R2Cross

Field Guide, User's Manual & Technical Guide

Prepared by

Colorado State University

Department of Civil and Environmental Engineering

&

One Water Solutions Institute

CIVIL AND ENVIRONMENTAL ENGINEERING
COLORADO STATE UNIVERSITY

ONE WATER SOLUTIONS INSTITUTE

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Contributors

Ryan R Morrison, Civil & Environmental Engineering, Colorado State University, Fort Collins, CO 80523-1372

Panagiotis D. Oikonomou, Colorado Water Institute, Colorado State University, Fort Collins, CO 80523-1033

Rumpal Sidhu, One Water Solutions Institute, Colorado State University, Fort Collins, CO 80523-1372

Tyler Wible, One Water Solutions Institute, Colorado State University, Fort Collins, CO 80523-1372

Prepared by
Department of Civil and Environmental Engineering
& One Water Solutions Institute
Colorado State University
Fort Collins, CO 80523-1372

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EXECUTIVE SUMMARY

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). 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 levels in natural lakes. These rights are administered within the state's water right priority system to preserve or improve the natural environment. Each year, recommendations for instream flow water rights are brought to the CWCB during the ISF Workshop by state and federal agencies, conservation groups and members of the public. R2Cross is one of the techniques used to develop instream flow recommendations.

This manual provides a user's guide and technical details of the latest version of R2Cross, which can be accessed at https://r2cross.erams.com. The updated R2Cross program is hosted in the eRAMS platform, an open platform supporting development of geospatially-enabled web applications for sustainable management of land, water, and energy resources. By using the eRAMS platform the following program functions have been included in R2Cross: 1) Standard 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 grainsize 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; and 7) Export tools for pdf reports and Excel files of model output.

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). 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 levels in natural lakes. These rights are administered within the state's water right priority system to preserve or improve the natural environment. Each year, recommendations for instream flow water rights are brought to the CWCB during the ISF Workshop by state and federal agencies, conservation groups and members of the public.

R2Cross is one of the techniques used to develop instream flow recommendations. The R2Cross method is based on a hydraulic model and uses field data collected in a stream riffle (Espegren, 1996). Riffles are most easily visualized as the stream habitat types that would dry up first should streamflow cease. The field data collected consists of streamflow measurements, surveys of channel geometry at a transect, and of the longitudinal slope of the water surface, and pebble counts to determine the grainsize distribution.

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 3 of 3 hydraulic criteria. The winter flow recommendation is based on meeting 2 of 3 hydraulic criteria.

In the early years of the Program, instream flow recommendations consisted of only single year-round flow amounts. These single year-round flow amounts were based on meeting two of the three critical hydraulic criteria identified by Nehring (1979). Initial flow recommendations were not adjusted due to water availability limitations, but Senate Bill 414 (SB 414) passed in 1981 requires an evaluation of the existing physical water supply for all future instream flow appropriations. In the mid 1980's, to incorporate these new changes into the program and address other concerns being raised regarding the R2Cross model, state biologists modified the original instream flow methodology of recommending single year round flows and began developing "seasonal flow recommendations" which would incorporate all 3 of the identified critical criteria into the flow recommendations.

Seasonal flow recommendations are an attempt to mimic the natural flow regime, albeit, on a simplistic and smaller scale. Colorado Parks and Wildlife (CPW) recommends meeting all 3 of the hydraulic criteria during the spring, summer, and fall, and meeting two of the three hydraulic criteria during the winter, typically during base flows. CPW believes the development of these seasonal flow recommendations better addresses the range of hydrologic and hydraulic conditions required for the habitat and its associated aquatic community. Research has shown that single year-round minimum flows, when maintained as a long-term condition, cannot be expected to sustain the same fish populations or aquatic life as a natural flow regime, where low flow conditions occur infrequently and for shorter periods (Stalnaker and Wick, 2000). Higher flows assist in maintaining the adjacent riparian zone and provide habitat protection for different life stages of the aquatic community. Higher flows also provide water quality protection from other outside factors such as effluent discharges, high metal concentrations, excess sedimentation and water temperature increases. Aquatic biologists may modify seasonal flow recommendations based upon biological considerations such as stream conditions, species composition, and aquatic habitat quality.

R2CROSS UPDATE

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

1) Standard 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 grainsize 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.

DOCUMENT STRUCTURE

This document is comprised of three sections. The first section (the Field Guide) describes recommended field procedures for collecting stream geometry and hydraulic data necessary for using the R2Cross program. The second section (the User's Guide) describes the components, capabilities, inputs and outputs of the R2Cross program. This section is intended to help users navigate the eRAMS tools. The third section (the Technical Guide) describes the underlying equations used in the R2Cross program, including the hydraulic equations, sediment distribution equations, and other relevant technical details.

FIELD GUIDE

The R2Cross method is a “Standard Setting” hydraulic based instream flow assessment technique. R2Cross instream flow recommendations are typically based on hydraulic and biological data collected during single or multiple field visits. Hydraulic data collection consists of setting up a transect, surveying stream channel geometry, water surface elevations, and measuring stream discharge. Biological data is gathered to document the existence of a natural environment. For proper data collection and field work techniques, refer to the R2Cross Field Methods Manual and Procedural Document.

FIELD DATA SITE SELECTION

The R2Cross method requires that stream discharge and channel profile data be collected in a riffle stream habitat-type. A riffle is a stream segment that is controlled by channel geometry rather than a downstream flow control. Riffles are most easily visualized as the stream reaches which would dry up most quickly should streamflow cease.

Biologically, riffles are essential to the production of benthic invertebrates and the passage, spawning, egg incubation, feeding, and protective cover of fish. Riffles are also the stream habitat type most sensitive to changes in hydraulic parameters with variation in discharge (Nehring 1979). Riffles are critical to a healthy aquatic environment because small reductions in streamflow may result in large reductions in water depth and the amount of wetted perimeter available for aquatic habitat. Maintaining adequate streamflow in riffles also preserves the natural environment in other important stream habitat-types such as pools and runs (Nehring 1979).

Each transect should represent the average stream width, depth, and cross-sectional area within the riffle being characterized. Transects should be located in areas that exhibit natural banks or grasslines and concentrated water flow, free from braiding. They should not be located on eroded or undercut streambanks.

HYDRAULIC DATA COLLECTION

Stream discharge is measured using standardized procedures established by the United States Geological Survey (USGS) (Buchanan and Somers 1969). Channel geometry should be measured using a land survey level and stadia rod (Benson and Dalrymple 1967).

The standard survey methodology consists of suspending a tape from bank to bank across the stream channel, perpendicular to the streamflow. Cross section stakes are driven into the ground above the grassline. The tape is suspended by attaching the zero-end of the tape to one of the stakes, stretching the tape across the stream, and then attaching the other end to a tape clamp fastened to the stake on the opposite streambank. The suspended tape is then used to measure the horizontal location of each cell vertical. The survey level and stadia rod are used to measure channel geometry and water depth. Simultaneously, a discharge measurement is collected

BIOLOGICAL DATA COLLECTION

Before the CWCB appropriates an ISF water right, an investigation of a natural environment is conducted. A natural environment is often indicated by the presence of a water dependent natural resource value, including but not limited to fish, macro invertebrates, riparian vegetation, or any mixture thereof. In most cases, instream flow appropriations have been based on the existence of a fishery or fish population. CPW prefers the use of existing fishery information, if it exists in CPW's database. This avoids additional sampling by electofishing, which can be somewhat stressful for fish. The fish sample is not tied directly to the R2Cross hydraulic modeling but may be used to refine the biologic instream flow recommendation to meet the specific habitat requirements of unique populations.

Other biological data typically consists of aquatic invertebrate sampling or riparian vegetation surveys.

THE FIELD FORM

The standardized field form should be used to record all field data and can be found in the R2Cross Field Methods Manual and Procedural Document. Using this form helps to ensure that all instream flow recommendations are based upon a uniform set of field data. The front page of the form provides space for cross section Stream Information, Location Information, Supplemental Data, Channel Profile Data, and Natural Environment Notes The back page is dedicated to R2Cross Cross-Section Data.

The Stream Information Section is used to record the stream name, date the cross-section was taken, and the names of the members of the field crew. The Cross-Section No. can be used as a nomenclature for when multiple cross-sections are taken on one stream.

The Location Information section of the field form is used to describe the location of the cross section. Geographic information can be obtained from USGS maps, United States Forest Service (USFS) maps, or handheld GPS Units. Water divisions can be obtained from the State Engineers' Office, the CWCB, or CPW.

The Supplemental Data section is used to provide supporting documentation of the field data collection effort.

The Channel Profile Data section of the form is used to establish the relationship between the cross section and the stream. Stadia rod readings are taken at each end of the suspended tape and at the water surface on the right and left streambanks. These readings are recorded within the Rod Reading (ft) column. They are used to assure that the ends of the tape are level. Water surface readings and horizontal distances are also recorded upstream and downstream of the suspended tape. These observations are used to establish the water surface slope for input into Manning's equation.

The right side of the Channel Profile Data section is used to graphically depict the relative locations of the suspended tape and survey level, the direction of streamflow, and any photographic documentation of the field data collection effort. Photographs of the suspended tape are taken looking up, down, and across the stream.

Biological observations are summarized in the Natural Environment Notes portion of the field form. Biological observations typically consist of an aquatic species and riparian vegetation. Any other observations made at the sight, such as valley type, geology, or water diversions, can be made in under the Other category.

The R2Cross Cross-Section Data portion of the field form is used to record all of the velocity measurements associated with the R2Cross Cross-section. A heading is provided to record the stream name, cross section number, date, time at the beginning of the measurement, time at the end of the measurement, staff gage reading at the beginning of the measurement, and staff gage reading at the end of the measurement. The table below the heading is used to record Features, Distance From Initial Point, Rod Reading, Water Depth, and Velocity. All discharge measurement procedures are as outlined by Buchanan and Somers (1969).

The first and last channel geometry measurements are always taken at the cross-section stakes. Channel geometry measurements should also be taken at the bankfull and waterline intersections and at all distinguishable slope breaks between these two intersection points. The horizontal locations of the bankfull and waterline intersections are also documented by placing a "BF" and a "WL" in the appropriate row of the Features column of the field form. Bankfull is identified at the normal high waterline, not flood stage, and is generally located above sedges, willows, and other plants that may survive submerged under high flows. The Feature column is also used to document the horizontal locations of the two cross section stakes ("S") and any rocks ("R") or other features that may have an impact on the discharge measurement.

USER'S GUIDE

R2CROSS ONLINE PROGRAM

The updated R2Cross program (https://r2cross.erams.com) is hosted in the eRAMS platform, an open platform supporting development of geospatially-enabled web applications for sustainable management of land, water, and energy resources. eRAMS harnesses open source technologies to provide geospatial data analysis, presentation, processing, and visualization to build custom analytical tools that incorporate model and data services. The R2Cross program can be accessed without registering an eRAMS account.

The R2Cross program includes five components:

1. The Getting Started page gives brief instructions on how to use each tool. It also provides blank templates and examples templates for each tool.
2. The main R2Cross Tool that can be used to determine instream flows based on field measurements input by the user.
3. A stand-alone Discharge Calculator that can be used to determine the discharge measured at a cross-section other than the one used in R2Cross.
4. A stand-alone Particle Size Calculator that can be used to determine statistical distributions of sediment sizes based on size classifications.
5. Data layers and mapping tools to locate the cross-section and display information related to hydrography, stream gages, water right structures and other coverages.

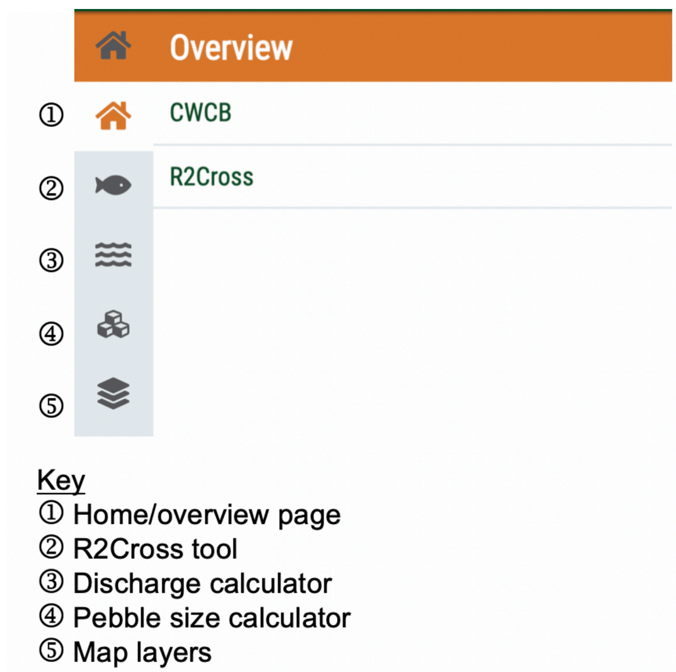

Figure 1. R2Cross program overview.

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

R2CROSS TOOL

With the R2Cross program interface open, click the 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 generally include 1) uploading the R2Cross data using a standard Excel file template; 2) running the tool using a specified equation to account for channel roughness; and 3) downloading a report of the results in either a pdf or Excel format.

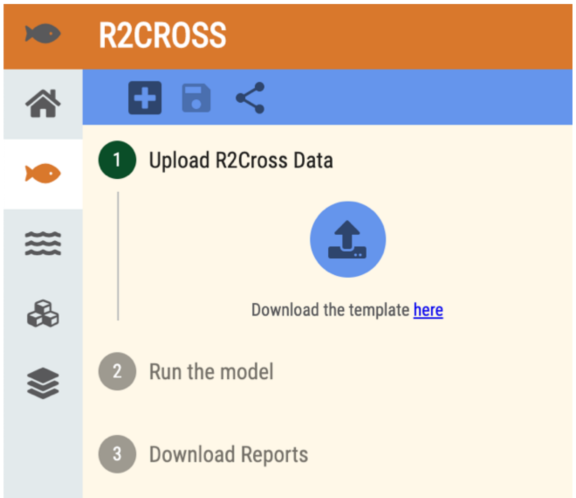

Figure 2. Accessing the R2Cross Tool

The main screen/window to the right of the steps used to run the model has two modes. Initially it shows a map of the primary rivers in Colorado. When R2Cross data is uploaded, the display changes to show information about the cross-section data. The mapping display can be viewed again by selecting the button which allows the user to toggle between mapping view and the model view. After R2Cross data is uploaded, the location of the data collection 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 "Back" or "Next" to toggle between available base layers. Options include: Open Street Map, USGS Imagery, USGS Imagery Topo, USGS Hydro-NHD, USGS Shaded Relief, and None. Additional mapping features are available using the Data Layers tool (see Data Layers section).

Upload R2Cross Data

With the R2Cross interface open, the user uploads the R2cross Data file by clicking the icon (upload icon) on the left dashboard. The upload icon opens a file selection window to select the R2Cross data file for upload. The upload will not work if the data is not correctly formatted. This will be indicated by an error message displayed at the top of the screen. A blank template file is also available for download. The blank R2Cross template provides basic instructions for the user to enter their data in the appropriate format (Figure 3). An example R2Cross filled with data is included on the Home page under the Getting Started Section.

COLORADO
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Date	
Observer	
Cross-section#	
Coordinate System	UTM Zone 13
X (easting)	
Y (northing)	

R2CROSS CROSS-SECTION NOTES				
Stream Name	Stream Location			Slope
Feature	Distance From Initial Point (ft)	Vertical Distance (ft)	Water Depth (ft)	Velocity (ft/s)

Figure 3. Blank template used to upload field date into R2Cross tool.

Once the R2cross data has been uploaded, the cross-section will be processed and displayed to the user (Figure 4). 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.

CROSS-SECTION

Stream Name: Marvine Creek abv W Marvine Ck
Stream Location: At Marvine Ranch/USFS Boundary
Cross-section Number: 1
Coordinate System: Lat Long
X (easting): -107.441584
Y (northing): 40.019821
Date: 06/28/2017
Observer: BLM
Slope: 0.0208

Feature	Station (ft)	Vertical Depth (ft)	Water depth (ft)	Velocity (ft/s)
	0	3.1		
	1	4.05		
Bankfull	2.2	4.9		
	3.5	5.5		
Waterline	4	6.01	0	0
	4	6.15	0.15	0
	5.5	6.3	0.3	1.09
	7	6.8	0.95	3.05
	8.5	6.9	1	3.03
	10	7	1.2	3.12
	11.5	6.95	0.95	4.06
	13	6.8	0.9	2.4
	14.5	6.95	0.9	3.85
	16	6.95	0.95	1.9
	17.5	7	0.95	1.9
	19	6.75	0.65	0.16

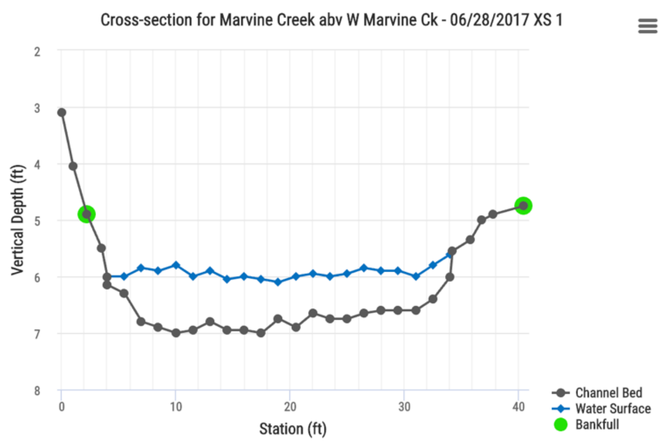

Figure 4. Cross-section tab showing information collected from the field data input form.

Cross-section Graph

The graph of the uploaded cross-section is interactive and available for download. Hovering over points on the graph will highlight them and display their X/Y coordinates and feature type. 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).

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 can be run using 2 different methods for calculating channel roughness (Figure 5). The default method is based on the variable-power resistance equation developed by Ferguson (2007; 2013) (hereafter the "Ferguson equation"), which considers depth-adjusted roughness in the channel. The Ferguson equation requires the user to input a D84 sediment size based on field conditions. The Ferguson equation is the preferred approach;

however, if D84 sediment size is not collected in the field, the user can use the Manning's equation to run the model. Each of these equations are discussed in more detail in the Technical Guide.

When using the Ferguson equation, the user needs to provide information regarding the D84 sediment size. The model provides two options for adding sediment size information. First, the user can upload pebble count data using the downloadable template, which is the same template used for the Pebble Size Calculator. After the pebble count data is uploaded, the program will calculate the D84 sediment size required for the Ferguson equation. The second option for providing a D84 sediment size is to manually enter a size value based on prior sediment size calculations. To enter a pre-determine D84 sediment size, the user needs to select the "User Supplied D84" option from the dropdown selection and enter the sediment size in units of millimeters.

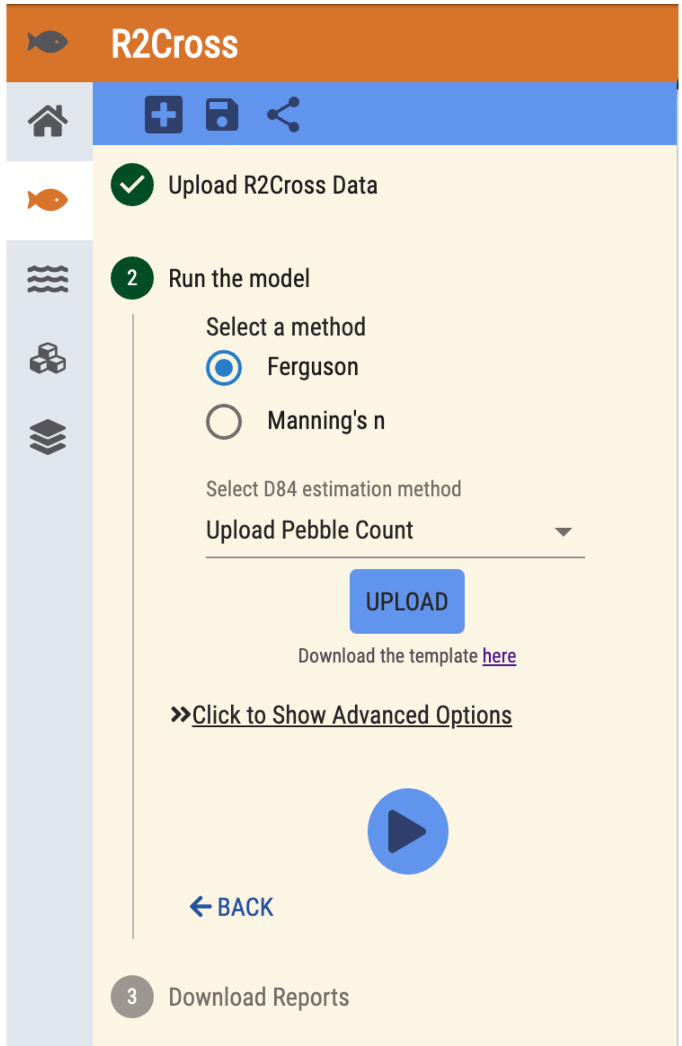

Figure 5. Options available to run the R2Cross model.

Advanced Options

As a default, the model will calculate the discharge based on the data provided in the R2Cross Data template. This is the most typical way to run the R2Cross model. However, in some circumstances it may be desirable to use a discharge measurement from another nearby location. In this case, the user can choose to use a different discharge either by uploading a discharge data file or by manually entering a discharge value under the Advanced Options menu. A blank discharge data template 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). Once completed, the following result tabs will be generated.

Staging Table Tab

The Staging Table tab includes a table of hydraulic variables for incremental stream stages (Figure 7). The hydraulic variables are calculated based on channel geometry and the roughness equation selected previously 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 collected in the field
- 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 ft 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 total flow area divided by the wetter perimeter
- Discharge (cfs): calculated as the product of mean velocity (see below) and flow area
- Mean Velocity (ft/s): calculated using the roughness determined from the user-selected hydraulic roughness equation
- Ferguson-n (only available if using the Ferguson roughness equation): the equivalent Manning's n roughness coefficient calculated using the Ferguson equation

In addition to the staging table, a dynamic figure is also included in the Staging Table tab (Figure 7). The figure 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.

R2Cross Summary Tab

The R2Cross Summary tab compares measured and model calculated values (Figure 6). Measured variables refer to the characteristics measured in the field at the time the cross-section data was collected. Calculated variables are calculated by the model using the chosen equation. Table 1 provides an explanation of the variables given on the R2Cross Summary Tab.

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 chosen equation
Measured Waterline (WLm)	The mean of the two waterline values indicated in the field
Calculated Waterline (WLc)	Model chosen 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

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 be caused by a number of reasons (e.g. surface waves, small differences in the surveyed bed and the measured depth location, etc.). Due to these potential differences, the model determines the waterline by finding the water level that minimizes the differences between the cross-sectional area based on the depth measurements and the cross-section area based on the bed measurements. There may be a slight differences 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.

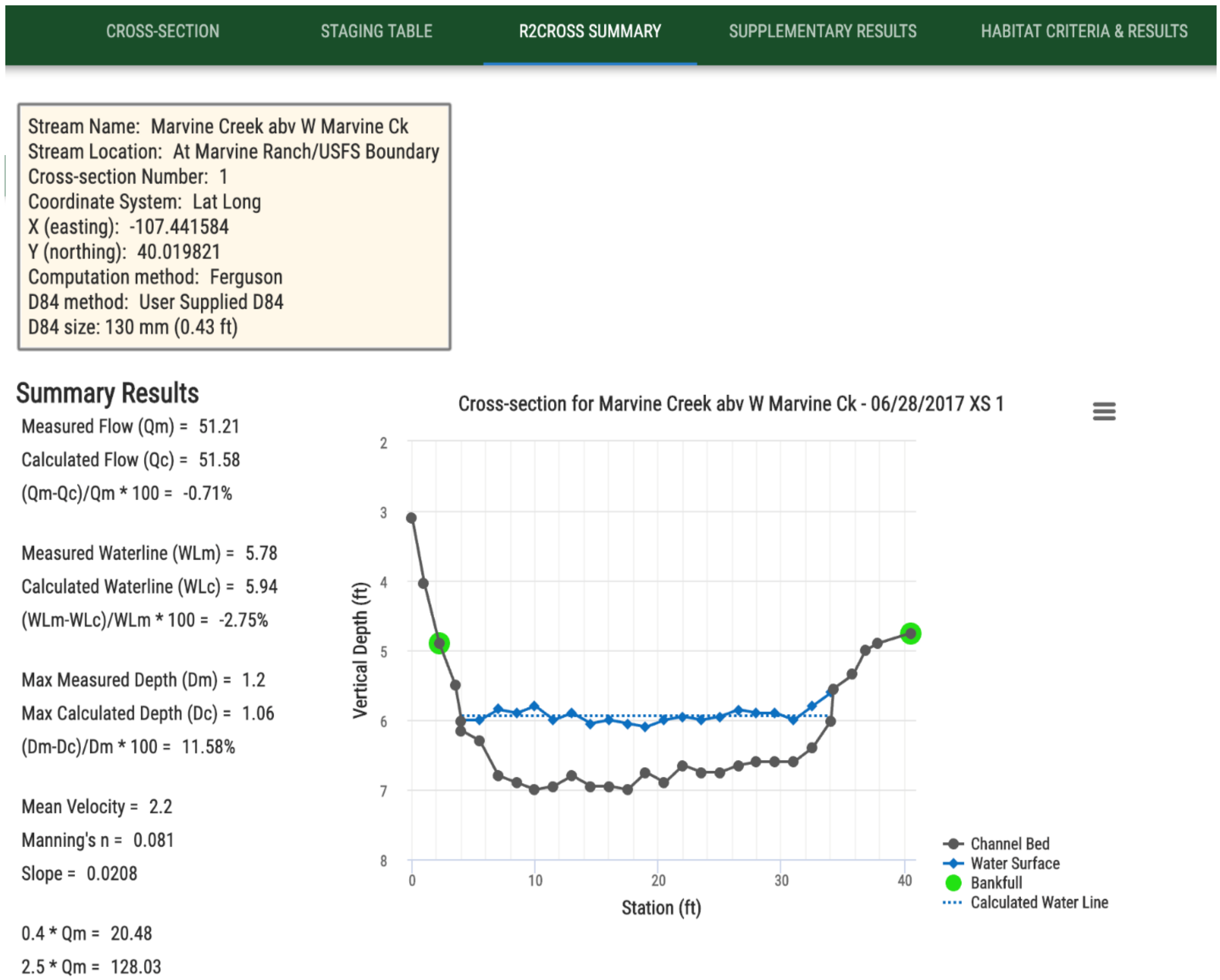

Figure 6. Example of information displayed in the R2Cross Summary tab.

If Manning's equation is the selected method, this tab will also include the limiting discharges of the Manning's equation (40% and 250% of the observed discharge). These indicate the lower and the upper thresholds for using the Manning equation.

Supplementary Results

The Supplementary Results tab (Figure 8) contains two tables that display: (1) measured data collected in the field (feature, station, vertical depth, 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.

CROSS-SECTION | STAGING TABLE | R2CROSS SUMMARY | SUPPLEMENTARY RESULTS | HABITAT CRITERIA & RESULTS

Stream Name: Marvine Creek abv W Marvine Ck
Stream Location: At Marvine Ranch/USFS Boundary
Cross-section Number: 1
Coordinate System: Lat Long
X (easting): -107.441584
Y (northing): 40.019821

Measured Data					Value Computed from Measured Field Data				
Feature	Station (ft)	Vertical Depth (ft)	Water depth (ft)	Velocity (ft/s)	Wetted Perimeter (ft)	Water Depth (ft)	Area (SQ ft)	Discharge (cfs)	Percent Discharge
	0	3.1			0	0	0	0	0
	1	4.05			0	0	0	0	0
Bankfull	2.2	4.9			0	0	0	0	0
	3.5	5.5			0	0	0	0	0
Waterline	4	6.01	0	0	0	0	0	0	0
	4	6.15	0.15	0	0.14	0.15	0.11	0	0
	5.5	6.3	0.3	1.09	1.51	0.3	0.45	0.49	0.96
	7	6.8	0.95	3.05	1.58	0.95	1.43	4.35	8.49
	8.5	6.9	1	3.03	1.5	1	1.5	4.54	8.88
	10	7	1.2	3.12	1.5	1.2	1.8	5.62	10.97
	11.5	6.95	0.95	4.06	1.5	0.95	1.43	5.79	11.3
	13	6.8	0.9	2.4	1.51	0.9	1.35	3.24	6.33
	14.5	6.95	0.9	3.85	1.51	0.9	1.35	5.2	10.15
	16	6.95	0.95	1.9	1.5	0.95	1.43	2.71	5.29
	17.5	7	0.95	1.9	1.5	0.95	1.43	2.71	5.29

Figure 8. Example of information displayed in the Supplementary Results tab.

Habitat Criteria & Results Tab

The Habitat Criteria & Results tab (Figure 9) contains a summary table of the three flow criteria based on the bankfull width of the R2Cross cross-section (Nehring, 1979). The discharge necessary to meet the 3 hydraulic criteria is interpolated based on the staging table data (Table 2). In addition, three dynamic graphs are included that show the relationship between these criteria and discharge. Detailed information about the habitat criteria is contained in the Technical Guide. The table displayed in this tab allows the user to sort the results according to discharge.

If the bankfull top width is greater than 60 feet, the user must select the appropriate percent wetted perimeter value from the dynamic graph (Figure 10). The user can click and drag on the percent wetted perimeter verses discharge graph (located at the top right) to zoom in to the area of interest, and then select the inflection point where the slope of the line changes most noticeably. If the inflection point occurs at a wetted perimeter value less than 70%, then the discharge that meets 70% wetted perimeter value should be used. If the inflection point occurs at a percent wetted perimeter value greater than 70%, the flow recommendation meeting the wetting perimeter criterion should be the inflection point flow. If more than one inflection point is present, the first inflection point (which corresponds to the flow that fully wets the bottom of the channel) should be selected. A second inflection point may occur where the flow starts to wet the flood plain on one or both banks. When the user selects at percent wetted perimeter value from the graph, the value will automatically be entered into the Habitat Criteria Results table.

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

Bankfull Top Width (ft)	*Average Depth (ft)*	*Percent Wetted Perimeter (%)*	*Average Velocity (ft/sec)*
1-20	0.2	50	1.0
21-40	0.2-0.4	50	1.0
41-60	0.4-0.6	50-60	1.0
61-100	0.6-1.0	> 70	1.0

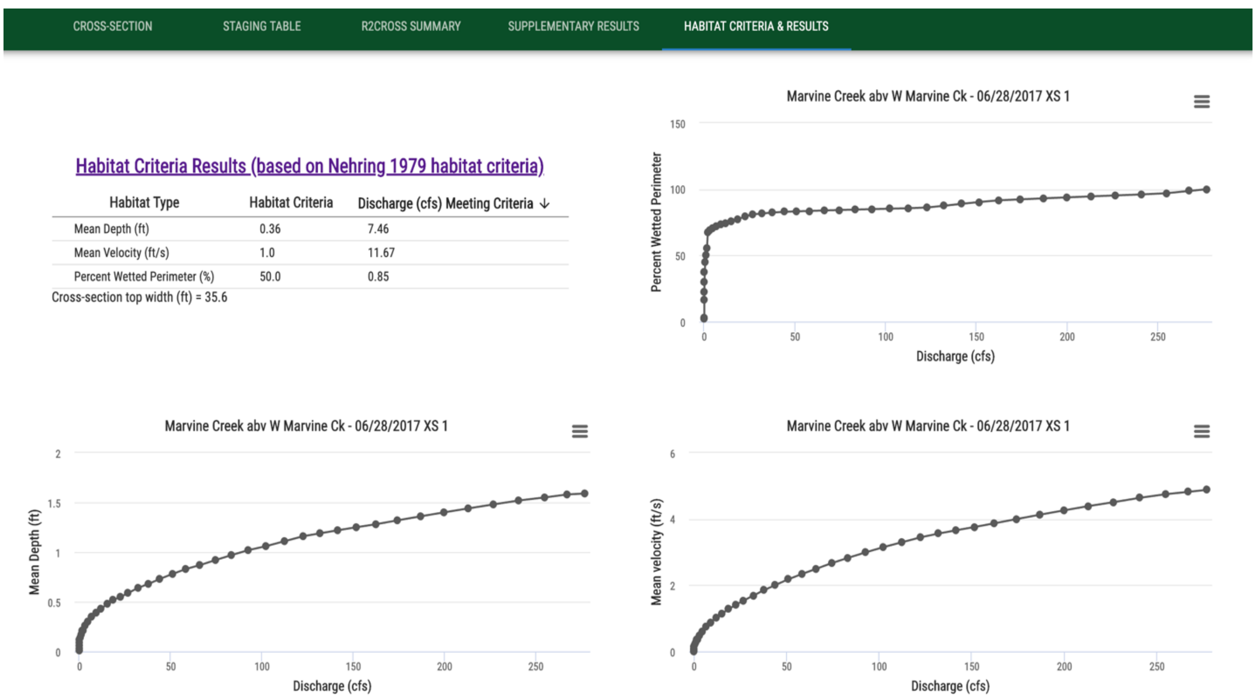

Figure 9. Example of information displayed in the Habitat Criteria & Results tab.

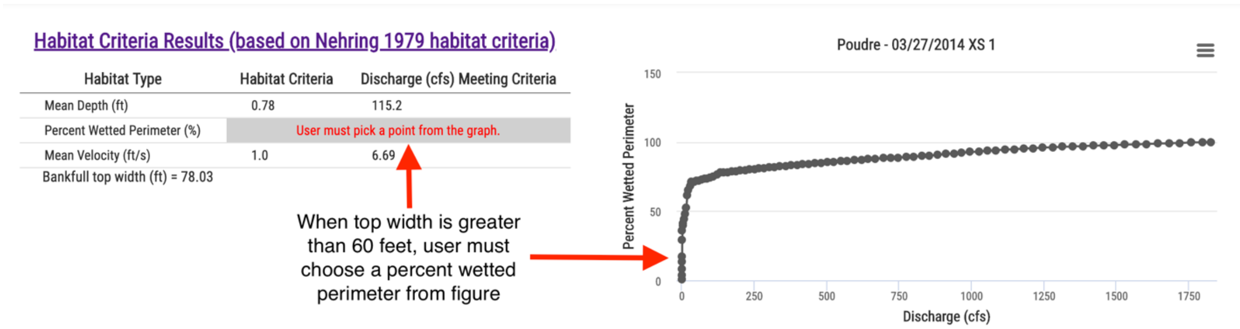

Figure 10. Example showing when bankfull top width is greater than 60 feet, requiring the user to select an appropriate percent wetted perimeter from the figure.

Download Reports

After running the model, 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 (Figure 11). Please note that all model output displayed in the web interface has been rounded to a 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.

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 (see Advanced Options in the R2Cross tool) or can be used completely independent of the R2Cross tool.

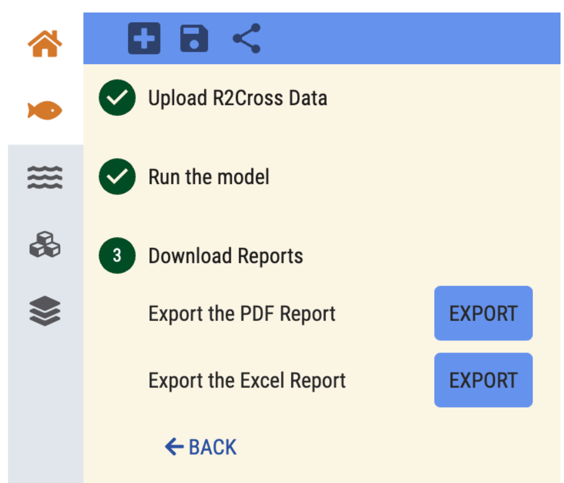

Figure 11. Downloading results in PDF or Excel format.

To begin using the Discharge Calculator, click the icon (Discharge Calculator icon) on the left dashboard (Figure 12).

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. The upload will not work if the data is not correctly formatted. This will be indicated by an error message displayed at the top of the screen. An example of the upload format is shown. The option to download a blank Discharge Data template that contains basic instructions for the user to enter their data in the appropriate format is also provided. An example discharge file filled with data is included on the Home page under the Getting Started Section.

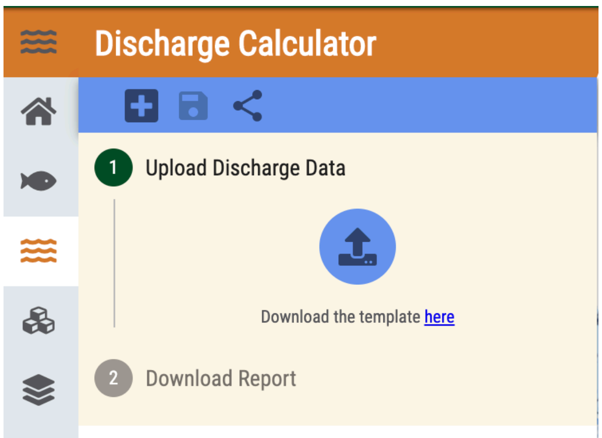

Figure 12. Discharge calculator

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	
Observer	
Cross-section#	
Coordinate System	UTM Zone 13
X (easting)	
Y (northing)	

R2CROSS CROSS-SECTION NOTES				
Stream Name	Stream Location			Slope
Feature	Distance From Initial Point (ft)	Vertical Distance (ft)	Water Depth (ft)	Velocity (ft/s)

Figure 13. Discharge Calculator data template.

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. The D84 results from the Particle Size Calculator can be used as input data for the Ferguson roughness equation.

To begin using the Particle Size Calculator, click the icon (Particle Size Calculator icon) on the left dashboard (Figure 14).

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. The upload will not work if the data is not correctly formatted. This will be indicated by an error message displayed at the top of the screen. The option to download a blank Pebble Count data template (Figure 15), 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.

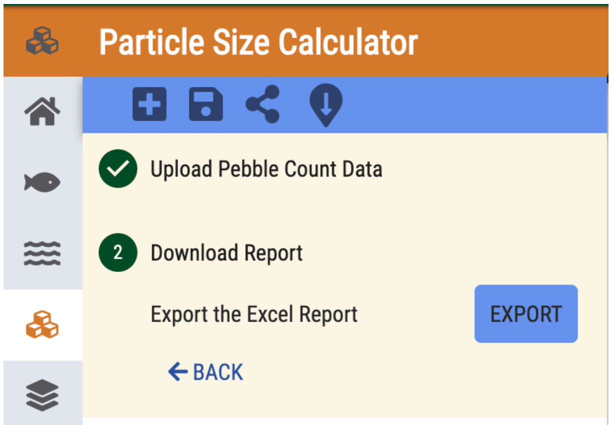

Figure 14. Particle Size Calculator

Once particle size data has been uploaded, the information will be processed and displayed to the user (Figure 16). 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	
	Observer	
	Coordinate System	UTM Zone 13
	X (easting)	
	Y (northing)	
PEBBLE COUNT OBSERVATIONS		
Stream Name	Stream Location	Cross-Section No.
Description of Particle Size	Size (mm)	Count (integer number)
Sand and Silts	<2	
Very Fine Gravel	2 - 4	
Fine Gravel	4 - 6	
Fine Gravel	6 - 8	
Medium Gravel	8 - 11	
Medium Gravel	11 - 16	
Coarse Gravel	16 - 22	
Coarse Gravel	22 - 32	
Very Course Gravel	32 - 45	
Very Course Gravel	45 - 64	
Small Cobble	64 - 90	
Small Cobble	90 - 128	
Large Cobble	128 - 180	
Large Cobble	180 - 256	
Small Boulder	256 - 362	
Small Boulder	362 - 512	
Medium Boulder	512 - 1024	
Large Boulder	1024 - 2048	
Very Large Boulder	2048 - 4096	
Bedrock	>4096	

Figure 15. Particle Size Calculator data

RESULTS

D16	D25	D50	D75	D84	D95	Geometric Mean	Geometric Standard Deviation	Gradation Coefficient
6.798 mm	18.69 mm	46.89 mm	80.88 mm	103.1 mm	158.82 mm	32.03	3.89	4.55

Description	Size (mm)	Count	Percentage	Cumulative Percentage
Sand and Silts	<2	54.0	10.53	10.53
Very Fine Gravel	2 - 4	6.0	1.17	11.7
Fine Gravel	4 - 6	16.0	3.12	14.81
Fine Gravel	6 - 8	14.0	2.73	17.54
Medium Gravel	8 - 11	13.0	2.53	20.08
Medium Gravel	11 - 16	15.0	2.92	23.0
Coarse Gravel	16 - 22	21.0	4.09	27.1
Coarse Gravel	22 - 32	50.0	9.75	36.84
Very Course Gravel	32 - 45	57.0	11.11	47.95
Very Course Gravel	45 - 64	90.0	17.54	65.5
Small Cobble	64 - 90	71.0	13.84	79.34
Small Cobble	90 - 128	62.0	12.09	91.42
Large Cobble	128 - 180	29.0	5.65	97.08
Large Cobble	180 - 256	7.0	1.36	98.44
Small Boulder	256 - 362	8.0	1.56	100.0
Small Boulder	362 - 512	0.0	0.0	100.0
Medium Boulder	512 - 1024	0.0	0.0	100.0
Large Boulder	1024 - 2048	0.0	0.0	100.0
Very Large Boulder	2048 - 4096	0.0	0.0	100.0
Bedrock	>4096	0.0	0.0	100.0

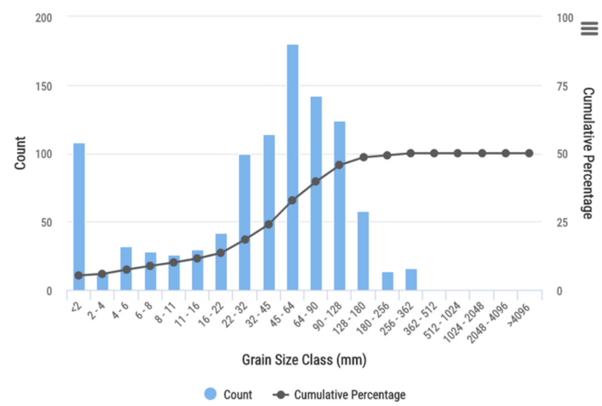

Figure 16. Results from the Particle Size Calculator.

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

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 17). 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 (pan, scroll). Multiple data layers can be displayed simultaneously.

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 19.

Each of the data types in this data set have their own legend as shown in Figure 18.

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 forthcoming). Currently operating gages and discontinued historical gages are shown with differing symbols.

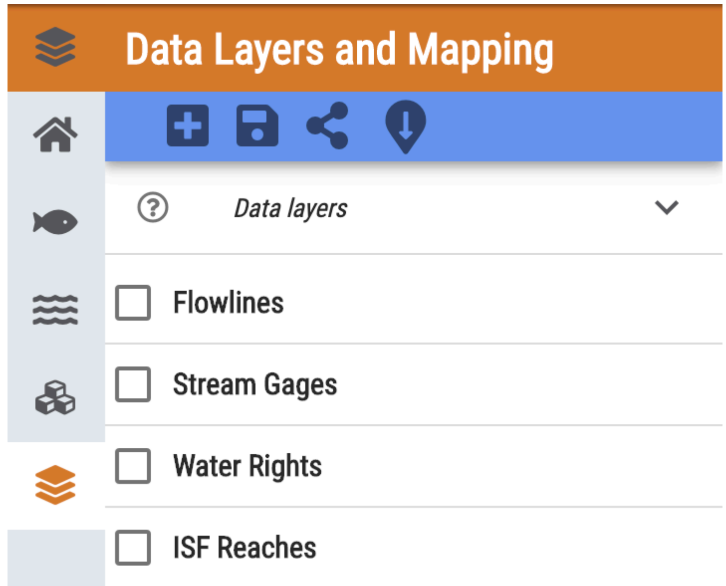

Figure 17. Data layer options

Clicking any of the gaging locations (on the list on the left or on the map in Figure forthcoming) 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 extend. A link to the webpage from the data sour (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).

Clicking on any of the diversions (on the list on the left or on the map in Figure 21) a summary of the water rights for that location will be displayed, as shown in Figure 20. 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.

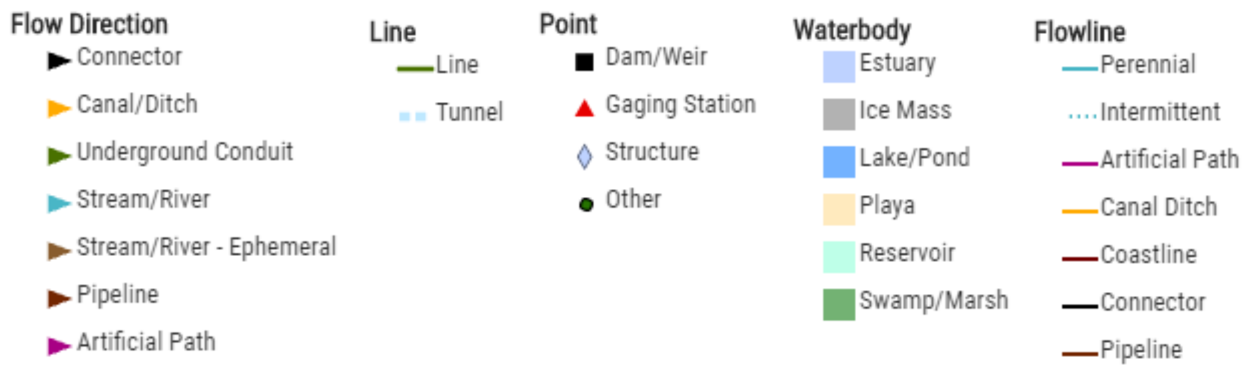

Figure 18. Legend options for NHD+ data

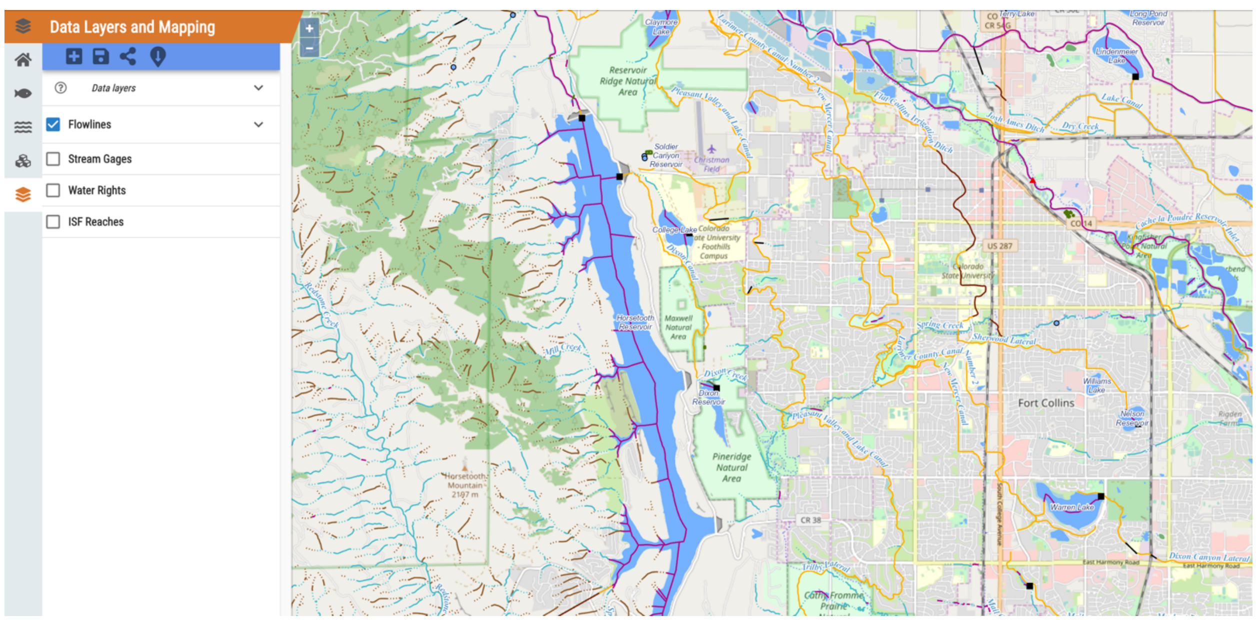

Figure 19. Flowlines Map

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 22.

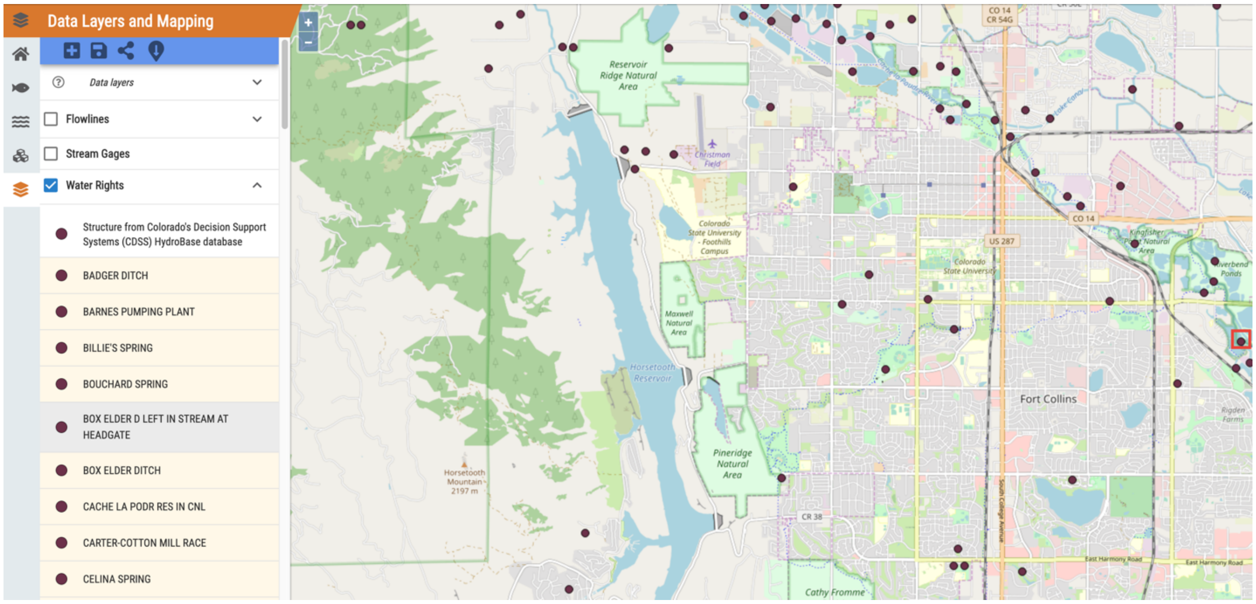

Figure 21. Water rights map

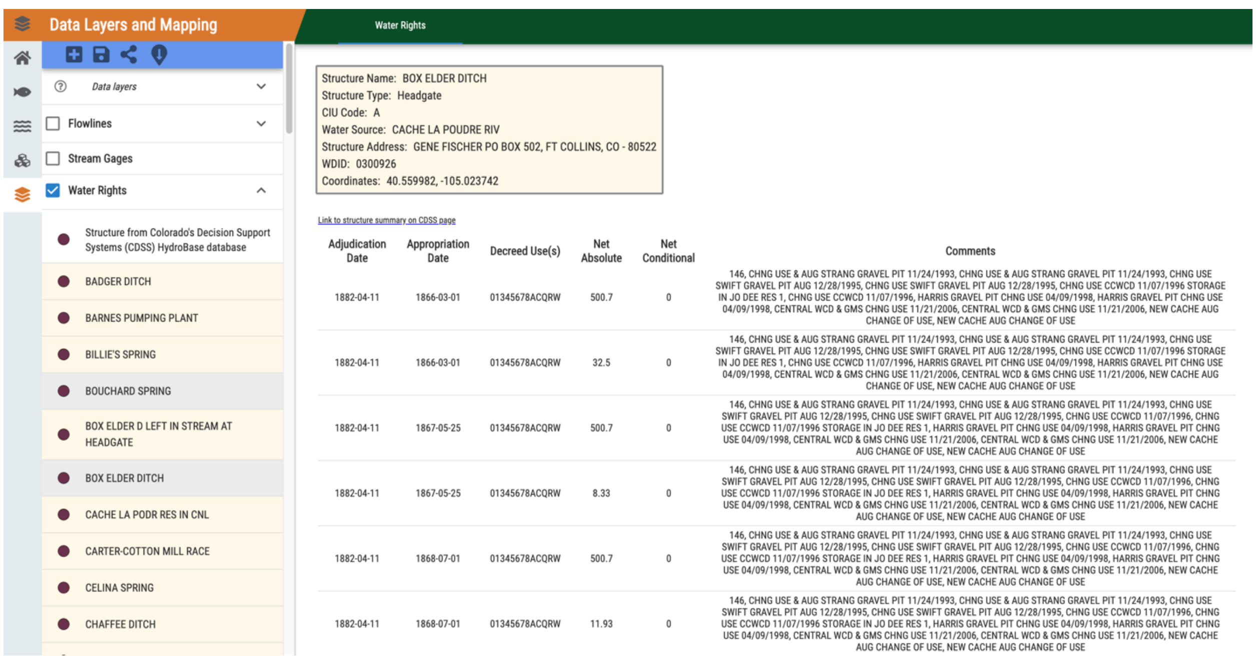

Figure 20. Hydrobase water rights summary

Clicking on any of the ISF water rights on the list in the left panel (Figure 21) produced a summary of the water rights for that location, as shown in Figure 20. The line segments include information about the type 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.

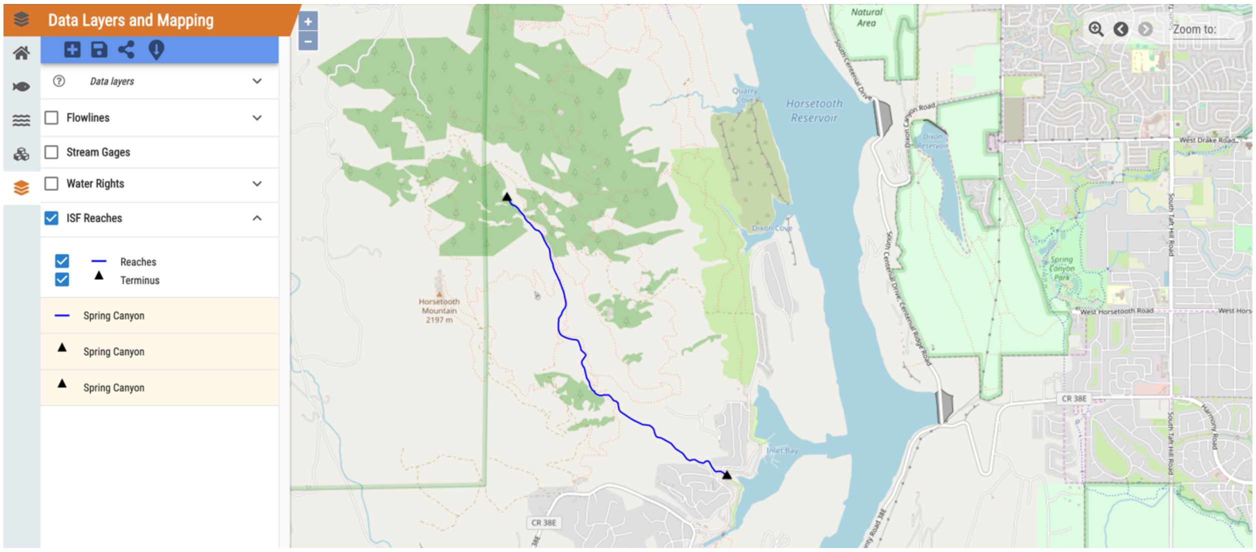

Figure 22. CWCB map of instream flow rights

NOTES AND TIPS

When a cross-section is uploaded in the R2CROSS or Discharge Calculator, the map will display the location of the data collection site base on the coordinates provided.

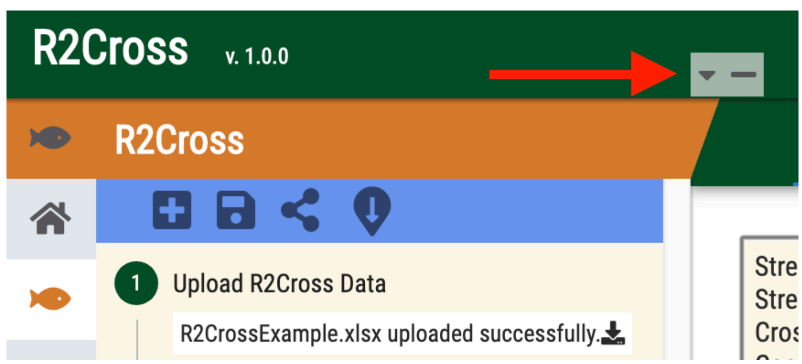

Figure 23. Minimize tab to see maps view

At any time while using the tools, the summary and result sections can be minimized using the arrows at the top left (shown with a red arrow in Figure 23) to return to the map page or maximized to return to the results page.

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 Manning's equation, which assumes a constant channel roughness and uniform flow conditions. However, numerous 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. These equations generally relate 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 program allows the user to select either the Ferguson or Manning flow resistance equations that have been well-documented in literature. Each equation contains assumptions and limitations, which are described in the following sections. In general, the preferred approach is to collect particle size information in the field and use the Ferguson equation. If grain size information is not available, the Manning equation can be used.

FLOW RESISTANCE EQUATIONS

The R2Cross tool contains both the Ferguson equation (Ferguson 2007) and the Manning equation (Chow 1959) for estimating roughness and hydraulic variables at a channel cross section. The roughness estimation in each of these equations is different, which implies that each method will produce slightly different results. In open channels, the classical resistance coefficients used are those of Chezy (C), Manning (n) and Darcy-Weisbach friction factor (f), and average velocity (U). The relation of each other for US customary units is shown below.

$$\frac{C}{\sqrt{g}} = \frac{1.486\sqrt[6]{h}}{n\sqrt{g}} = \sqrt{\frac{8}{f}} = \frac{U}{u_*} \qquad (1)$$

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

Manning Equation

The most commonly used equation for the estimation of mean velocity is Manning equation, which was developed in 1885 through curve-fitting of 170 experiments (Yen, 1992). An underlying assumption of the Manning equation is that the flow is uniform. This condition is rarely satisfied in practice. Uniform flow in a channel can be achieved if the depth, flow area, and velocity at every cross section are constant, and when the energy grade line, water surface, and channel bed are all parallel. The Manning equation for mean velocity in US customary units is:

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

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

n = Manning's roughness coefficient

R = hydraulic radius (ft)

S = channel slope (ft/ft)

The roughness coefficient n represents only the boundary roughness. In the R2Cross tool, Manning's n is calculated based on the channel velocity and geometry measurements collected in the field at a single flow rate. The same constant value of n is then used to predict the hydraulic parameters for a variety of channel depths. It should be noted that the quality of the estimation is directly associated with the quality of the measurements, and, to limit potential inaccuracies, the ISF program has limited the use of the Manning equation to results that are within 40% and 250% of the measured discharge. For example, if the discharge calculated using the Manning equation for a habitat criterion is less than 40% or greater than 250% of the measured discharge, the calculated discharge should not be used to make instream flow recommendations.

Ferguson Equation

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. Ferguson's equation, shown below, was fitted based over 400 reaches with slopes ranging between 0.00001-0.21, D84 ranging between 0.2 mm to 0.8 m, and relative submergence $\left({R}/{D_{84}}\right)$ ranging between 0.1-26. Thus, the Ferguson equation has been tested over a wide range of stream settings. However, the Ferguson equation should be used with caution when wood interacts with clasts in channels steeper than about 2.5-3% to increase vertical variability in the longitudinal profile. This method is reported to outperform other flow resistance equation based on 2,890 cross-sections (Rickenmann and Recking, 2011). More detailed descriptions of the Ferguson equation can be found in Ferguson (2010, 2013).

$$U = u_* \frac{a_1 a_2 (R/D84)}{[a^2{}_1 + a^2{}_2 (R/D84)^{5/3}]^{1/2}}$$

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, which was the coefficient determined by Ferguson (2007) and Rickenmann and Recking (2011) to best fit a wide range of stream conditions
>
> R = Hydraulic radius (ft)
>
> $D84$ = 84th percentile of a particle-size distribution (ft)

The Ferguson equation requires an estimate of channel-bed sediment size. A common indicator of bed material size is the 84th percentile (84% finer), which is derived by the cumulative frequency distribution of the sediment sample size. The 84th percentile, also denoted as D84, assumes a normally distributed sample and is the upper limit of one standard deviation from the sample's median value (the lower is D16).

Using the relationships shown previously, an equivalent Manning's *n* (referred to as "Ferguson-n" in the Staging Table) is calculated based on results from the Ferguson equation.

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.

BIOLOGICAL INSTREAM FLOW RECOMMENDATIONS

Three instream hydraulic parameters—average depth, average velocity, and percent wetted perimeter—are used to develop biological instream flow recommendations in Colorado. The Colorado Parks and Wildlife (CPW) has determined that by maintaining these three hydraulic parameters at adequate levels across riffle habitat-types, aquatic habitat in pools and runs will also be maintained for most life stages of fish and aquatic invertebrates (Nehring, 1979).

The three critical hydraulic parameters are estimated for various stages using one of the flow resistance equations described previously. Biological instream flow recommendations are developed by locating the modeled streamflow(s) in the R2Cross staging table that satisfy the hydraulic criteria summarized in Table 4. As stated above, Colorado's Instream Flow Program was created in 1973, and since that time the Program, along with the science of determining instream flows, has continued to evolve. For the Instream Flow Program to be successful, instream flow water rights must be able to balance the ever-changing needs and values of the public while honoring existing uses. The greatest asset of the Program, to date, has been its ability to evolve and meet those challenges.

Table 4: Criteria used to determine minimum flow requirements (Nehring, 1979)

Bankfull Top Width (ft)	Average Depth (ft)	Percent Wetted Perimeter (%)	Average Velocity (ft/sec)
1-20	0.2	50	1.0
21-40	0.2-0.4	50	1.0
41-60	0.4-0.6	50-60	1.0
61-100	0.6-1.0	> 70	1.0

In the early years of the Program, CPW's instream flow recommendations consisted of only single year-round flow amounts. These single year-round flow amounts were based on meeting only two of the three critical hydraulic criteria identified by Nehring. For the first third of the Program, these initial flow recommendations were not adjusted due to water availability concerns. It was not until the passage of Senate Bill 414 (SB 414) in 1981, that future instream flow appropriations would require an evaluation of the existing physical water supply. In the mid 1980's, to incorporate these new changes into the Program and address other concerns being raised regarding the R2Cross model (mainly the tendency of the R2Cross model to overestimate the criteria), state biologists modified the original instream flow methodology of recommending single year round flows and began developing "seasonal flow recommendations" which would incorporate all 3 of the identified critical criteria into the flow recommendations.

These seasonal flow recommendations are an attempt to mimic the natural flow regime, albeit, on a simplistic and much smaller scale. CPW currently believes spring/summer flows require flow recommendations which meet all three of the critical hydraulic criteria and fall/winter flows require flow recommendations which meet two of the three critical hydraulic criteria, whenever possible. CPW believes the development of these seasonal flow recommendations helps address the full range of hydrologic and hydraulic conditions required to maintain important stream characteristics and its associated aquatic community. Research has shown that single year-round minimum flows, when maintained as a long-term condition, cannot be expected to sustain the same fish populations or aquatic life as a natural flow regime, where low flow conditions occur infrequently and for shorter periods (Stalnaker and Wick, 2000). Higher spring and summer flows provide the water and resultant habitat required to maintain the adjacent riparian zone, the geomorphology of the stream channel and additional habitat and protection for different life stages of the aquatic community. In addition, protection from increasing recreational uses such as rafting, kayaking, boating, tubing, swimming and fishing is gained during these flow periods. Higher spring and summer flows also provide water quality protection from other outside factors such as effluent discharges, high metal concentrations, excess sedimentation and water temperature increases. Aquatic biologists may modify summer and winter flow recommendations based upon biologic considerations such as stream conditions, species composition, and aquatic habitat quality.

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