaging locations (on the list on the left or on the map) will display a summary of the available streamflow data. A graph of streamflow data is also displayed, and the user can zoom in by selecting a box and zoom out by resetting the extent. A link to the webpage from the data source (USGS/DWR) is also included.

Water Rights

Water Rights data from the Colorado Decision Support System's Hydrobase database is available for summary in the R2CROSS analysis tool. Checking this data layer will show all the diversion structures in the current extent on the map (Figure 21).

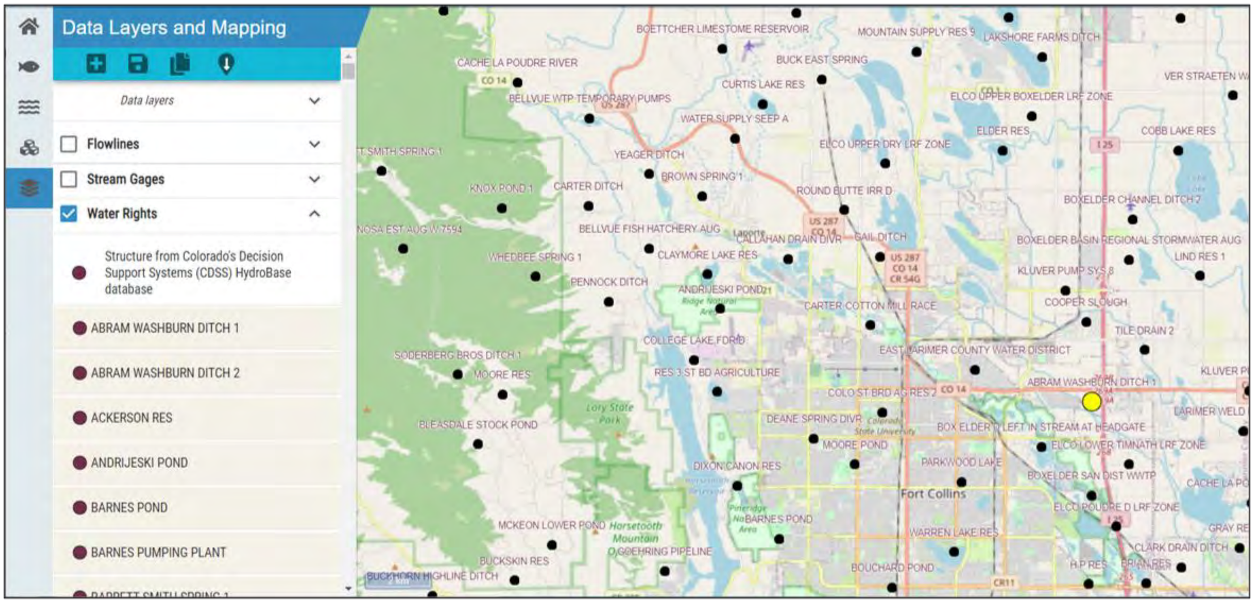


Figure 22. Water rights layer.

Clicking on any of the diversions (on the list on the left or on the map in **Error! Reference source not found.** a summary of the water rights for that location will be displayed, as shown in **Error! Reference source not found.**. This includes information on adjudication and appropriation dates of the water rights associated with these structures as well as their decreed uses, absolute and conditional volumes. A link to the Structure Summary on the Division of Water Resources page is also included for each water right.

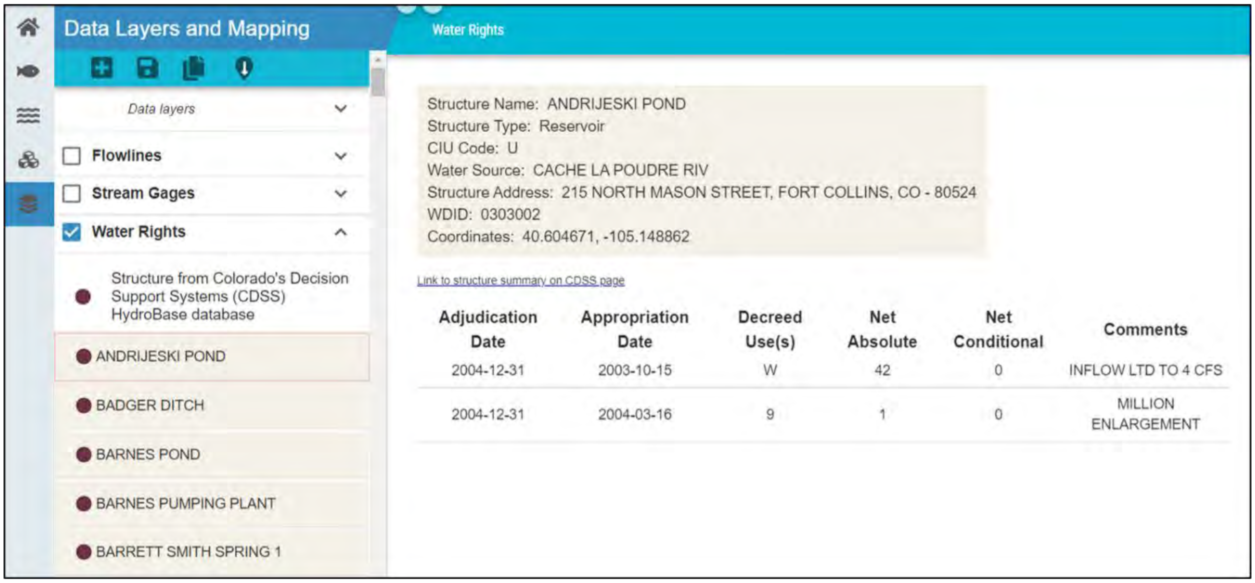


Figure 23. Hydrobase water rights summary.

ISF Reaches

The CWCB maintains a dataset of the instream flow reaches in Colorado. Selecting this data layer will display them on the map, as shown in Figure .

Clicking on any of the ISF water rights on the list in the left panel produces a summary of the water rights for that location (Figure 23). The line segments include information about the type of appropriation, status, case number and segment length. The type of appropriation can be "appropriated" meaning a new appropriation was made or recommended on the segment, "increase" meaning that an increase was recommended or made in addition to an original ISF right on the segment, or "acquired" meaning that the reach was acquired through the ISF acquisition program. The Status field indicates what stage of process the ISF right is in including decreed, recommended (but not decreed), or pending in water court.

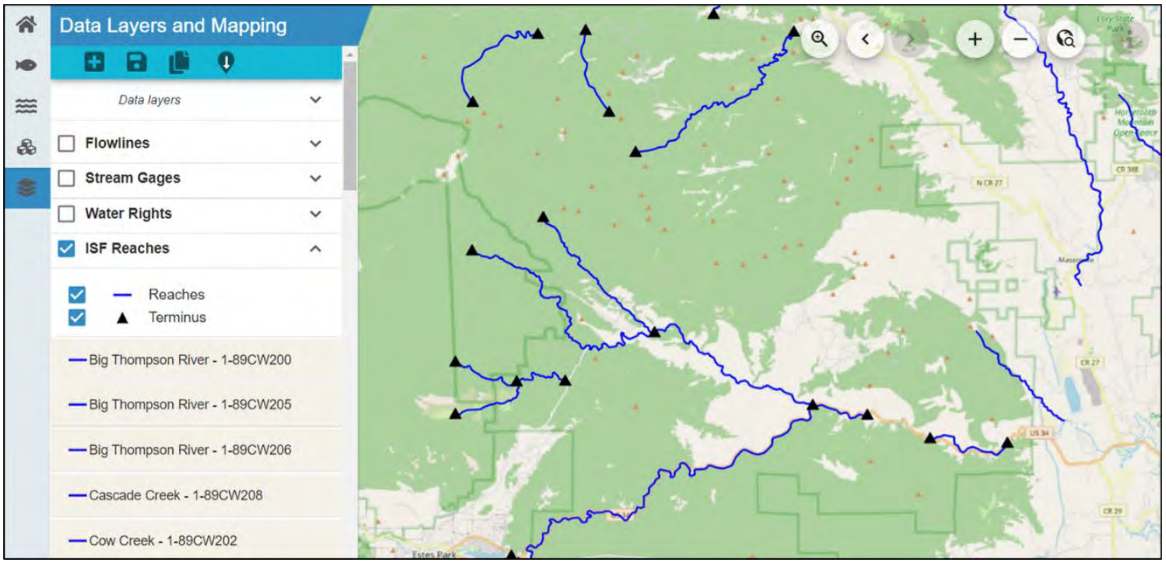


Figure 24. CWCB map of instream flow rights

TECHNICAL GUIDE

INTRODUCTION

The R2Cross program uses stream discharge and channel cross-section information, which is collected in the field, to estimate hydraulic conditions in the channel at different flow depths. The hydraulic conditions, such as depth, velocity, and percent wetted perimeter, are compared to habitat criteria to determine biological instream flow recommendations.

Numerous equations have been developed to predict instream hydraulic conditions based on channel geometry and roughness (e.g., Chow 1959). The most common empirical formula is the Manning equation, which assumes a constant channel roughness and uniform flow conditions. However, additional formulas have been developed to account for changes in overall channel roughness (represented by a flow resistance coefficient) as a function of flow depth, such as Ferguson's Variable-Power Equation (VPE) (Ferguson 2007, 2021). Ferguson's VPE equation relates the flow resistance coefficient to the ratio of flow depth and channel bed sediment size (this ratio is commonly referred to as relative submergence). The R2Cross tool uses the VPE equation, which is described in more detail below, to estimate roughness and hydraulic conditions at a cross-section.

FERGUSON'S VARIABLE-POWER EQUATION (VPE)

Ferguson (2007) proposed a variable-power equation that is asymptotic to the Manning-Strickler equation and the roughness-layer relationship as relative submergence becomes very small or very large, respectively. The main assumption under the variable-power equation suggested by Ferguson is that these two extreme relationships for deep flow and shallow flow are additive for a general coarse-bed stream. Unlike the Manning equation, Ferguson's equation adjusts the hydraulic roughness as the relative submergence changes in the channel. Originally, Ferguson's equation was fitted based on 376 cross-sections with slopes, D_{84}, and relative submergence (R/D_{84}) spanning between 0.00007-0.21, 0.05-0.8, and 0.1-26, respectively (Ferguson 2007). This method is reported to outperform other flow resistance equation based on 2,890 cross-sections (Rickenmann and Recking, 2011). However, as with any hydraulic roughness equation, the Ferguson equation may overestimate or underestimate the channel roughness depending on channel conditions.

Recently, Ferguson demonstrated that at cross-sections where single discharge and stage measurements are collected, a single calibrated effective roughness height (k) can be used to estimate hydraulic conditions at different stages (Ferguson, 2021). This calibrated effective roughness height does not require the user to assume or measure a D_{84} sediment size. Thus, the VPE equation used to calculate channel velocity at a given stage is given by:

$$U = u_* \frac{a_1 a_2 (R/k)}{[a_1^2 + a_2^2 (R/k)^{5/3}]^{1/2}}$$

where, $U =$ is the average channel velocity

$u_* = (gRS)^{1/2}$ is the shear velocity, g is the gravitational acceleration, R is the hydraulic radius, S is the reach-average slope

a_1, a_2 = Empirical coefficients 6.5 and 2.5 respectively

R = Hydraulic radius (ft)

k = effective roughness height (ft)

An equivalent Manning's *n* is calculated based on results from Ferguson's VPE equation and shown in the R2Cross Staging Table. This is done for all water stages, including the stage associated with the calculated waterline. The Manning's *n* equation is given by:

$$U = \frac{1.486}{n} R^{2/3} S^{1/2}$$

where, U = average velocity in the cross section (ft/s)

n = Manning's roughness coefficient

R = hydraulic radius (ft)

S = channel slope (ft/ft)

PARTICLE SIZE CALCULATOR

The R2Cross program calculates sediment size distributions according to the size classes presented in Table 3. Following the methodology of Bunte and Abt (2001), the *D*84 is calculated using the equation below. A generalized form of this equation can be used to calculate any size percentile, *Dn*, by replacing *D*84 with any percentile *n*.

$$D_{84} = 10\hat{}\left\{[log\,(D_{>84}) - \,log\,(D_{<84})] * \left(\frac{84 - CPF_{<84}}{CPF_{<84} - CPF_{>84}}\right) + log\,(D_{<84})\right\}$$

where, D_{84} = 84th percentile of a particle-size distribution (mm)

$D_{>84}$ = The particle class that is larger than the 84th percentile (mm)

$D_{<84}$ = The particle class size that is smaller than the 84th percentile (mm)

$CPF_{>84}$ = Cumulative percent finer that is larger than 84

$CPF_{<84}$ = Cumulative percent finer that is smaller than 84

Table 3: Example of sediment classification based on size (mm) and the corresponding number of particles for each size class.

Description of Particle Size	**Size (mm)**	**Count** (Frequency)	**Percent**	**Cumulative Percent Finer**
Sand and Silts	<2	54	10.53	10.53
Very Fine Gravel	2 - 4	6	1.17	11.70
Fine Gravel	4 - 6	16	3.12	14.81
Fine Gravel	6 - 8	14	2.73	17.54
Medium Gravel	8 - 11	13	2.53	20.08
Medium Gravel	11 - 16	15	2.92	23.00
Coarse Gravel	16 - 22	21	4.09	27.10
Coarse Gravel	22 - 32	50	9.75	36.84
Very Course Gravel	32 - 45	57	11.11	47.95
Very Course Gravel	45 - 64	90	17.54	65.50
Small Cobble	64 - 90	71	13.84	79.34
Small Cobble	90 - 128	62	12.09	91.42
Large Cobble	128 - 180	29	5.65	97.08
Large Cobble	180 - 256	7	1.36	98.44
Small Boulder	256 - 362	8	1.56	100.00
Small Boulder	362 - 512	0	0.00	100.00
Medium Boulder	512 - 1024	0	0.00	100.00
Large Boulder	1024 - 2048	0	0.00	100.00
Very Large Boulder	2048 - 4096	0	0.00	100.00
Bedrock	>4096	0	0.00	100.00

Using the example data shown in Table 3, D_{84} is calculated as follows:

$$D_{84} = 10\hat{}\left\{[\log(128) - \log(90)] * \left(\frac{84 - 79.34}{91.42 - 79.34}\right) + \log(90)\right\} = 103.10\ mm$$

DISCHARGE CALCULATOR

The discharge calculator uses the U.S. Geological Survey method described by Buchanan and Somers (1969) to calculate the total discharge at a cross section. The total discharge is calculated using the following equation:

$$Q = \sum (av)$$

where a is the individual partial cross-section area collected in the field and v is the corresponding mean velocity of the flow normal to the partial area.

REFERENCES

Bovee, K.D. and Milhous, R., 1978, Hydraulic simulation in instream flow studies: theory and techniques. Instream Flow Information Paper No. 5. Washington, DC: U.S. Fish and Wildlife Service (FWS/OBS-78/33). 143 pp.

Bunte, K. and Abt, S.R., 2001, Sampling Surface and Subsurface Particle-Size Distributions in Wadable Gravel- and Cobble-Bed Streams for Analyses in Sediment Transport, Hydraulics, and Streambed Monitoring (No. General Technical Report RMRS-GTR-74). United States Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Chow, V.T., 1959, Open-channel hydraulics, McGraw-Hill civil engineering series. McGraw-Hill, New York.

Espegren, G.D., 1996, Development of instream flow recommendations in Colorado using R2CROSS. Colorado Water Conservation Board, Department of Natural Resources, Water Rights Investigations Section.

Ferguson, R.I., 2007. Flow resistance equations for gravel- and boulder-bed streams. Water Resources Research 43. https://doi.org/10.1029/2006WR005422

Ferguson, R.I., 2021. Roughness Calibration to Improve Flow Predictions in Coarse-Bed Streams. Water Res 57. https://doi.org/10.1029/2021WR029979

Leathe, S.A. and Nelson, F.A., 1986, A literature evaluation of Montana's wetted perimeter inflection point method for deriving instream flow recommendations. Montana Department of Fish, Wildlife, and Parks, Helena, Montana, 76 p.

Nehring, R.B., 1979, Evaluation of instream flow methods and determination of water quantity needs for streams in the State of Colorado. Colorado Division of Wildlife, Fort Collins, Colorado.

Turnipseed, D.P., and Sauer, V.B., 2010, Discharge measurements at gaging stations: U.S. Geological Survey Techniques and Methods book 3, chap. A8, 87p. http://pubs.usgs.gov/tm/tm3-a8/

Yen, B.C. (Ed.), 1992. Channel flow resistance: centennial of Manning's formula. Water Resources Publications, Littleton, Colorado.