FishXing

Version 3
February 2006

User Manual and Reference

FishXing 3 was generously sponsored by:

Pacific Northwest Research Station
Forest Service Engineering T&D Program
Federal Highway Administration
Stream Systems Technology Center
Rocky Mountain Research Station
US Fish and Wildlife Service

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Table of Contents

Introduction

Pronounced **"Fish Crossing"** this software is designed to assist engineers, hydrologists and fish biologists in the evaluation and design of culverts for fish passage. It is free and available for download at the FishXing website.

FishXing 3 is a unique software tool for the assessment and design of culverts for fish passage. FishXing models the complexities of culvert hydraulics and fish performance for a variety of species and crossing configurations. The model has proven useful in identifying culverts that impede fish passage, leading to the removal of numerous barriers. As a design tool, FishXing accommodates the iterative process of designing a new culvert to provide passage for fish and other aquatic species.

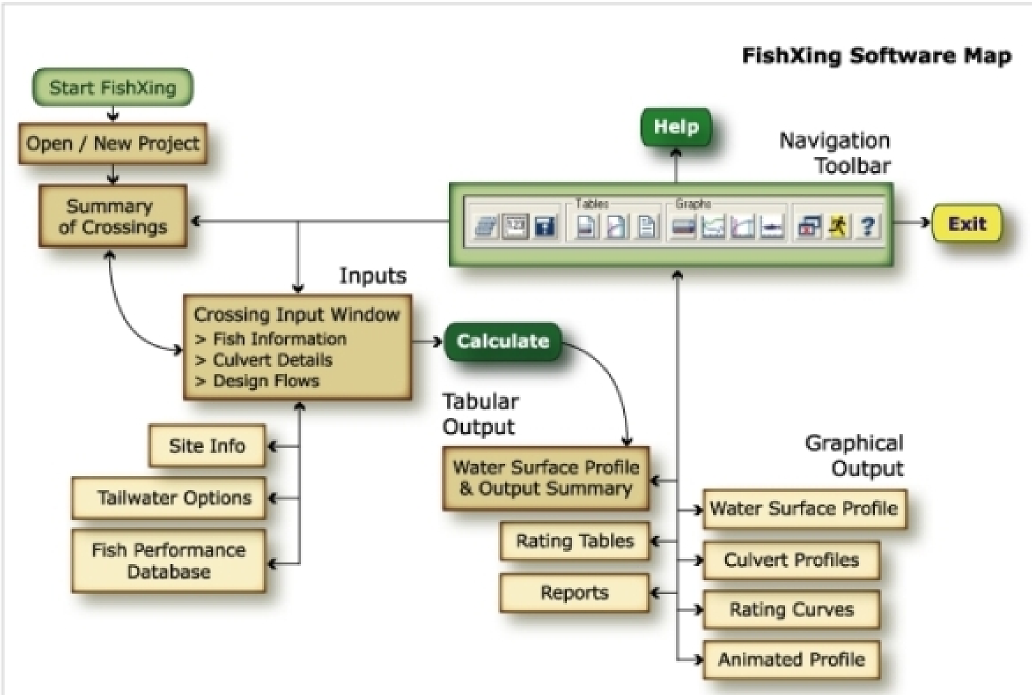
FishXing is an interactive software package that integrates a culvert design and assessment model for fish passage. The software models organism capabilities against culvert hydraulics across a range of expected stream discharges. Water surface profiles can be calculated for a variety of culvert shapes using gradually varied flow equations. The program then compares the flows, velocities and leap conditions with the swimming abilities of the fish species of interest. The output includes tables and graphs summarizing the water velocities, water depths, and outlet conditions, then lists the limiting fish passage factors and flows for each culvert.

Version 3 is a complete rewrite of previous versions based on user feedback and our own experience in the field of fish passage and engineering. There are many new features that have been added to this version.

See also: Feature List, Help System Table of Contents, Contact Info, Software Map, About Help, Credits

FishXing Software Map

The FishXing Software Map is a tool for understanding the flow of the program and navigating the Help files. Click on an area of the map to explore the topic in the Help files.



Feature List

FishXing 3 Features

- Redesigned user interface to make data entry and results more usable and informative
- Manage multiple crossing sites by grouping into projects
- List summary information for crossings within a project including:
  - Type of crossing
  - Location and characteristics of crossing
  - Range of flows passable
  - Percent passable of flows passable
  - Passage Problems
- Navigation Toolbar
- Customize and save settings for passage criteria and output graphs, tables, and reports
- Data Input Options:
  - Site Information
    - Lat/long location, notes, link to photos of the site
  - Culvert Info
    - Analyze multiple culverts per crossing
    - Choose from 8 culvert shapes with predefined or custom input dimensions
    - Installation at Grade or Embedded
    - Separate roughness factor for culvert and for bottom material
    - Entrance loss coefficient
  - Fish Information
    - Fish Performance Database for selecting swim speeds
    - Define your own swim speeds for burst and prolonged swim modes
    - Define acceptable hydraulic criteria
    - Define Passage criteria
    - Select between hydraulic and swim speed based passage criteria
    - Optional velocity reduction factors for slow flow along culvert wall
    - Customize and save settings for swim modes and hydraulic criteria
  - Design Flows
    - Enter low and high fish passage flows
    - Flow calculator for additional trial flows
  - Tailwater Methods
    - Constant Elevation
    - User defined Rating Curve
    - Calculated rating curve from user defined cross section

- Multiple Output Formats:
  - Output Summary
    - Percent of flow passable between Low and High Passage Flows
    - Passable flow range
    - Barrier Types as flow varies
    - Normal, Critical, Headwater, Tailwater Depth
    - Headwater to Diameter Ratio

- Inlet Contraction Velocity
- Total Swim Time

<u>Culvert Profile and Table</u>

- Distance Down Culvert
- Water Depth
- Critical Depth
- Normal Depth
- Velocity Head
- Velocity - Average
- Velocity - Occupied
- Ground Speed
- Swim Mode
- Cumulative Prolonged Swim Time
- Cumulative Burst Swim Time
- Barrier Type
- Froude Number
- Specific Momentum
- Shear Stress
- Stream Power
- Composite Roughness
- EDF (Energy Dissipation Factor)
- Hydraulic Curve
- Wetted Area
- Wetted Perimeter
- Top Width
- Hydraulic Radius
- Hydraulic Depth
- Bottom Elevation
- Water Surface Elevation
- Critical Elevation
- Energy Grade Line
- Water Surface Slope
- Energy Grade Line Slope

<u>Rating Curve and Table</u>

- Flow Rate
- Outlet Velocity
- Inlet Velocity
- Maximum Velocity
- Velocity at Normal Depth
- Inlet Depth
- Outlet Depth
- Depth at Culvert Midpoint
- Normal Depth
- Minimum Depth
- Outlet Pool Depth
- Outlet Drop
- Vertical Leap Distance
- Horizontal Leap Distance
- Total Burst Swim Time
- Total Prolonged Swim Time
- Shear Stress at Inlet
- Shear Stress at Midpoint
- Shear Stress at Outlet
- Barrier Type

Animated Profile

Animation of model results showing water surface, fish performance and barriers

Automated Reports

- Help and Learning System (fully searchable and indexed)
  - Full documentation of equations used in calculations
  - Example applications of FishXing
  - Guided tutorial for using FishXing
  - Hydraulic, Culvert and Fisheries reference sections
  - Glossary of terminology
    - Library of related publications
    - Extensive annotated bibliography

About Help

This Help File is designed to provide you with detailed information about how to use the FishXing Software and includes an extensive reference section to provide a better understanding of fish passage through culverts for making informed decisions about analysis and design of culverts for stream crossings.

FishXing Help is divided into two sections as shown on the FishXing Table of Contents:

- **Using the Software** - Provides explanations of all the input fields on the Crossing Input Window, how FishXing performs calculations, Viewing results and Examples
- **References** - Additional information about Culverts, Hydraulics and Fish Performance. A glossary of terms and links to fish passage resources are also provided

A good place to start in understanding the flow of the program is the Software Map which can also be used to jump to parts of the Help file.

- The **Previous** button will take you to the previous topic in the Table of Contents
- The **Next** Button will take you to the next topic in the Table of Contents
- The **Book** button will take you to the topic level Table of Contents
- There are two kinds of links in this help system:
  - A normal link (solid underline) that will point you to another topic in the help system, for example, this link goes to credits.
  - A pop up link (dashed underline) that will pop up either text or imagery to quickly illustrate a point. For example, here's a few images of fish leaping.

Back to Main Topics:

TOC Map Run Results Calculate Culvert Hydraulic Fish Glossary

A pdf version of this help manual that can be printed is available at:

http://www.fsl.orst.edu/geowater/FX3/FX3_manual.pdf

See also: Feature List, Help System Table of Contents

Contact Information

Email

If you have any questions regarding FishXing, please email Michael Furniss at:

mfurniss@fs.fed.us

Website

If you are looking for the FishXing software, please download the latest version from the FishXing website. The FishXing website is also a portal for updates, videos, case studies and useful links for fish passage work.

http://www.stream.fs.fed.us/fishxing/

Order the FishXing CD

The FishXing CD is a multimedia experience with resources, videos and a fish passage library. To see a couple of examples on what you will find on the CD, please watch the FishXing videos and check out the Case Studies on the FishXing website.

For the CD, send a request to:

Publications

USDA Forest Service
San Dimas Technology and Development Center
444 E. Bonita Ave.
San Dimas, CA 91773

or call: (909) 599-1267

...and ask for the FishXing CD. (pronounced "Fish Crossing")

See Also: FishXing Credits, Help System Table of Contents

Credits

FishXing 3 was created by:

- **Michael Furniss**
  USDA-Forest Service, Pacific Northwest Research Station, Aquatic and Land Interactions Program, Corvallis OR
- **Michael Love**
  Hydraulic Engineer, Michael Love & Associates, Eureka CA
- **Susan Firor**
  Engineering Hydrologist, TerraGraphics Environmental Engineering, Moscow ID
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  Fisheries Biologist, US Fish and Wildlife Service, Portland OR
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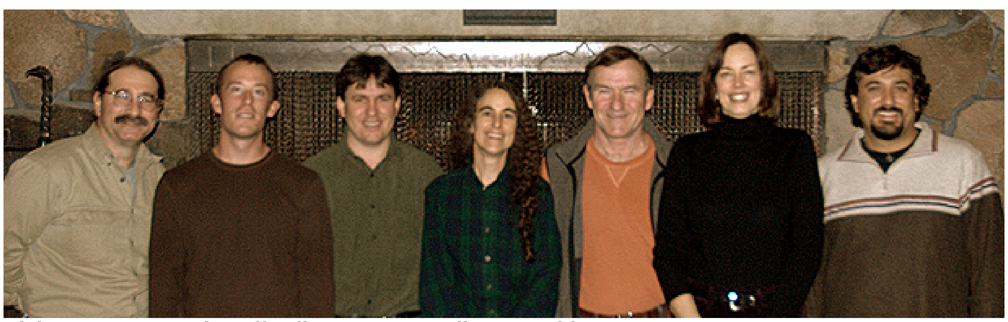
  Professional Engineer, Michael Love & Associates, Eureka CA
- **Jeff Guntle**
  Web and Interface Developer, Pacific Northwest Research Station, Arcata CA
- **Robert Gubernick**
  Engineering Geologist, USDA, USGS, Tongass National Forest, Petersburg, AK



FishXers L to R: Bob, Jeff, Mike L., Susan, Mike F., Kathi, Tony

Additional thanks go to:

Kozmo Ken Bates, Ted Castro-Santos, Kim Clarkin, Thomas Dunklin, John Fehr, Tom Grey, Dick Jones, Chris Katapodis, Margaret Lang, Steven Levesque, Jorge Garica Molinos, Jeff Moll, Kemset Moore, Tom Moore, Jill Ory, Riley Quarles, Terry Roelofs, Vaughn Stokes, Jeremy Svehla, Traci Sylte, Ross Taylor, Bill Trush, Mark Weinhold, Marcin Whitman, Alan Yamada

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[Forest Service Engineering T&D Program]

[Federal Highway Administration]

[Stream Systems Technology Center]

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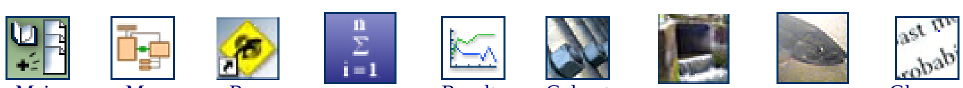
Running FishXing

Topics:

Back to Main Topics:



Starting a FishXing Project

1. Run FishXing. The first windows to open are the Navigation Bar and the Open a Project windows.

2. Use the default FishXing folder or press the **New Project** button.

3. Locate the directory for your new FishXing Project. For more information on organizing projects in FishXing see below.

4. Name the new project folder and press **Continue**.

5. In the Project Summary window press the **Add** button to start data input for a new FishXing crossing file.

6. In the Site Information window enter the Crossing, Stream, and Road names and press Continue.

7. In the Crossing Input Window enter Culvert Dimensions, Fish Capabilities, Tailwater Condition and Fish Passage flows.

8. Press **Calculate** to view results.

> **Tip:** You can have FishXing always open a project folder of your choice by going to the Navigation Bar and selecting "Set Default Project Folder" from the **Project** menu pull down. You can also Open and create New project folders from there.
> **Tip:** The Software Map is designed to give you a birds eye view of the flow of the program.

More about FishXing projects

Data for each culvert is saved in a crossing file (filename.xng). A collection of crossing files is stored in a project folder. The default location for project folders is in the *FishXing* program directory (C:/Program Files/FishXing V3). When you run *FishXing* the first window you will see is the **Open an Existing Project** window. Opening a project will display all of the crossing files in the Project Summary Window where you can open an existing crossing file or start a new one.

Saving the crossing files in a project is useful for organizing your analysis. For instance, a regional inventory can have its own project or multiple design alternatives for a single site can be kept in a unique project. Once you have decided how you will organize your crossing files you can create new project folders from the Open a Project Window or by using Windows Explorer.

Data Requirements

The data required to run *FishXing* is largely based on the culvert and the hydrology of the crossing. Swim Speeds can be selected from the database and adjusted based on experience and judgement. If fish performance data is available *FishXing* can accommodate custom data and agency criteria or guidelines.

See the Crossing Input Window for more information about specific data fields in the software.

Site Info

- Crossing Name
- Stream Name
- Road Name
- Mile post (optional)
- Latitude and Longitude (optional)
- Notes (optional)
- Photo/Images (optional)

Culvert Information

- Culvert Shape
- Dimensions (diameter, rise, span)
- Material and Corrugation
- Installation (At Grade or Embedded)
- Roughness of culvert material (and bottom if embedded)
- Culvert Length
- Culvert Inlet Bottom Elevation (or Culvert Slope)
- Culvert Outlet Bottom Elevation
- Entrance Loss

Fish Information

- Species
- Fish Length
- Time to exhaustion
- Swim mode (Burst, Prolonged or Both)
- Maximum Leap Speed (outlet pool exit velocity)
- Velocity Reduction Factors (optional)

Fish Passage Flows

- High Fish Passage Flow
- Low Fish Passage Flow
- Peak Flow (optional)

Tailwater Method

FishXing uses one of the following methods

Constant Tailwater

- Outlet Pool Surface Elevation
- Outlet Bottom Pool Elevation

User Defined Rating Curve

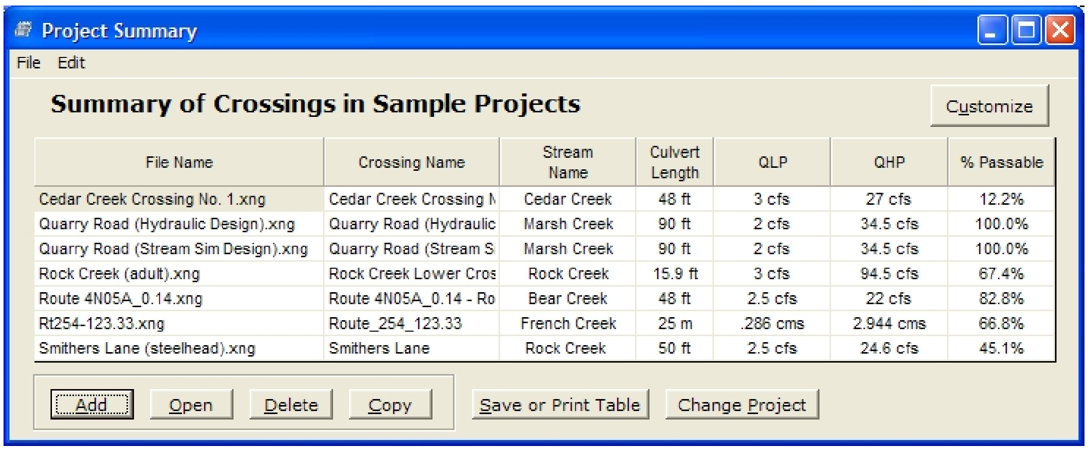
- Outlet Bottom Pool Elevation
- Stage and Discharge data for downstream channel

Channel Cross section Method

- Cross Section Data (Station and Elevation) for downstream channel
- Channel Slope
- Outlet pool bottom elevation
- Manning's Roughness estimate for downstream channel

Project Summary

All of the *FishXing* Files are stored in **Project Folders** located on your computer or network drives. New crossing files are added to the project folder and existing files are selected and opened from the Project Summary window.



File Name	Crossing Name	Stream Name	Culvert Length	QLP	QHP	% Passable
Cedar Creek Crossing No. 1.xng	Cedar Creek Crossing N	Cedar Creek	48 ft	3 cfs	27 cfs	12.2%
Quarry Road (Hydraulic Design).xng	Quarry Road (Hydraulic	Marsh Creek	90 ft	2 cfs	34.5 cfs	100.0%
Quarry Road (Stream Sim Design).xng	Quarry Road (Stream S	Marsh Creek	90 ft	2 cfs	34.5 cfs	100.0%
Rock Creek (adult).xng	Rock Creek Lower Cros	Rock Creek	15.9 ft	3 cfs	94.5 cfs	67.4%
Route 4N05A_0.14.xng	Route 4N05A_0.14 - Ro	Bear Creek	48 ft	2.5 cfs	22 cfs	82.8%
Rt254-123.33.xng	Route_254_123.33	French Creek	25 m	.286 cms	2.944 cms	66.8%
Smithers Lane (steelhead).xng	Smithers Lane	Rock Creek	50 ft	2.5 cfs	24.6 cfs	45.1%

Summary Table

Additionally the data and results for each crossing can be summarized and viewed at a glance in the Project Summary Table. Use the **Customize** button to select from a variety of parameters including culvert descriptions and fish passage results. By clicking on the table headers the table will be sorted alphabetically according to that field. This Summary Table can be saved for export or printed using the button at the bottom.

See Project Summary Results for more information.

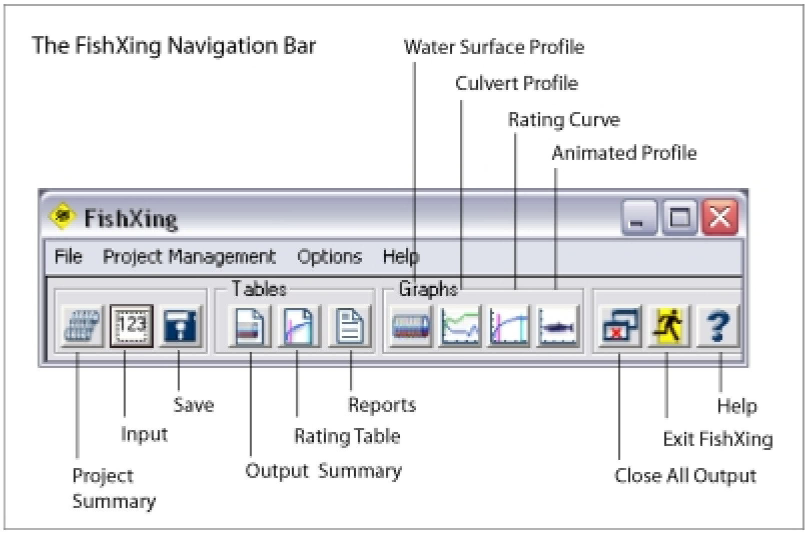
The Add, Open, Delete and Copy functions apply to individual crossing files within the Project.

- **Add** - open a blank crossing file (*.xng), ready for data input.
- **Open** - open the currently selected file.
- **Delete** - permanently erase a crossing file from the Project Folder.
- **Copy** - create a copy of the selected crossing file.

Note: The underlined A in Add indicates that pressing Alt+A will initiate the New feature. This functions the same for the Customize, Open, Delete, Copy, Save and Change Project buttons as well.

Navigation Bar

The Navigation toolbar provides easy access to various features of the software. The Navigation Bar is divided into four sections: Project and Crossing Input, Tabular Output, Graphical Output, and Exit/Help options.



Project Summary

FishXing files (.xng) are organized by Crossings in Project Folders. Crossing files can be opened, copied or deleted in the Project Summary Window. The Project Summary Window also allows you to view information and results about all of the crossings in project in a customized table.

Your FishXing files can be moved to another project folder using Windows Explorer.

Input

The Crossing Input Window is the main interface for data input. Here you can enter the culvert dimensions, flow characteristics, fish capabilities and the passage criteria.

Save

The Save button saves the current crossing file (filename.xng). All of the information entered in the data fields on the Input Window and nested input windows are stored in this file.

Output Summary

When Calculations are complete the Output Summary window will open. This is the primary results window that contains a fish passage summary detailing the types of barriers and range of flows associated with each barrier, hydraulic conditions specific to the selected flow, a flow calculator, and a customized table which displays a wide range of flow specific variables.

Rating Table

Hydraulic results and fish performance for the crossing are reported throughout the range of analysis flows.

Reports

All of the input data and output results can be printed in a customized report that is saved as a text file (.rtf) for import into spreadsheet and word processor applications.

Water Surface Profile

Graph of the Water Surface, Critical Depth and Normal Depth along the length of the culvert. The culvert dimensions, Headwater, Tailwater and Outlet Pool Bottom are also displayed.

Culvert Profile

Display of hydraulic data and fish performance along the length of the culvert.

Rating Curve

Graphical presentation of hydraulic results and fish performance versus flow.

Animated Profile

FishXing animates the hydraulics and fish performance within the culvert Using the numerical results of the model.

Close All Output

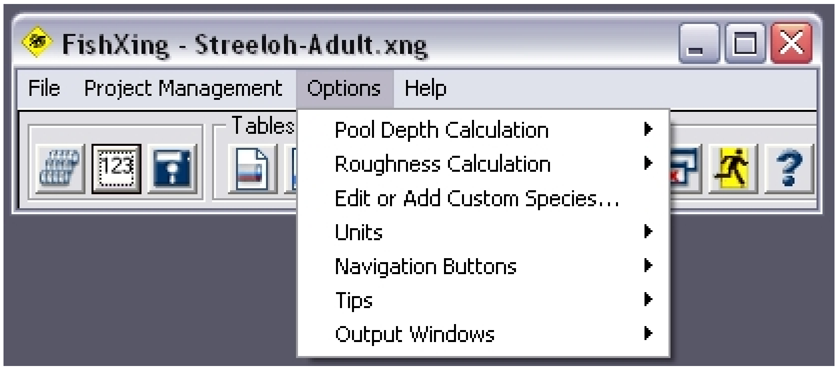
Closes all of the output windows that are currently open and returns to the Input Screen.

Exit FishXing

Closes all of the FishXing windows and exits the program. You will be prompted to save any changes first.

Help

Activates the Help system. The Help drop down menu brings up a variety of other Help options.



The following menus items are also available through the Navigation Bar:

File: allows the user to Open, Create, and Save FishXing files and Exit the program.

Project: FishXing Files are stored and retrieved in Project Folders that can either be accessed from this menu, the Project Summary Window or with Windows Explorer.

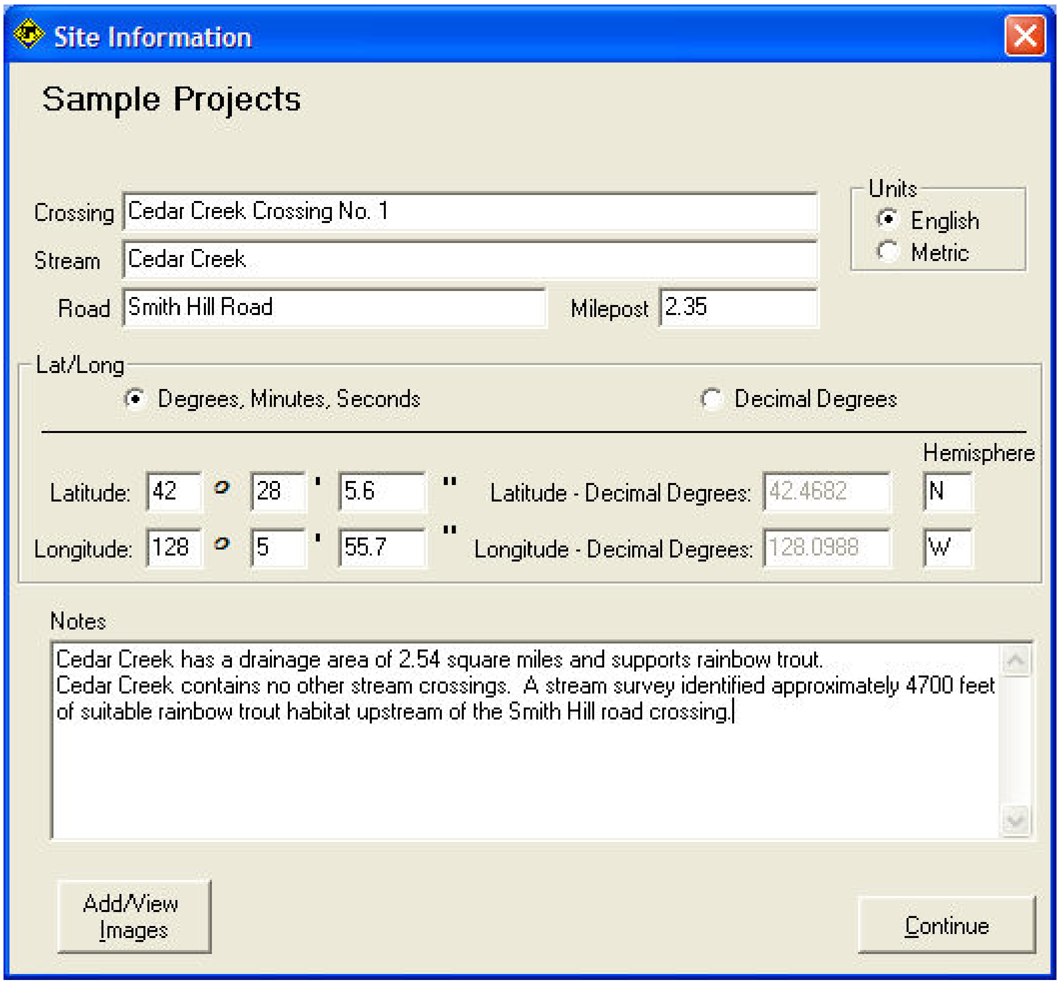
Options: Settings for analysis and user functionality are set in the Options Menu. The following settings can be toggled and set as user defaults.

- **Pool Depth Calculation:** Defines the Depth of the outlet pool as a barrier if it is either less than 1.5 x the fish length or less than 2 x the leap height.
- **Roughness Calculation:** Select the flow resistance method for the culvert Flow resistance in the culvert can be represented by either 1) Manning's n, 2) Darcy Friction Factor or 3) the Chezy Coefficient.
- **Units:** Input and output can be represented in English (US Customary) or Metric (SI) Units.
- **Navigation Buttons:** The Navigation Bar can be displayed as small Icon buttons or larger Text buttons.
- **Tips:** Flyouts that provide a brief description of each field can be turned on or off.
- **Output Windows:** Open in one window or separate windows.

Help: You are here.

Site Info

The Site Information Window allows you enter and save additional information about the crossing. This information is optional and not used for calculations, but is available as output in a Culvert Report.



Crossing / Stream / Road / Milepost

Descriptive identifiers about the crossing site and adjacent landmarks. Mile post will change to Kilopost if metric units are used.

Units

Selecting units on the Site Information window will determine the units used for data entered on the Crossing Input Window.

Lat/Long

Latitude and Longitude can be entered in Degrees, Minutes, Seconds or in Decimal Degrees.

Notes

Enter any text you like that further describes the site.

Continue

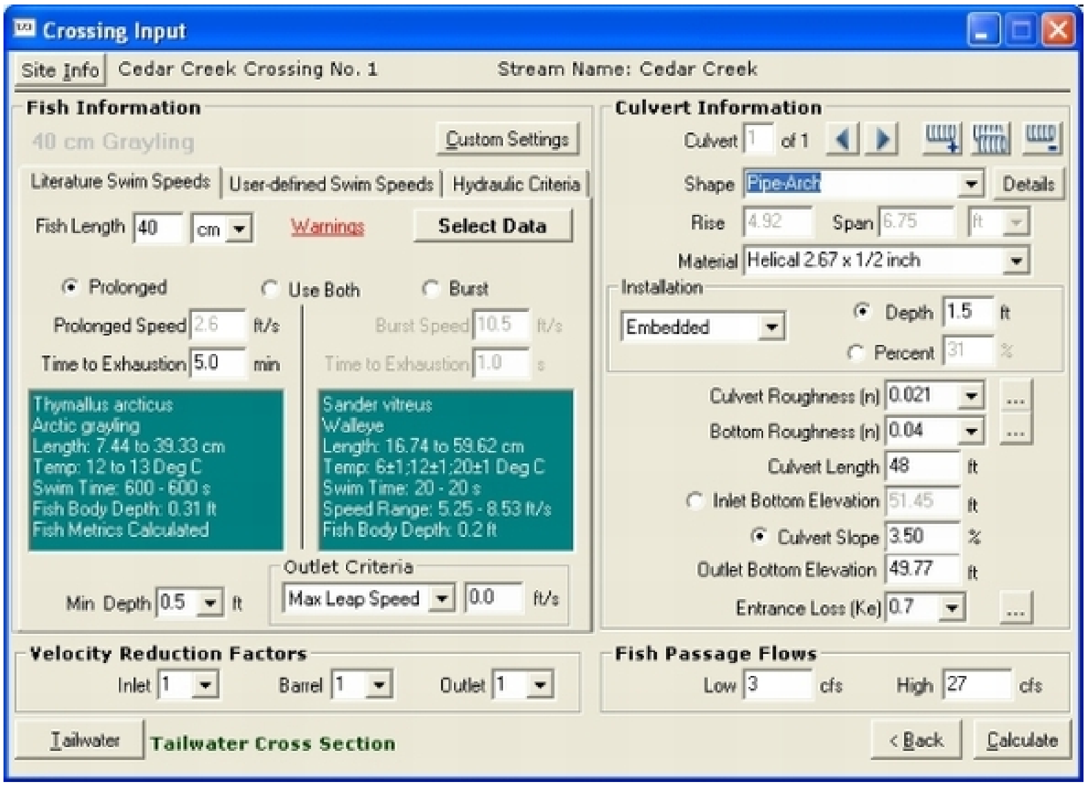
Continue to the Crossing Input Window.

Add/View Images

Note: Images are linked to the crossing description, they are not actually saved with the FishXing (.xng) file. If you move the pictures from their original location you will need to point FishXing to their new location.

Crossing Input Window

The Crossing Input Window is where you specify the characteristics of the stream crossing and fisheries information. This window is divided into three sections addressing the biological, hydraulic and flow components of the crossing.



> **Note:** The underlined C in Calculate indicates that pressing Alt+C will activate calculations. This functions the same for the Site Info, Tailwater Options, and Back buttons as well.

Site Info:

The Site Info Window contains information about the crossing including site description, latitude and longitude, and photos. You can also change the units between English and metric for the crossing file here.

Fish Information:

Fish performance and passage criteria are determined from swim speed data or hydraulic criteria. Select from swim speed data derived from scientific literature, enter your own swim speed data, and define hydraulic conditions required for passage. More about Fish Information.

Culvert Information:

Culvert shape, material, dimensions, and placement. Includes reference tables for complex culvert shapes, entrance coefficients and roughness factors. More about Culvert Information.

Velocity Reduction Factors:

Velocity Reductions Factors used to account for fish swimming against water flowing slower than the calculated average cross sectional velocity.

Fish Passage Flows:

Low and High Fish Passage Flows define the range of flows that fish passage is required. FishXing analyzes passage conditions throughout this range of flows.

Tailwater:

Water surface elevation immediately downstream of the crossing is defined using one of three methods. The tailwater elevation changes with flow, affecting the culvert outlet hydraulics and fish passage. More about Tailwater Methods.

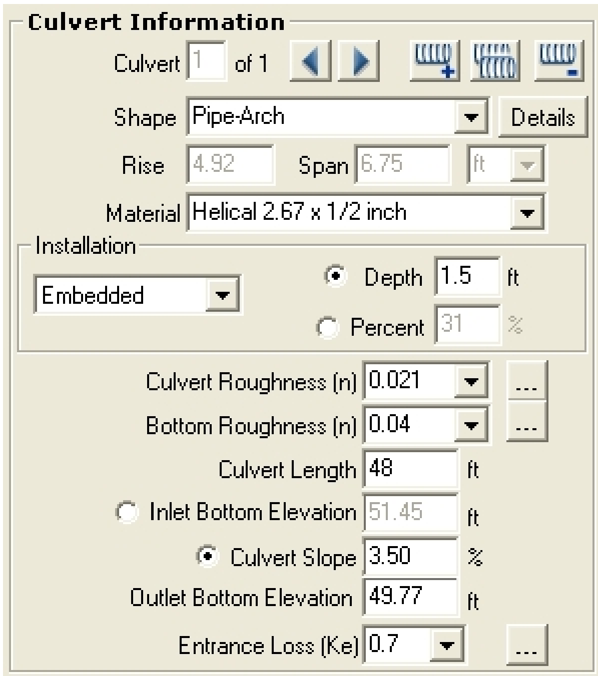
Back:

Returns to the previous Project Summary Window where you can open a different crossing file or create a new one.

Calculate:

Once data is entered, press Calculate and proceed to the Output Summary Window to view results.

Culvert Information



Culvert Information

The Culvert Information portion of the Input Window allows you to specify each culvert's shape, size, material, and placement.

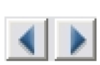
Culvert Number

For crossings with multiple culverts, this field informs you which culvert is currently displayed and the total number of culverts at the crossing. When inputting multiple culverts, its standard practice to go from left to right (looking in the downstream direction).

 **Add** an Additional Culvert. Inserts a new culvert with the data fields left blank.

 **Copy** Currently Displayed Culvert. Adds a new culvert with the same data as the currently displayed culvert.

 **Delete** Culvert. Removes the currently displayed culvert from the crossing.

 **Scroll** through multiple culverts.

Note: The culvert data that is actively displayed at the time of Calculation will be the culvert analyzed for fish passage.

Shape

Choose a culvert shape from the drop down list. Options are;

- Circular,
- Horizontal ellipse,
- Metal box,
- Box,
- Pipe-arch,
- High or low-profile arch, and
- Single radius arch.

If selecting a high or low profile arch, pipe-arch, or metal box, a window containing a list of predefined sizes to select from will open. After a size is selected, the dimensions can be reviewed and changed by pressing the Details button. For a description of the different culvert types and shapes, see Culvert Shapes.

Details

When a culvert shape that has pre-defined dimensions (high and low profile arches, pipe-arches, or metal boxes) is selected, use the **Details** button to change culvert dimensions. The button will open another window that displays a list of the different culvert dimensions available.

Dimensions

Culvert dimensions can be entered in feet, inches or centimeters for:

- Diameter (circular culverts)
- Span and Rise (arch, metal box, and elliptical culverts)
- Height and Width (box culverts)

When a culvert shape with pre-defined sizes (high and low profile arches, pipe-arches, or metal boxes) is selected, the Details button will open another window that lists the available dimensions for that culvert type. Use the Details button to change culvert dimensions. For a description of how the dimensions are defined for the different culvert shapes, see Culvert Shapes.

Material

Use the drop down menu to select the culvert construction material. If the culvert consists of corrugated metal, select the appropriate corrugation dimensions. The selected material will determine the default Mannings roughness coefficient (n) for the culvert. If your culvert material is not in the drop down menu, you may enter a text description into the field and input your own roughness coefficient. See Culvert Material and Construction and Corrugations for more information.

Installation

The installation field has two options, At Grade and Embedded:

> **At Grade** - Standard installation, with the culvert bottom (invert) placed on the surface of the channel bed. Except for arches and metal boxes, which have open bottoms, the At Grade option assumes the bottom material is the same as the rest of the culvert.
>
> **Embedded** - Culvert bottom (invert) is depressed (countersunk) below the streambed to retain stream material, producing a natural channel bottom throughout the culvert. The embedded installation can also be used if the culvert bottom has been lined with concrete or other material.

After selecting the Embedded option enter either the depth the culvert bottom is placed below the streambed material (if it is concrete lined, enter the thickness of the concrete) or enter the percent of the total culvert height that is embedded. FishXing will auto-calculate the corresponding depth. For additional information see Entering Embedded Culvert Data.

Note: FishXing assumes that the embedded depth is uniform throughout the length of the culvert. The program does not directly allow for a partially embedded culvert or where the embedded depth varies.

Culvert Roughness

Enter or select a roughness coefficient for the selected culvert material. FishXing uses Manning's Roughness Coefficient (n) by default, but you can also choose to use the Darcy Friction Factor (f) or the Chezy Coefficient (C) from the Options pull-down menu on the Navigation Bar. Default values are entered automatically when you select the culvert Construction Type. The ellipsis button (...) will open a new window with an expanded T of Manning's n values.

Bottom Roughness

Enter or select a Manning's roughness coefficient (n) for the material along the culvert bottom. It may be natural streambed material, engineered rock and streambed material, smooth or roughened concrete or other materials. The ellipsis button (...) will open a new window with an expanded Table of Manning's n values.

This field is only activated for embedded or open-bottom culverts. Open-bottom shapes available in FishXing are:

- Single radius arches
- High and low profile arches
- Metal boxes

Culvert Length

Enter the total length measured from the culvert inlet bottom to the culvert outlet bottom.

Culvert Elevations and Slope

FishXing allows you to choose between:

(1) Entering the inlet and outlet bottom elevations and have the software auto-calculate the slope or

(2) Entering the outlet bottom elevation and the culvert slope and have the inlet bottom elevation auto-calculated.

Select the field you wish to enter, by activating the radio button. The non-selected field will be grayed-back and display the auto-calculated value. The inlet and outlet elevations should correspond to the locations used to determine the culvert length.

Inlet Bottom Elevation - Enter the elevation of the inlet bottom (invert). If the culvert is embedded or is an open-bottom culvert, enter the elevation of the channel bed at the inlet.

Culvert Slope - Enter the percent slope of the culvert bottom. If the culvert is embedded or is an open-bottom arch, enter the slope of the bed within the culvert.

Outlet Bottom Elevation - Enter the elevation of the culvert outlet bottom (invert). If the culvert is embedded or is open-bottom enter the elevation of the channel bed at the outlet.

FishXing assumes the bottom slope of an embedded or open bottom culvert is the same as the culvert slope. FishXing cannot directly model hydraulics of culverts containing a bottom slope substantially different from the slope of the installed culvert. See Embedded Culverts for more information.

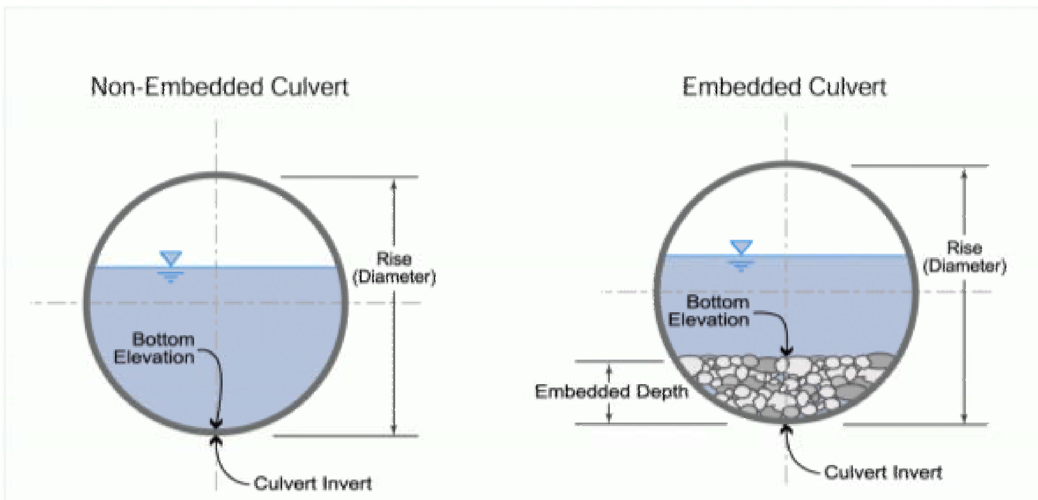
Note: All elevations entered in FishXing should be tied to a common datum.

Entrance Loss

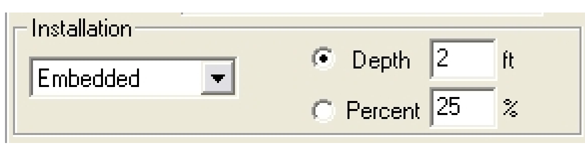
The Entrance Loss Coefficient (Ke) is a constant used to determine the amount of energy loss as the water enters the culvert inlet. The entrance loss coefficient is based on the culvert inlet configuration. The coefficient can range between 0 and 1, with larger values associated with greater energy loss. See Inlet Head Loss Coefficient for more information.

Entering Embedded Culvert Data

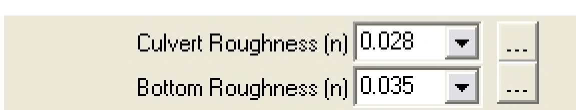
If the culvert in your analysis is embedded, open bottomed or has a bottom material that is different than the side material, use the Embedded Culvert option in the Installation section of the Crossing Input Window.



Step 1. Select **Embedded** Form the **Installation** drop down and select Depth for a known depth or select Percent for a new design, FishXing will auto calculate the corresponding value.



Step 2. Select a roughness coefficient for the Culvert and for the Bottom Material using the drop down menu or by entering your own estimate.

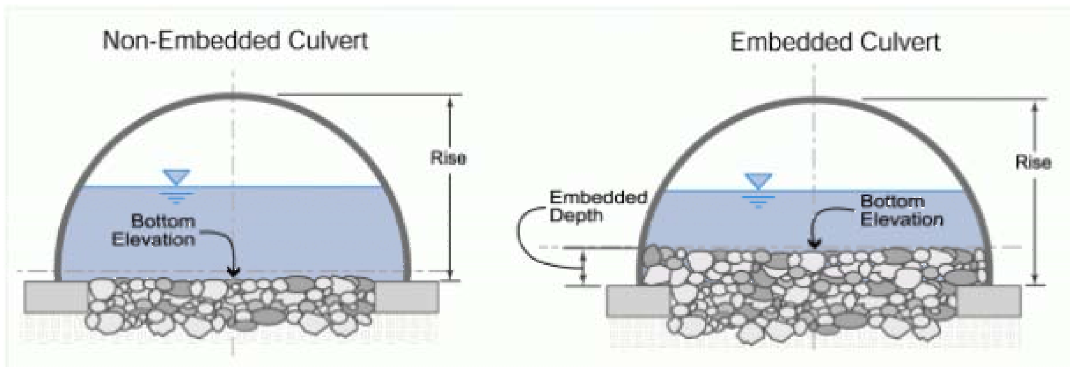


FishXing uses **Manning's n** as a default roughness coefficient, an expanded table of Manning's n values is available by pressing the Ellipsis Button to the right of the field.

Step 3. The **Bottom Elevations** and **Slope** that are entered in the Culvert Information are for the channel bed within the culvert. FishXing will use the embedded depth to place the invert of the culvert below the channel grade.

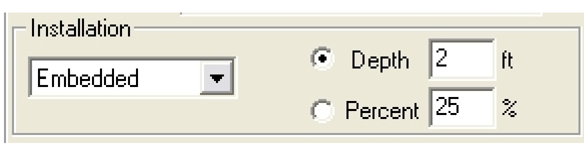
> **Note:** FishXing assumes that the bottom material is flat as viewed in section across the culvert and the depth is uniform throughout the culvert at the same slope of the culvert.

If the culvert is an **Open Bottom** structure (High /Low Profile Arch, Single Radius Arch or Metal Box) the bottom material may be streambed material, concrete, corrugated metal or some other type of paving. In this case the culvert might not be embedded but still has a different bottom roughness. FishXing will prompt you to enter a Bottom Roughness value.



Percent embedded is calculated with respect to the rise or diameter of the culvert at the centerline. many regional design guidelines have a minimum embedment depth criteria that is based on a percent of the culvert rise.

Example:
For an 8 foot circular culvert that is embedded 2 feet, the % Embedded is 25%.



See also: Embedded Culverts, Culvert Shapes and Entering Roughness Coefficients

Fish Passage Flows

The Fish Passage Flows portion of the Crossing Input Window is where you enter the Low and High Fish Passage design flows. Profiles will be generated for each of these flows and fish passage conditions will be examined at all flows between them.

- **Low and High Passage Flow** - The Low Passage Flow and High Passage Flow define the range of discharges that will be analyzed for fish passage. There are few situations in which fish passage can be maintained during flood flows. Additionally, it may not be necessary to provide upstream passage conditions during periods of low flow when fish are not attempting to move upstream. Many state and Federal agencies have guidelines for selecting the low and high passage flows, commonly referred to as fish passage design flows. See Design Flow Guidelines for a list of current guidelines.

Standard engineering practices dictate that culverts need to be designed to pass water and in many cases wood, bedload and debris at high flows. Commonly the event with a 100-year return period is the maximum design flow. You can use FishXing to model additional flows by using the **Flow Calculator**, which is located on the Output Summary Window.

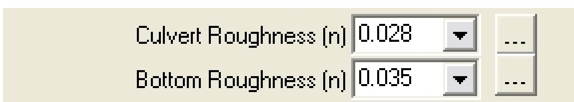
Entering Roughness Coefficients

The roughness of a culvert will have a significant effect on the flow through the culvert. The energy loss due to the hydraulic resistance or roughness of a culvert is part of the "hydraulic price" of flow through a pipe. Two commonly used equations to describe the flow as a function roughness in a culvert are the Darcy equation and the Manning equation. In these equations the roughness is represented with a resistance or roughness coefficient, either Manning's n or the Darcy Friction Factor.

Manning's n

FishXing uses Manning's n as a default resistance coefficient for both culvert material and bottom material, when different. FishXing will require you to enter a Bottom Roughness if the culvert installation is Embedded or if the selected culvert shape is an open bottom structure (High /Low Profile Arch, Single Radius Arch or Metal Box). FishXing then computes a Composite Roughness for determining flow resistance in the hydraulic calculations.

To select a roughness coefficient for the Culvert and for the Bottom Material use the drop down menu or by entering your own estimate. FishXing provides default values of roughness only when using Manning's n.

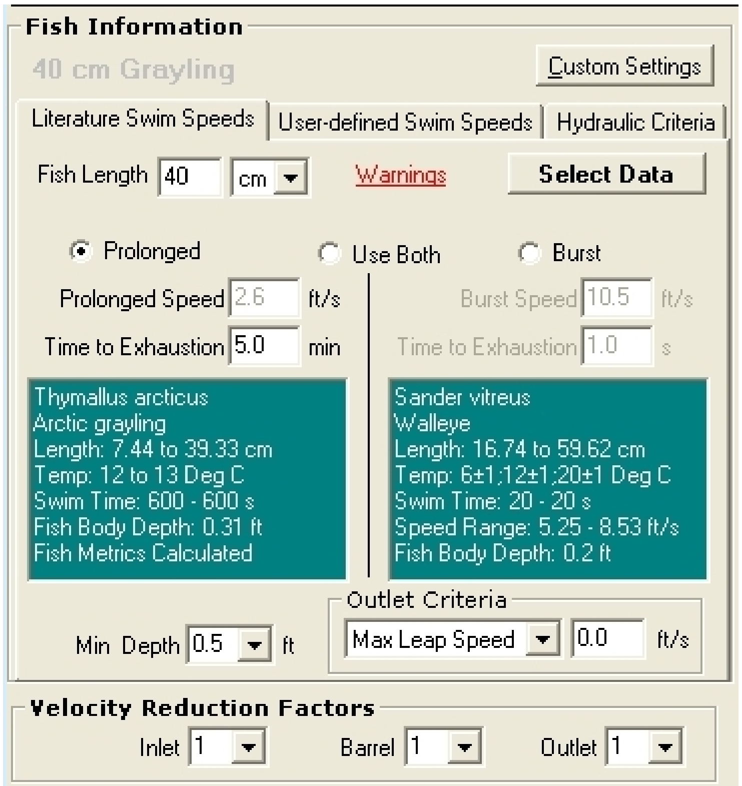


An expanded table of Manning's n values is available by pressing the Ellipsis Button to the right of the field. These are provided as a reference and are not directly selectable. You must type in the desired value or copy and paste from the table using the Ctrl+C and Ctrl+V commands respectively.

Darcy and Chezy Friction Factor

You can change the resistance method used by for hydraulic calculations by selecting **Roughness Calculations** in the **Options** menu on the **Navigation Bar**. If the Darcy-Weisbach Friction Factor or the Chezy Coefficient is selected you may only enter a single roughness coefficient for the culvert, even if it is embedded. When values are available the Darcy or Chezy methods can be used to model Baffle Hydraulics in the culvert.

Fish Information



Fish Information:

The Fish Information portion of the Input Window for entering the parameters and criteria used to evaluate fish passage conditions. You may select from three different methods to describe the fish capabilities and fish passage requirements:

- Literature Swim Speeds – select from a list of swimming abilities that has been compiled from the available literature.
- User-Defined Swim Speeds – enter swim speed data for a specific fish.
- Hydraulic Criteria – use water velocity, water depth, and outlet drop criteria to assess passage conditions

Although data entered into each tab will be retained, the tab that is active will be the method used in the analysis.

Custom Settings:

Use the **Custom Settings** button to create predefined Fish Information settings. This feature allows you to save the currently entered fish information as a custom setting, allowing you to quickly recall the saved settings when analyzing other crossings. The Fish Information Custom Settings can be used to save information entered into any of the three tabs. Hydraulic Criteria and Swim Speeds are each saved separately. Each custom setting must be given a unique name, which is listed in the drop down menu below the custom settings button.

To save data entered into the active fish information tab:

1. Open the **Custom Settings** dropdown by clicking the button
2. Select **Edit or Add Settings** or **Save Current Settings**
3. Enter a unique name for the settings and press **Save**
4. The saved settings should now be available in the Custom Settings dropdown

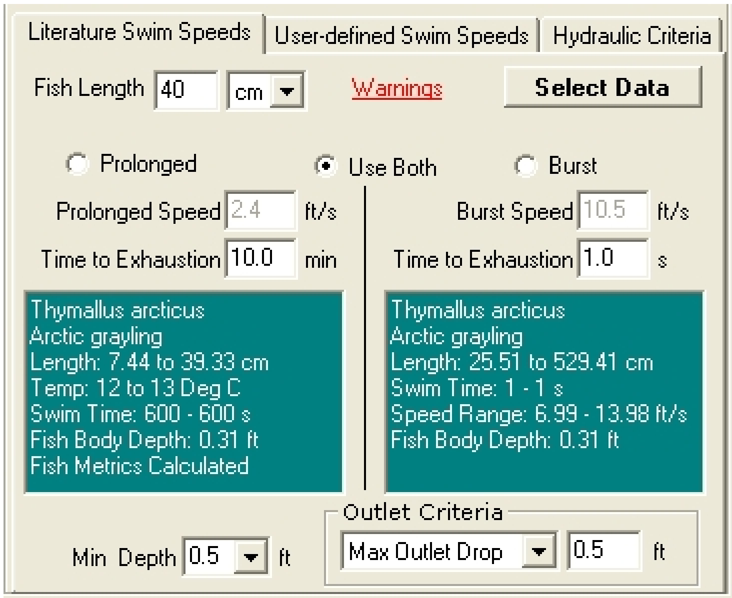
To use previously saved fish information settings, select from the list of names that appear in the **Custom Settings** dropdown menu.

The Name given to the Custom Setting is displayed in the upper left-hand corner of the Fish Information box. If no Custom Setting has been selected the field will remain blank. If you change any of the fish information or select a different tab, the name will become grayed-back. This is to warn you that the fish information associated with the selected Custom Setting is no longer being used.

Velocity Reduction Factors:

Ratio of occupied water velocity (velocity within the region where the fish swims) to cross sectional average water velocity. The calculated average water velocity is multiplied by the reduction factor to account for areas of reduced velocity utilized by a swimming fish to conserve energy. The use of Velocity Reduction Factors is usually only applicable for small fish. Different Velocity Reduction Factors can be applied to the inlet, barrel, and outlet zones. A default value of 1.0 is provided.

Literature Swim Speeds Input Window



Literature Swim Speeds Tab

In the Literature Swim Speeds tab, you select swim capabilities from a provided set of swim speed information obtained from available literature. Select the desired swim speed from the compiled database by clicking the **Select Data** button, which will bring up the Literature Swim Speeds Window.

Fish Length:

Enter the Total Length of the fish, if only fork length is available, you may use the Fish Length Conversion Table to estimate total length. The difference between fork and total length is likely only significant for smaller fishes.

Warnings:

If any of the user-defined variables are outside the range of conditions that define the Literature values, a red *Warnings* link will be displayed. Clicking on the link will display the warnings in a new window. Warnings are assigned when entering a fish length or time to exhaustion that falls outside of the lengths or swim times associated with the selected swim speed test. A warning is also given if you enter a minimum water depth less than the reported Fish Body Depth. The warnings are only applicable to the Literature Swim Speeds tab. They are informational and do not impede calculations.

Select Data:

Pressing the **Select Data** button will open the Literature Swim Speeds Window. From the database you can select Prolonged and Burst Swim speeds for a variety of species. Selecting a line in the table will display the reference in the information box. The complete references can be found in References. The complete data set can be viewed and copied by pressing the **View Swim Speed Data** button on the lower left. The entire data table can also be downloaded in a spreadsheet format from the help files in the Swim Speed Table section.

Prolonged / Use Both / Burst:

Select the Swim Mode to be used in the model run. Swimming performance is classified into three major categories: sustained, prolonged and burst. FishXing uses only prolonged and burst. If either **Burst** or **Prolonged** are selected, the swimming speeds associated with the category will be exclusively used throughout the culvert. If **Use Both** is selected FishXing allows the fish to switch between prolonged and burst speeds as needed. The fish are able to maintain burst or prolonged speeds for the duration of time entered in the Time to Exhaustion field.

Choosing **Use Both** can be useful when water velocities in the barrel of the culvert are low enough for passage in the prolonged swim mode, but the velocities within the inlet and outlet zones of the culvert are fast enough to require swimming in the burst mode.

Prolonged Speed:

Prolonged swim speeds usually can be maintained by the fish for 20 seconds to 200 minutes before ending in fatigue. Most fish passage velocity criteria are based on the prolonged swim speed of the target fish.

Burst Speed:

Burst speeds are the highest speeds attainable by the fish and can be maintained for only short periods of time, usually less than 20 seconds. Fish may need to use burst speeds to swim through areas of high velocities in the culvert.

Time to Exhaustion:

Time to Exhaustion is the period of time that a fish can maintain the swim speed selected before becoming exhausted. Times typically range between 20 seconds to 200 minutes for prolonged swimming speeds and 1 to 20 seconds for burst swimming speeds.

Notes and References:

The green notes area displays information about the literature swim speed selected from the database, including scientific and common species names and test conditions used to derive the swim speed.

Min Depth:

The minimum water depth is the depth of flow within the crossing required for successful fish passage. A depth barrier is reported if the calculated water depth is below the specified Min Depth. The Min Depth should be sufficient to fully submerge the species being modeled because fish that are not fully submerged cannot obtain optimal swimming performance. If the Min Depth is less than the Fish Body Depth reported in the Notes (green text box), a warning will be issued. See Water Depth for Swimming for a discussion on the limitations of swim speed equations when a fish is not fully submerged.

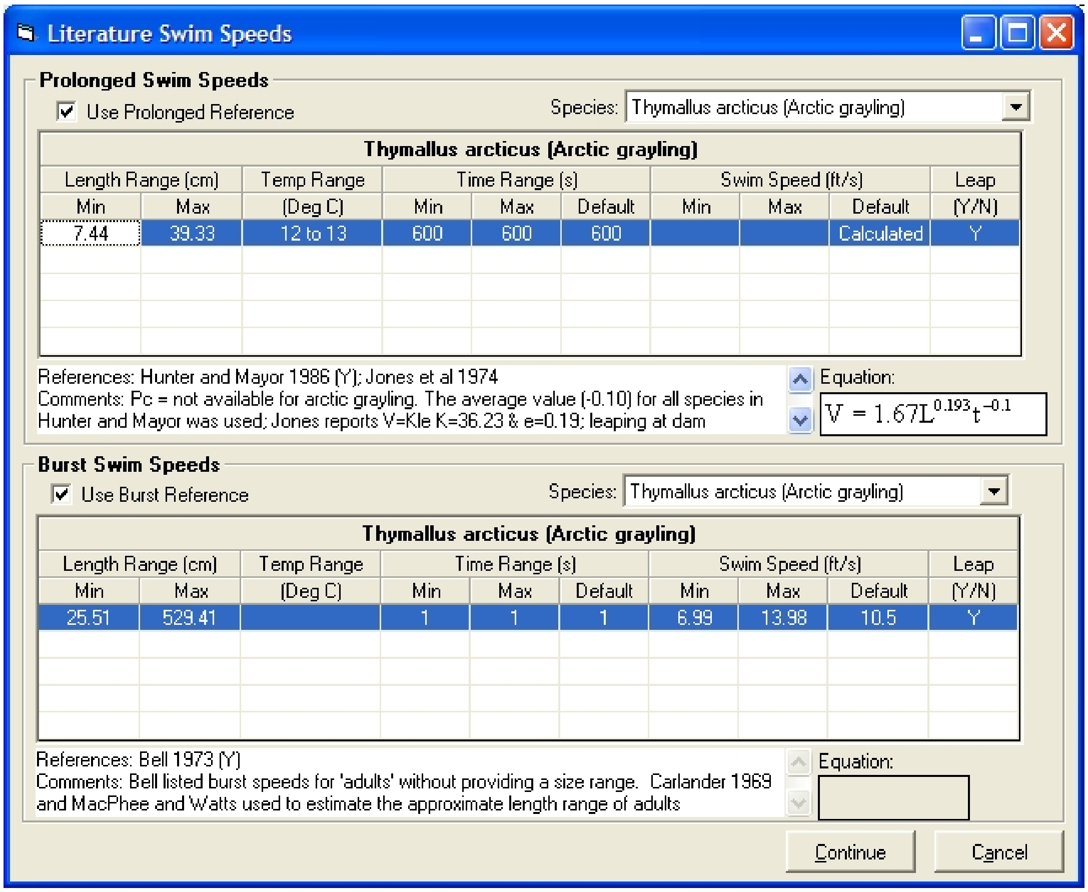
Outlet Criteria:

From the dropdown select the method you wish to use for analyzing fish passage conditions at the culvert outlet. The two options are:

> **Max Leap Speed** – Enter the maximum speed the fish can leap out of the water when attempting to leap into the culvert outlet. This speed is often at the upper end of the fish's burst swimming ability. Leaping calculations only occur when the fish is unable to swim into the culvert. See Leaping Calculations and Entering the Culvert: Outlet Leap or Swim or an explanation of how FishXing determines when the fish can swim into a culvert rather than leap.
>
> **Max Outlet Drop** – Enter the maximum allowable drop in water surface at the outlet. FishXing will identify a drop barrier when the outlet drop is greater than the specified Max Outlet Drop. The outlet drop is measured between the water surface in the outlet and the tailwater surface. Unlike the leaping calculations, the outlet drop criteria apply even when the tailwater elevation is above the culvert bottom. See Outlet Drop Criteria for a discussion on how and when the drop is calculated.

Swim Speed Table

To view the complete table click here, View Swim Speed Table



FishXing includes a table that contains swim performance information for various species. The performance information was compiled from the available literature and is of two basic types: 1) burst and prolonged swimming speeds (cm/s); and 2) swim speed equations that calculate swimming speeds using factors that influence swim speed such as time to exhaustion and/or fish length. The variability regarding the swimming speed estimate was included when available.

The table also includes useful information about the conditions of the tests from which the swimming speeds or equations were derived such as: length of the fish, type of swimming test, test variables (time to exhaustion, and time between velocity increases), water temperature, comments about test procedure or the reliability of the swimming speed estimate, and literature cited.

Selecting Burst and Prolonged Swim Speeds

The Swim Speed Window contains two grids that show a subset of the data compiled in the complete table. The data shown are intended to inform your decision as to which (if any) lines to use as your analysis fish. If the particular reference cited included the following information then it is included in the table: Fish Length Range, Water Temperature in which experiment was conducted, Time Range (depends on experimental method used), Swim Speed Range, and whether the species is known to leap. For each line in the table the References and any comments made during compilation of the information.

Use Prolonged Reference and Use Burst Reference Check Boxes

This window requires you to select one reference for Prolonged swimming and one for Burst unless one of these check boxes is unchecked. If an analysis using only Burst or only Prolonged swimming is desired, uncheck the box associated with the other speed mode and a reference for that mode will no longer be required. Upon return to the main Input page the appropriate mode will be selected (Burst or Prolonged).

See **Prolonged / Use Both / Burst:**

Selecting Species

Choose a species from either the Prolonged or Burst Species drop-down lists. The first time you choose a species, if there is a corresponding entry in the other list it will be shown. For example, upon opening the form you go to the Prolonged Species list and choose *Lampetra tridentate*. This species will show up in both the Prolonged and Burst grids. However, if you now change either species, the other one will not change.

Each grid will show a list of references available for that species. You can choose one from each list that most closely represents the species, size class, and water temperature range for the analysis being performed.

Link to Fish Performance

The complete Swim Speeds Table can be viewed by clicking here: **Swim Speeds Table.** More information about fish performance can be viewed by clicking here: **Fish Performance.**

Calculated Speeds

If the word “Calculated” appears in the default swim speed column it means that the swim speeds derived from that reference are dependent on Fish Length, Time to Exhaustion, or both. When the reference is chosen the equation used will show in the Equation box. If the reference is used, upon return to the main Input page, the swim speeds will be calculated. If you change either the fish length or time to exhaustion the speed will be recalculated dynamically.

Length Range – shows the range of fish total lengths used in the research associated with each reference which was provided by the author.

Temp Range – shows the range of water temperatures used in the research associated with each reference which was provided by the author.

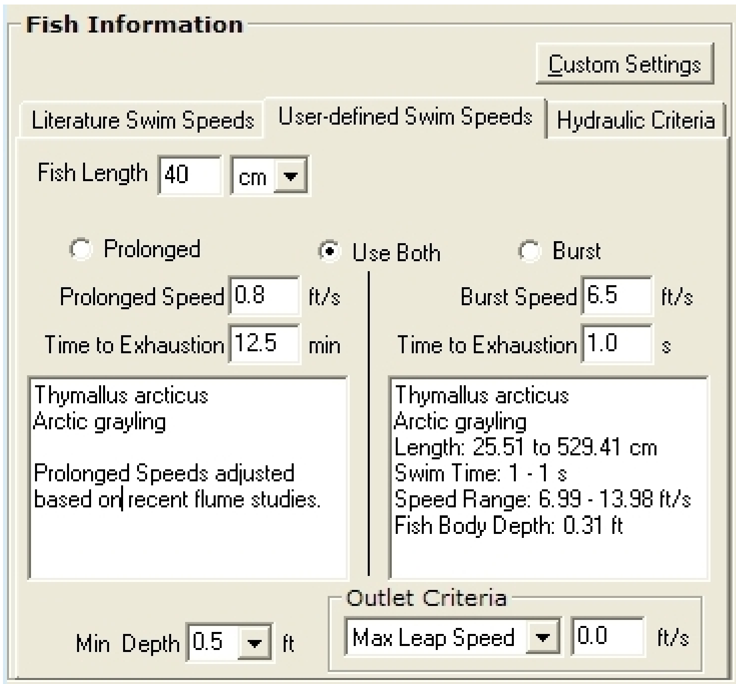
Time Range – shows the range of times to exhaustion used in the research associated with each reference which was provided by the author. If it was not provided default values of 5 seconds for burst and 30 minutes for prolonged were inserted in the table.

Swim Speed – shows the range of fish swimming speeds observed in the research associated with each reference which was provided by the author. The default swim speed was derived from some measure of central tendency of the range of speeds. The measures used are shown in the complete **Swim Speeds Table.**

Leap – indicates whether the species is known to leap. In many cases this is not known and it is assumed that the fish can leap. If a fish is not a leaper then the outlet criteria is set to Max Leap Speed and the Maximum Leap Speed is defaulted to zero indicating that the fish is unable to negotiate a leap of any magnitude.

References and Comments – for the selected line in the grid are shown in the box below each grid.

User Defined Swim Speeds Input Window



User Defined Swim Speeds Tab

The User Defined Swim Speeds tab allows you to enter and modify swim capabilities.

Note: When data from the Literature Swim Speeds tab is saved as a **Custom Setting** it will be saved as a User Defined Swim Speed.

Fish Length:

Enter the Total Length of the fish, if only fork length is available, you may use the Fish Length Conversion Table to estimate total length. The difference between fork and total length is likely only significant for smaller fishes.

Prolonged / Use Both / Burst:

Select the Swim Mode to be used in the model run. Swimming performance is classified into three major categories: sustained, prolonged and burst. FishXing uses only prolonged and burst. If either **Burst** or **Prolonged** are selected, the swimming speeds associated with the category will be exclusively used through out the culvert. If **Use Both** is selected FishXing allows the fish to switch between prolonged and burst speeds as needed. The fish are able to maintain burst or prolonged speeds for the duration of time entered in the **Time to Exhaustion** field.

Choosing **Use Both** can be useful when water velocities in the barrel of the culvert are low enough for passage in the prolonged swim mode, but the velocities within the inlet and outlet zones of the culvert are fast enough to require swimming in the burst mode.

Prolonged Speed:

Prolonged swim speeds usually can be maintained by the fish for 20 seconds to 200 minutes before ending in fatigue. Most fish passage velocity criteria are based on the prolonged swim speed of the target fish.

Burst Speed:

Burst speeds are the highest speeds attainable by the fish and can be maintained for only short periods of time, usually less than 20 seconds. Fish may need to use burst speeds to swim through areas of high velocities in the culvert.

Time to Exhaustion:

Time to Exhaustion is the period of time that a fish can maintain the swim speed selected before becoming exhausted. Times typically range between 20 seconds to 200 minutes for prolonged swimming speeds and 1 to 20 seconds for burst swimming speeds.

Notes and References:

This Notes area is a text box available for entering comments or referencing the source of the inputted swim speeds.

Min Depth:

The minimum water depth is the depth of flow within the crossing required for successful fish passage. A depth barrier is reported if the calculated water depth is below the specified Min Depth. The Min Depth should be sufficient to fully submerge the species being modeled because fish that are not fully submerged cannot obtain optimal swimming performance. If the Min Depth is less than the Fish Body Depth reported in the Notes (green text box), a warning will be issued. See Water Depth for Swimming for a discussion on the limitations of swim speed equations when a fish is not fully submerged.

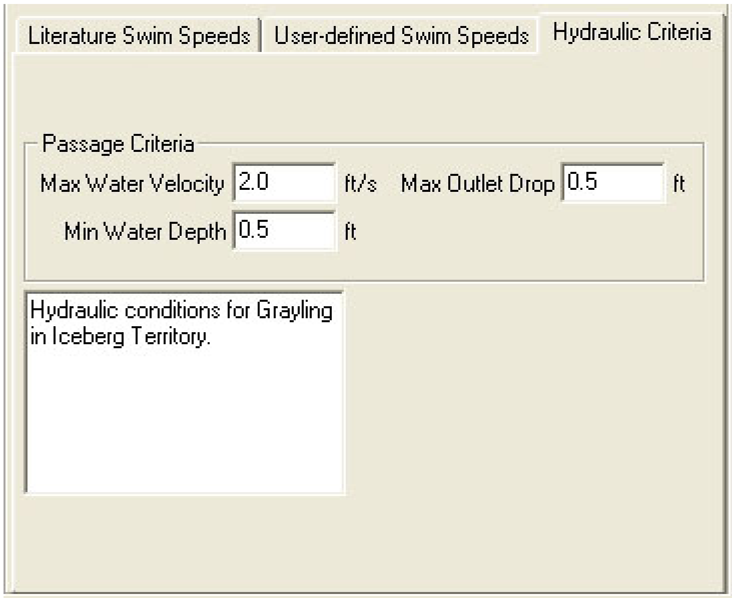
Outlet Criteria:

From the dropdown select the method you wish to use for analyzing fish passage conditions at the culvert outlet. The two options are:

Max Leap Speed – Enter the maximum speed the fish can leap out of the water when attempting to leap into the culvert outlet. This speed is often at the upper end of the fish's burst swimming ability. Leaping calculations only occur when the fish is unable to swim into the culvert. See Leaping Calculations and Entering the Culvert: Outlet Leap or Swim or an explanation of how FishXing determines when the fish can swim into a culvert rather than leap.

Max Outlet Drop – Enter the maximum allowable drop in water surface at the outlet. FishXing will identify a drop barrier when the outlet drop is greater than the specified Max Outlet Drop. The outlet drop is measured between the water surface in the outlet and the tailwater surface. Unlike the leaping calculations, the outlet drop criteria apply even when the tailwater elevation is above the culvert bottom. See Outlet Drop Criteria for a discussion on how and when the drop is calculated.

Hydraulic Criteria Input Window



Hydraulic Criteria Tab:

In many cases fish passage conditions may be evaluated based on established hydraulic criteria rather than entering swimming abilities. In the Hydraulic Criteria tab you enter specific hydraulic requirements that must be satisfied to meet desired fish passage conditions.

Maximum Water Velocity:

Fastest water velocity in the culvert that still allows for fish passage. A velocity barrier is identified if water velocity (reduced by the velocity reduction factors, if applicable) within any portion of the culvert is above the entered Maximum Water Velocity.

Max Outlet Drop:

The maximum allowable water surface drop at the outlet that the fish will be able to enter the culvert. The drop is calculated as the difference between the water surface in the outlet and the tailwater surface. FishXing will identify a drop barrier when the calculated outlet drop is greater than the specified Max Outlet Drop. Unlike the leaping calculations, the outlet drop criteria apply even when the tailwater surface is above the culvert bottom. See Outlet Drop Criteria for a discussion on how and when the drop is calculated.

Min Water Depth:

The depth of flow within the culvert required for successful fish passage. A depth barrier is reported if the calculated water depth is below the specified Min Depth at any location within the culvert. The shallowest depth that allows fish passage is usually the depth required to completely submerge the species of interest. See Water Depth for Swimming for a discussion on the limitations of swim speed equations when a fish is not fully submerged.

Notes and References:

Notes area is a text box available for entering comments or referencing the source of the inputted hydraulic criteria.

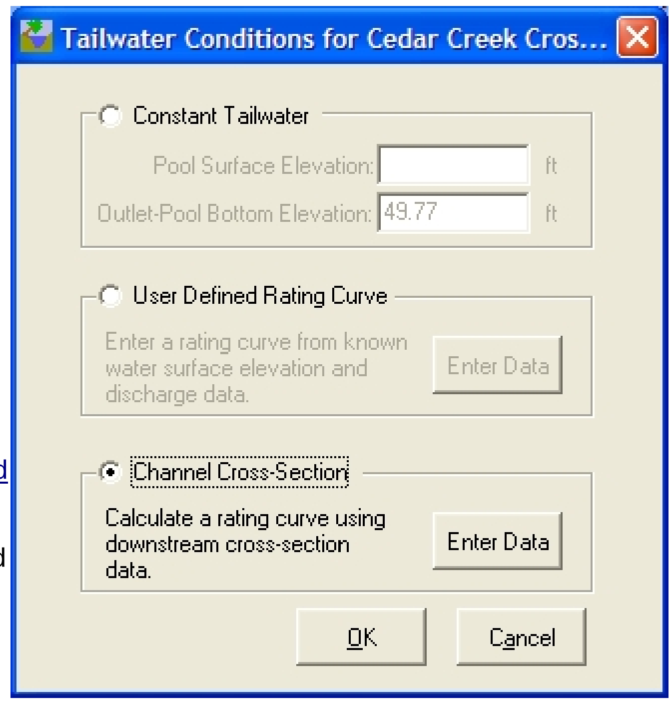
Velocity Reduction Factors

Ratio of occupied water velocity (velocity within the region where the fish swims) to cross sectional average water velocity. The average water velocity is multiplied by the reduction factor to account for areas of reduced velocity utilized by a swimming fish to conserve energy. The use of Velocity Reduction Factors is usually only applicable for small fish. Different Velocity Reduction Factors can be applied to the inlet, barrel, and outlet zones.

See: Occupied Velocity, Culvert Zones

Tailwater Methods

FishXing allows you to define the Tailwater elevation using any of three different methods. The tailwater elevation can be constant or varying with the flow as described by a Rating Curve.



The Tailwater Method window is opened from the Crossing Input Window, and specifies tailwater elevations for the crossing. As discharge through the culvert increases, the tailwater elevation may also increase. FishXing offers three different methods for defining tailwater elevation:

1) Constant Tailwater Method

2) User Defined Rating Curve Method

3) Channel Cross-Section Method

The water surface immediately below the culvert outlet is referred to as the Tailwater. Typically the tailwater is a function of the flow rising as flows increase.

The height of the tailwater can have a significant influence on passage conditions. A high tailwater can backwater the culvert. A low tailwater may force the fish to leap to enter the culvert.

To select the desired tailwater method to use in the culvert calculations:

• Press the Tailwater button on the Crossing Input Window and select the radio button next to the desired method. The text in the activated box will be highlighted, leaving the other methods grayed-out.

• If you select the User Defined Rating Curve Method or the Channel Cross-Section Method, click on the Enter Data button to open the data entry window.

The method that is currently being used for analysis will be displayed next to the Tailwater button on the Crossing Input Window.

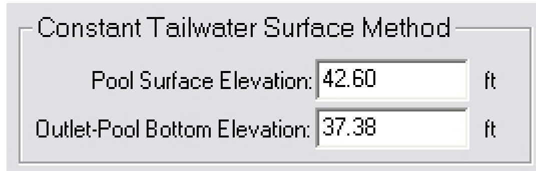
To change the Method for calculating tailwater elevations:

• Activate the desired method by clicking into the grayed-out box on the Tailwater Methods Window. The data entered into the previously selected method(s) will be saved, allowing you to switch between tailwater methods without losing entered data.

See also: Tailwater Control

Constant Tailwater Method

The Constant Water Surface Method is useful where tailwater elevation does not change with changes in discharge. This method requires the least amount of site information and may be appropriate for preliminary culvert assessments.



Pool Surface Elevation - Enter the water surface elevation of the outlet pool.

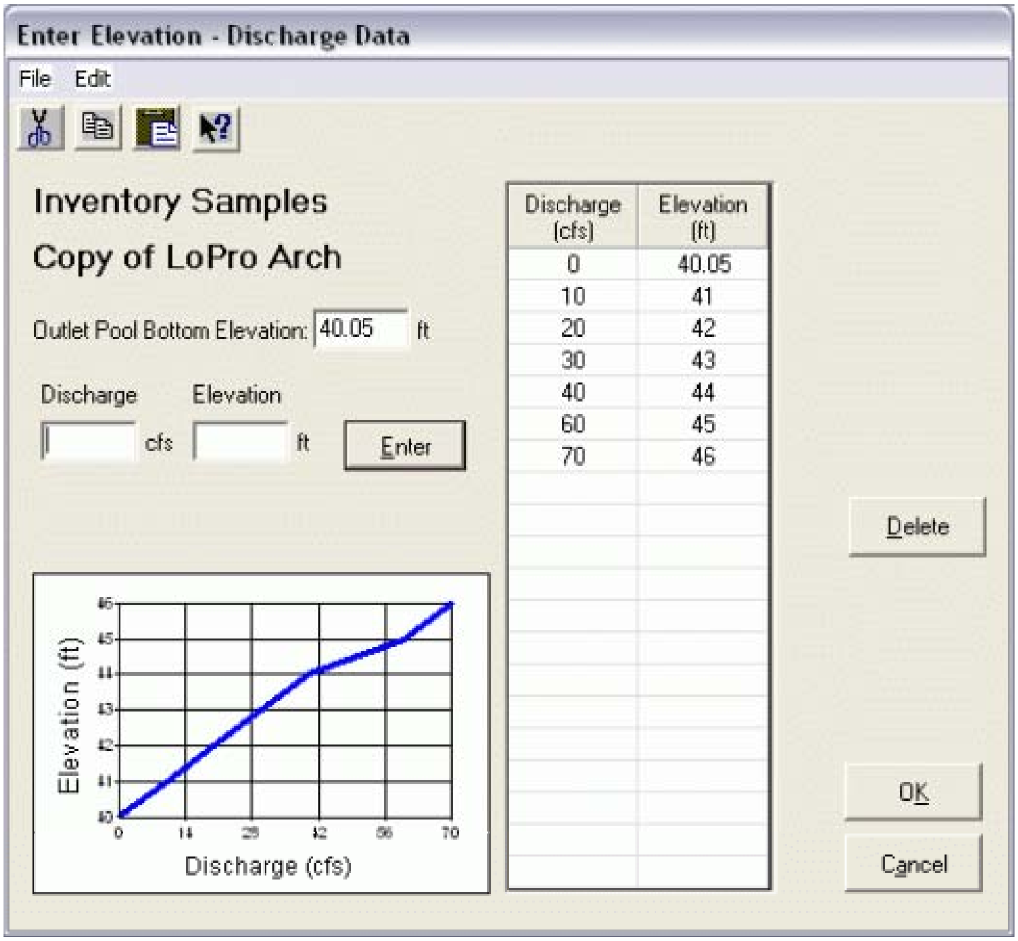
Outlet Pool Bottom Elevation – Enter the elevation of the lowest point in the outlet pool. The Pool Bottom Elevation will be used to calculate the pool depth at the culvert outlet and to determine if there is sufficient depth for leaping when required.

> **Note:** All elevations should be tied to the surveyed elevation of the culvert inlet and outlet by use of a common datum.

See also: Pool Depth and Leaping Calculations

User Defined Rating Curve Method

The Rating Curve Method allows you to specify tailwater elevations corresponding to specific flows, forming a rating curve relating flow and tailwater elevation.



Outlet Pool Bottom Elevation – Enter the elevation of the lowest point in the outlet pool bottom. The pool bottom elevation must be less than or equal to the tailwater elevation at zero flow. This Pool Bottom Elevation will be used to calculate the pool depth at the culvert outlet.

Elevation – The tailwater elevation at a given flow.

Flow – The flow rate corresponding to the tailwater elevation.

Entering Flow and Elevation:

1. Enter the tailwater elevation in the field directly under Elevation. Then press tab to move to the next field.

2. Enter the corresponding discharge into the field directly under Discharge. Then press the Enter key or click on the Enter button to input the point into the table on the right.

3. To delete a point(s) that has been entered into the table on the right, highlight the row(s) you wish to delete using the mouse. Then click on the Delete Row button.

4. When all the points are entered, click on the Done button.

Note: The first tailwater elevation must have a corresponding discharge value equal to zero. Also, the tailwater elevation cannot be less than the Outlet-Pool Bottom Elevation.

Alternate Method for Entering Data:

If you already have data entered into a spreadsheet you can copy and paste the data directly into the FishXing Rating Table.

1. Select the data from its original location and copy it.

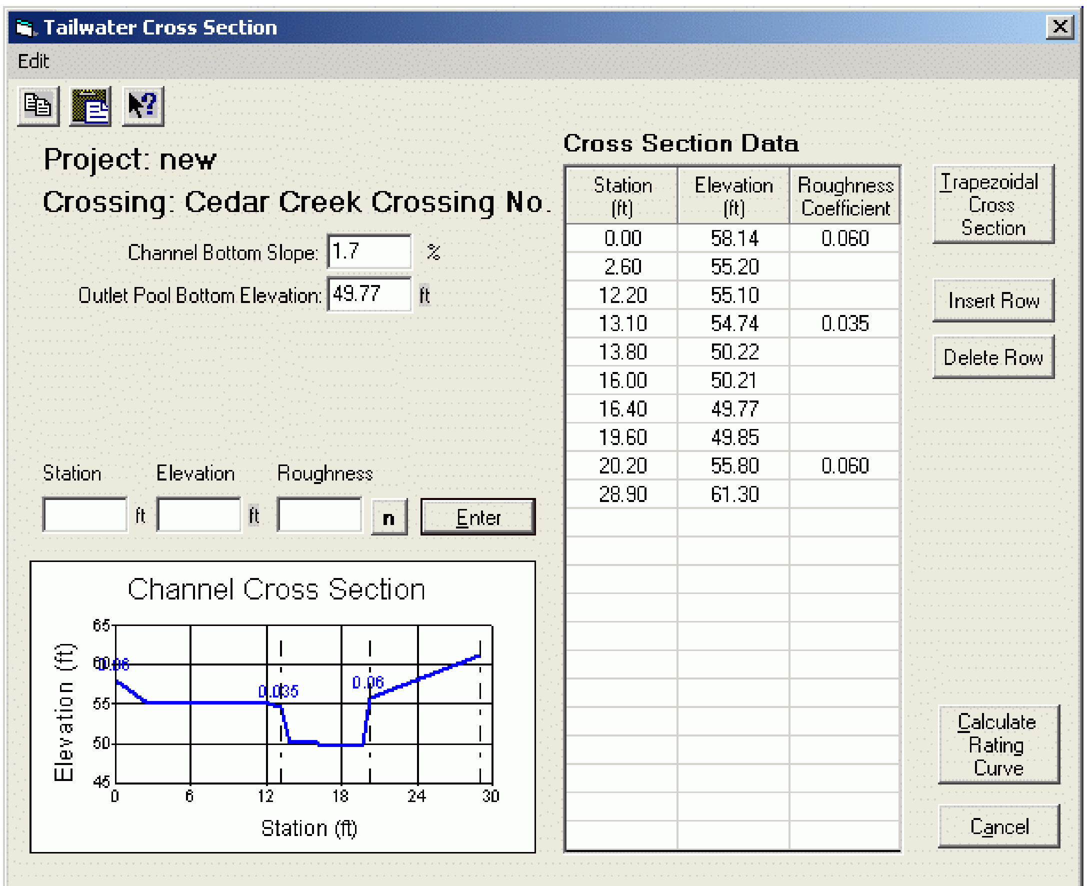
2. Data can then be pasted directly into the Rating Table by highlighting the desired area and selecting paste from the edit menu.

Note: Ctrl+C and Ctrl+V will also carry out the copy and paste function to import data from a spreadsheet or export from FishXing to a spreadsheet.

Channel Cross-Section Method

The Channel Cross-Section Method allows you to create a Rating Curve that relates tailwater elevation to flow by entering a channel cross section located at the downstream Tailwater Control. FishXing calculates tailwater elevations at different flows by using Manning's Equation which assumes Uniform Flow.

This method requires a surveyed downstream channel cross-section, the downstream channel slope, and an estimate of the Manning's Roughness Coefficient of the downstream channel bottom.



Channel Bottom Slope – Enter the percent slope of the channel bottom or water surface downstream of the cross section. The slope should be representative of the channel at and immediately downstream of the cross section. The slope must be positive in the downstream direction.

Outlet Pool Bottom Elevation – Enter the elevation of the lowest point in the outlet pool. This Pool Bottom Elevation will be used to calculate the pool depth at the culvert outlet.

Note: All elevations should be tied to the surveyed elevation of the culvert inlet and outlet by use of a common datum.

Manning's Roughness Coefficient, n – Select or enter a value for the Manning's roughness coefficient. The coefficient can be estimated based on the size and shape of the streambed material or back-calculated from direct measurement of the flow and corresponding channel geometry. The default roughness values in the drop-down box are from the USGS publication, Roughness Characteristics of Natural Channels (Barnes, 1967).

Each segment of the Cross Section can have a unique roughness coefficient to enable a more accurate modeling of overbank areas and will be shown on the Cross Section Graph in the **Tailwater Method** window. Flow in the cross section is calculated based on the n-value last entered in the column of data, if a new n-value is entered it then uses the new value.

Cross Section Survey

The cross-section should be surveyed at the control point in the channel, downstream of the culvert outlet. The control point is a channel section that influences the tailwater elevation. If an outlet pool exists, the control point will usually be located near the pool tail crest immediately downstream of the pool.

See also: Tailwater Control

Entering Cross Section Points:

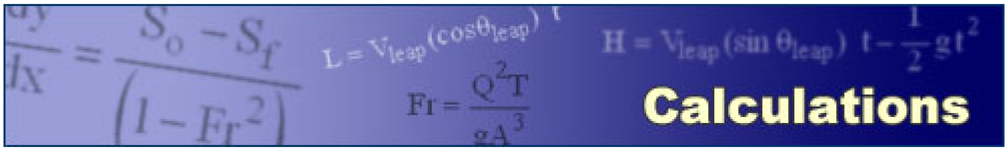
1. Enter the station (horizontal distance across the channel) in the field directly under Station. Then press the tab key to move to the next field.
2. Enter the corresponding elevation into the field directly under Elevation. Then press the Enter key or click on the Enter button to input the survey point into the table on the right. As you enter points into the table, the channel cross-section is auto-drawn in the graph below. All entries are auto-sorted in the table by station, and negative elevations are allowed.
3. To delete a point(s) entered into the table on the right, highlight the row(s) you wish to delete by using the mouse. Then click on the Delete Row button.
4. When all the surveyed points in the cross-section are entered, click on the Compute button. The tailwater–flow rating curve, hydraulic geometry and composite roughness is computed and displayed in a new window.
5. FishXing will automatically use the computed rating table after you click Ok.

Alternate Method for Entering Data:

If you already have data entered into a spreadsheet you can copy and paste the data directly into the FishXing Cross Section Table.

1. Select the data from its original location and copy it.
2. Data can then be pasted directly into the Cross Section Table by highlighting the desired area and selecting paste from the edit menu.

> **Note:** Ctrl+C and Ctrl+V are short cuts for the copy and paste function to import data from a spreadsheet or export from FishXing to a spreadsheet.



Calculations

Topics:

Calculations Overview

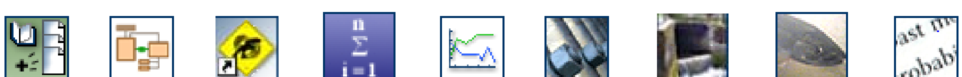
Culvert Hydraulic Calculations

- Water Surface Profiles
- Boundary Conditions
- Gradually Varied Flow
- Full Flow
- Rapidly Varied Flow
- Hydraulic Jumps
- Inlet, Barrel and Outlet Zones
- Headwater Calculations
- Inlet Contraction Velocity
- Tailwater Calculations
- Composite Roughness
- Plunging Flow
- Free Surface Outlet

Fish Calculations Overview

- Outlet Drop Criteria
- Entering the Culvert: Leap or Swim
- Leaping Calculations
- Minimum Plunge Pool Depth
- Insufficient Depth
- Swimming Algorithm

Back to Main Topics:



Main Map Run Calculate Results Culvert Hydraulic Fish Glossary

Calculations Overview

FishXing is a unique software tool that models both culvert hydraulics and fish swimming and leaping performance through the predicted hydraulic environment. The topics covered in *Calculations* are intended to give you a general understanding of the computational methods used by FishXing as well as the assumptions and limitations associated with them. Detailed description and discussion are provided for computational methods that are unique to FishXing.

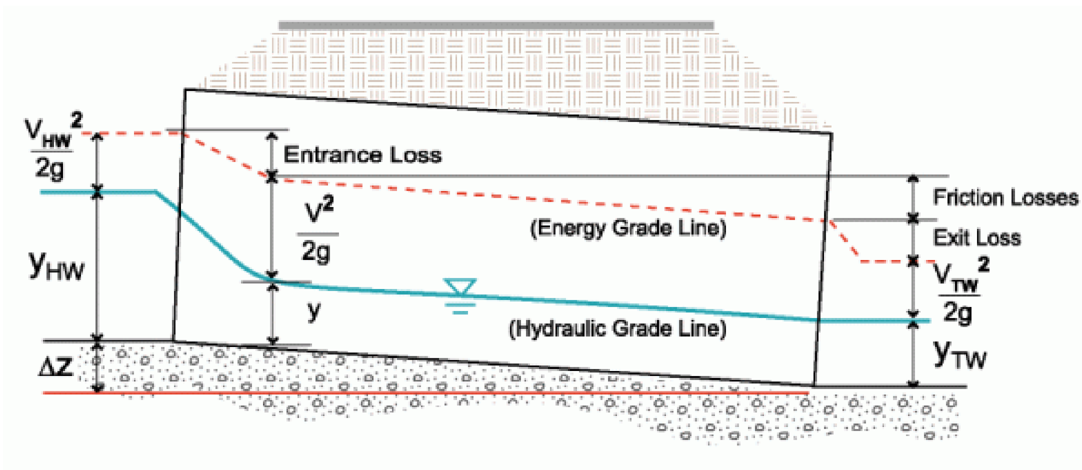
Culvert Calculations

Most culvert hydraulic models are specifically intended for determining culvert capacity at specific headwater elevations. However, they often fail to adequately describe the hydraulic environment a fish encounters within the culvert. Additionally, standard methods for determining culvert capacity typically include a number of assumptions. Although valid for estimating headwater elevations, some of these assumptions may oversimplify our understanding of the hydraulic environment encountered by fish as they swim upstream through a culvert. Since FishXing is principally a tool for evaluating fish passage through culverts, the FishXing model attempts to compute a more realistic hydraulic environment by addressing certain hydraulic conditions differently than standard culvert models. Many of these differences are covered in the Inlet Contraction Velocity and Boundary Conditions topics.

Flow conditions in a culvert encompass a variety of hydraulic environments. Calculating depth of flow in a culvert involves a series of computational decisions.

Fish Calculations

Culvert Hydraulic Calculations Overview



The hydraulic calculations from the culvert outlet to the culvert headwater immediately upstream of the inlet are based on the conservation of energy and mass. This is described in the basic energy balance equation:

$$y_{HW} + \frac{V_{HW}^{2}}{2g} + \Delta Z = y_{TW} + \frac{V_{TW}^{2}}{2g} + y_{\text{Friction Loss}} + y_{\text{Entrance Loss}} + y_{\text{Exit Loss}}$$

Where:

y = Depth (ft, m)

V = Velocity (ft/s, m/s)

ΔZ = Change in elevation (ft,m)

TW = Tailwater

HW = Headwater

g = Accceleration due to gravity (ft/s^2)

In most cases the approach velocity (V_{HW}) is low and the approach velocity head is neglected. Similarly the exit velocity can be neglected in the energy equation if the upstream and downstream channels are similar, reducing the energy equation to:

$$y_{HW} + \Delta Z = y_{TW} + y_{\text{Friction Loss}} + y_{\text{Entrance Loss}} + y_{\text{Exit Loss}}$$

FishXing assumes the headwater (approach) velocity and tailwater velocity are zero and does not include bend losses, junction losses, or grate losses. For determining water depths within the culvert, FishXing solves the appropriate form of the energy equation using a step method. Solutions are obtained at regular intervals throughout the culvert.

Below is an outline of the generalized procedure used in FishXing for determining the water surface profile and water velocities within a culvert at a specific flow:

1. Determine the Tailwater Elevation at the desired flow.

2. Determine Boundary Conditions for solving the Gradually Varied Flow equations.

    - Determine Hydraulic Slope (Mild, Steep, Adverse, Horizontal, Full Flow)

    - Determine Curve Type (Type 1, 2, or 3) based on Hydraulic Slope and Tailwater depth

    - Determine if Free Surface Outlet conditions apply. If so,

        - Calculate the location near the outlet that flow switches from Gradually Varied Flow to Rapidly Varying Flow conditions.

        - Determine the water depth at the Free Surface Outlet.

    - Determine starting location and depth for the downstream and/or upstream boundary.

3. Solve the Gradually Varied Flow or Full Flow equations to obtain a water surface profile through the culvert.

    - Use backwater calculations for non-steep slopes or backwatered steep slope culverts.

    - Use frontwater calculations for steep slopes.

    - For steep slopes, check for a Hydraulic Jump within the culvert.

4. Determine Headwater Depth based on energy losses within the culvert.

5. Calculate average cross sectional water velocities within the culvert and the Contraction Velocity within the Inlet Zone.

6. Calculate Outlet Plunge characteristics.

Classification of Water Surface Profiles

The water surface profile within a culvert can be classified two different ways:

1. **Hydraulic Slope,** which is based on the slope of the culvert bottom and
2. **Hydraulic Curve,** which is based on the relationship of the water depth relative to critical depth and normal depth.

FishXing uses these classifications to determine the appropriate inlet and outlet boundary conditions.

Hydraulic Slope Classifications

The Hydraulic Slope of a culvert at a specific flow classifies the hydraulic regime and defines the type of solution generated from the Gradually Varied Flow calculations.

Hydraulic Slope is determined from:

1. The culvert bottom slope (So) and
2. The relationship between critical depth (y_c) and normal depth (y_n) at a specific flow.

There are five slope classifications:

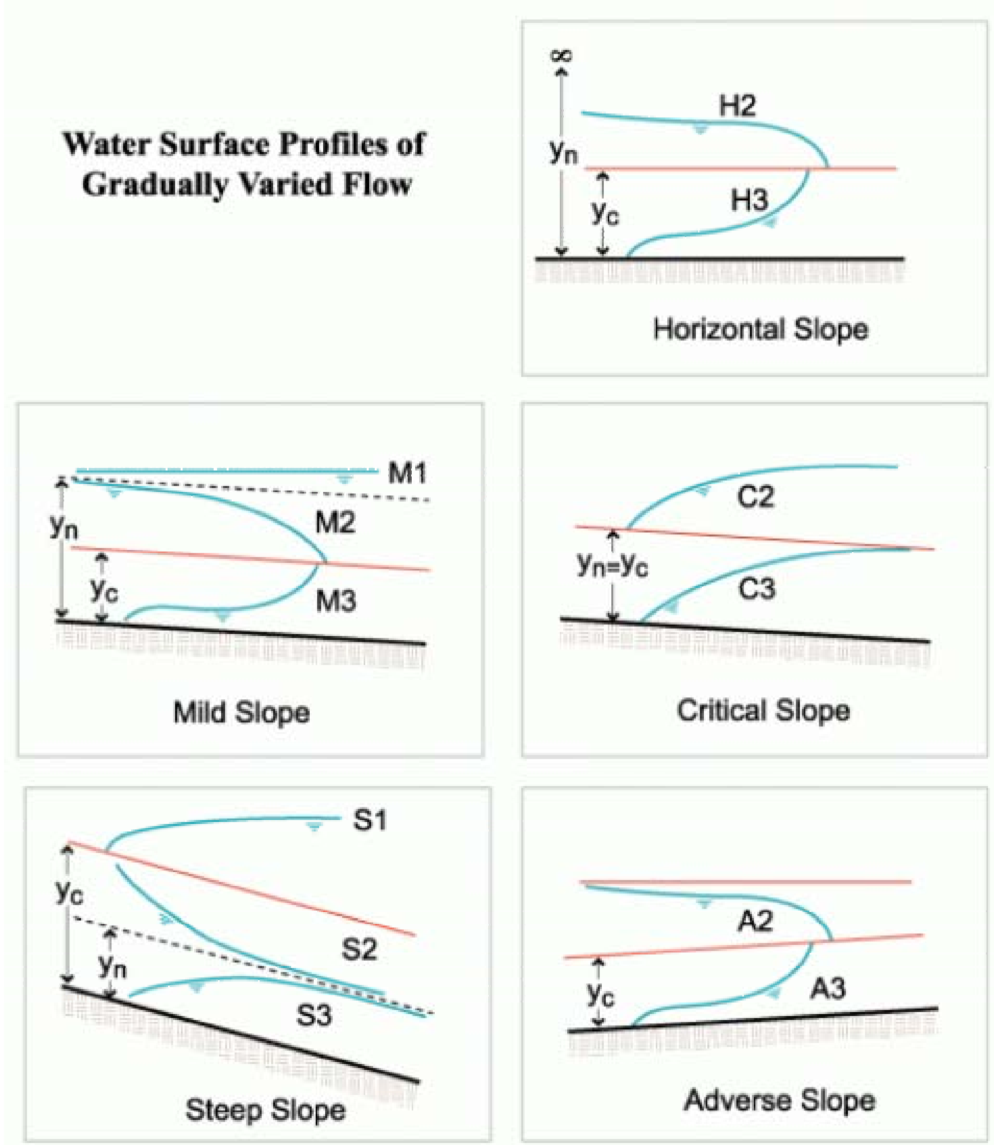
- **Adverse (A)** if So < 0 (slope is positive in the downstream direction)
- **Horizontal (H)** if So = 0
- **Critical (C)** if Yo = y_c
- **Mild (M)** if So> 0 and $y_n > y_c$
- **Steep (S)** if So > 0 and $y_n < y_c$

For culverts with slopes > 0, the slope classifications change as flows change. It is not uncommon for a culvert to switch from being Mild Slope to Steep Slope as flows increase.

Hydraulic Curve Classifications

Hydraulic Curve classifications are used to describe the shape of the water surface profile at a specific flow. The curves are based on the Hydraulic Slope (A, H, C, M, or S) and the relative position of the actual flow depth to normal and critical depth as designated by the numbers 1, 2, and 3.

- Type 1 curve: Depth is greater than y_c and y_n, flow is subcritical
- Type 2 curve: Depth is between $y_c$and y_n, flow can be either subcritical or supercritical
- Type 3 curve: Depth is less than both $y_c$and y_n, flow is supercritical.



Since normal depth (y_n) is undefined for Horizontal and Adverse slopes, they only experience Type 2 and Type 3 curves.

> **Note:** Since FishXing does not model slope breaks within a culvert, therefore type 3 curves do not occur within the model.

Boundary Conditions

To develop a water surface profile (WSP) through the culvert using Gradually Varied Flow calculations one or more boundary condition must be defined. A boundary condition is a section of the channel where the depth of flow is known at a given flow rate. For culverts, these boundary conditions occur at or near the inlet and outlet.

For backwater calculations (WSP calculated from downstream to upstream) a downstream boundary condition is necessary. When performing frontwater calculations WSP calculated going downstream) an upstream boundary condition is required. Determining the type of boundary condition and calculation (backwater verses frontwater) needed is a function of the hydraulic slope and tailwater depth. In FishXing the tailwater depth is defined by one of the available Tailwater Methods.

Boundary Conditions used by FishXing for Gradually Varied Flow Calculations are illustrated below.

Where:

y_{TW} = Tailwater depth, measured from outlet bottom (negative below bottom, positive above bottom)

y_c = Critical depth

y_n = Normal depth

y_{fs} = Free surface depth, a function of (0.71*Ac)

A_c = Cross sectional area at critical depth

H_L = Inlet headloss

GVF = Gradually Varied Flow (arrow shows the direction of calculation)

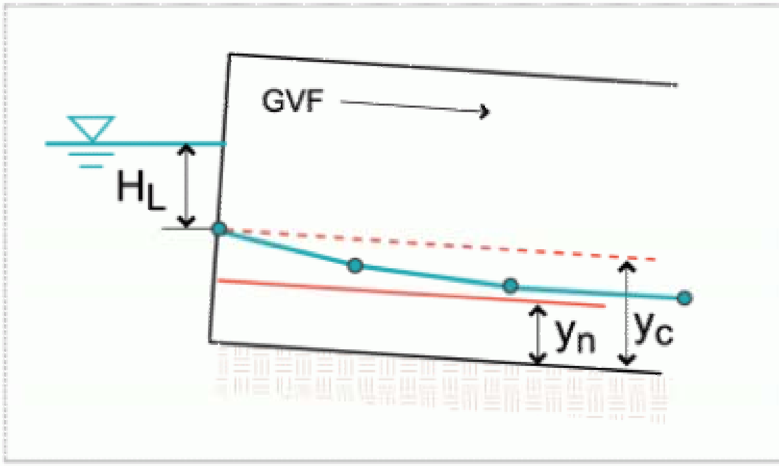
RVF = Rapidly Varied Flow (arrow shows the direction of calculation)

Inlet Boundary Conditions Used in FishXing

In FishXing, inlet boundary conditions are only required for hydraulically Steep sloping culverts ($y_c > y_n$).

Steep Slopes

GVF Boundary Conditions = Critical Depth at inlet.



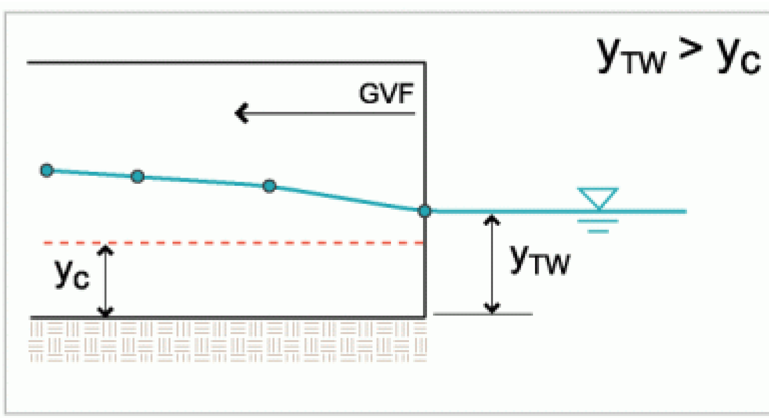
Frontwater GVF Calculations begin at critical depth at inlet and end at outlet

Outlet Boundary Conditions Used in FishXing

Outlet boundary conditions required on non-Steep slopes or on Steep slopes with tailwater depth > critical depth ($y_{TW} > y_c$).

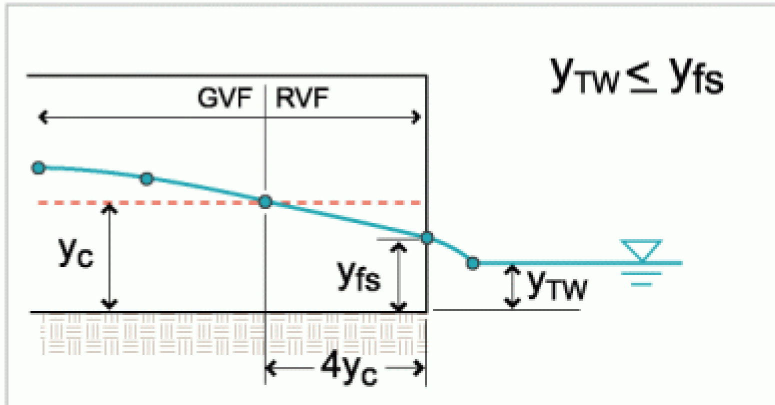
Mild, Horizontal, Adverse, Critical Slopes

Type 1: GVF Boundary Condition = Tailwater Depth



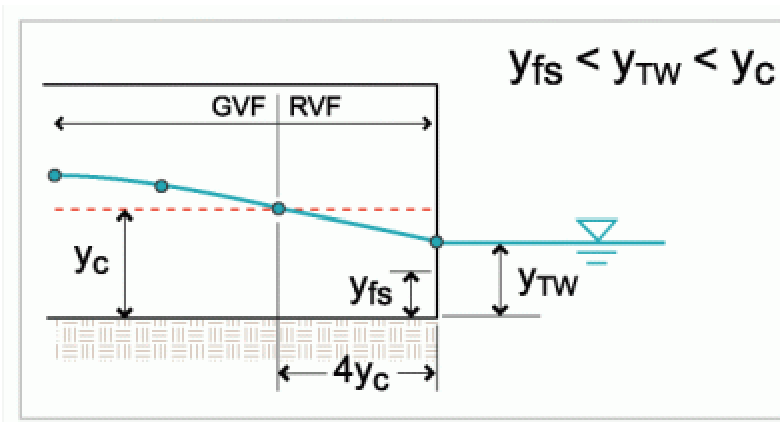
When the Tailwater Depth (y_{TW}) is greater than Critical Depth (y_c) the culvert is controlled by the downstream water surface. Backwater GVF calculations begin at the outlet and proceed upstream to the inlet.

Type 2: GVF Boundary Condition = Critical Depth



When Tailwater Depth (y_{TW}) is less than the Free Surface Depth (y_{fs}) the flow is passing through Critical Depth (y_c) and entering a zone of Rapidly Varied Flow. RVF is approximated linearly by drawing the flow profile from critical depth at a distance of $4y_c$ from the outlet through y_{fs} at the outlet. When y_{TW} is negative, an outlet plunge exists.

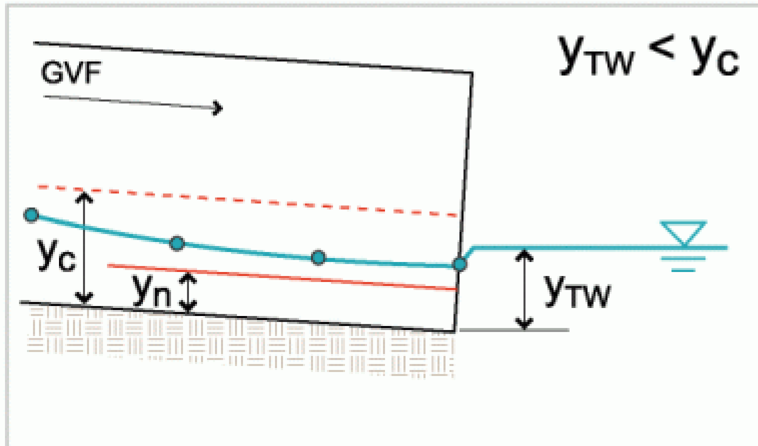
Type 3: GVF Boundary Condition = Critical Depth



When Tailwater Depth (y_{TW}) is less than the Critical Depth (y_c) and greater than Free Surface Depth (y_{fs}) the flow is passing through critical and entering a zone of Rapidly Varied Flow. The water surface within the RVF zone is approximated by drawing the flow profile from the tailwater elevation at the outlet to critical depth at a distance of $4y_c$ upstream from the outlet.

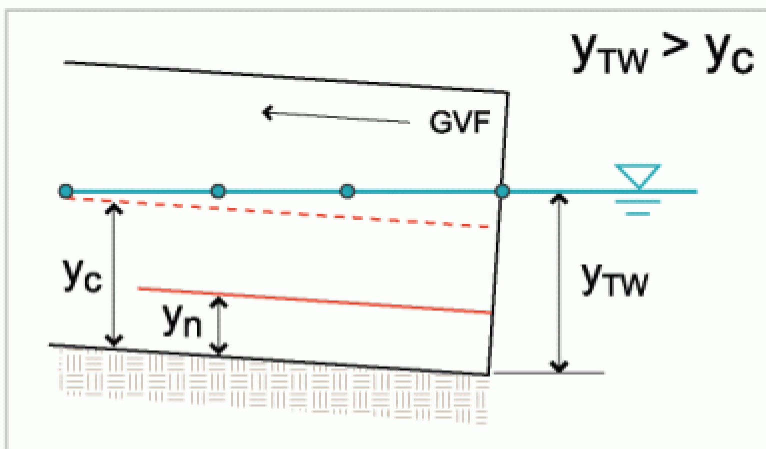
Steep Slopes

For Steep slope culverts, a downstream boundary condition is only needed if a backwater calculation is required.



In this case the Tailwater Depth (y_{TW}) is below critical depth, so no backwater calculation is required.

Type 4: Steep Slope with GVF Boundary Condition = Tailwater Depth



For hydraulically Steep slopes, if the Tailwater Depth (y_{TW}) is greater than the Critical Depth (y_c) then the downstream boundary condition is y_{TW} and a backwater calculation is performed. In addition, for all Steep sloping culverts a frontwater calculation is also performed. Determine the extent the flow profile is influenced by the tailwater depth requires comparing the frontwater and backwater generated profiles and identifying the location of a hydraulic jump, if one exists.

See: Outlet Plunge, Outlet Drop, Tailwater Calculations, Hydraulic Jumps,

Gradually Varied Flow

When not flowing full, water surface profiles within a culvert are generally calculated using equations that describe Gradually Varied Flow (GVF) conditions. The GVF equations account for gravitational and frictional forces acting on the water, and are used to calculate water depths throughout the culvert. A GVF profile is also known as a water depth profile and applies to steady-state, or constant flow, conditions.

Limitations of Gradually Varied Flow equation:

1. Steady State Flow
2. One Dimensional (can only calculate average cross sectional water velocity)

General form of the Gradually Varied Flow equation is:

$$\frac{dy}{dx} = \frac{S_o - S_f}{\left(1 - Fr^2\right)}$$

Where:

S_o = Bottom slope, positive in the downward direction
S_f = Friction slope, positive in the downward direction
y = Water depth, measured from culvert bottom to water surface
x = Longitudinal distance, measured along the culvert bottom
Fr = Froude number

The Friction slope is approximated from Mannings Equation:

$$S_f = \frac{n^2 V^2}{\varphi R^{\frac{4}{3}}}$$

Where:

S_f = Friction slope, positive in the downward direction
n = Mannings roughness coefficient
V = Average cross section velocity
φ = Constant equal to 1.49 for English units and 1.00 for SI units.
R = Hydraulic radius, (Wetted Area / Wetted Perimeter)

Numerical Integration of the GVF Equation:

The GVF differential equation does not have an analytical solution. Therefore, FishXing uses numerical integration to generate a water surface profile. Numerical integration is a technique of dividing the channel, or culvert, into numerous short reaches and then performing the computations from one end of the reach to the other.

$$\Delta E = \Delta x\left(S_o - S_{f\ ave}\right)$$

FishXing primarily uses the Standard Step Method of numerical integration. The following form of the equation is used:

$$E = y + \frac{Q^2}{2g\,A^2}$$

Where:

ΔE = Change in specific energy from one end of the reach to the other

S_{fave} = Average friction slope across the reach

Δx = Longitudinal distance from one end of the reach to the other

y = Depth of water

Q = Flow rate

g = Gravitational acceleration

A = Wetted cross sectional area

Since the friction slope and wetted area are functions of depth, solving for depth at a given distance (Δx) requires an iterative solution. FishXing uses a bisection method to find the solution.

Backwater and Frontwater Calculations

The water surface profile can be calculated from downstream going upstream (backwater calculations) or from upstream going downstream (frontwater calculations). The direction depends on the classification of the water surface profile (hydraulic slope and type of curve). For Mild, Critical, Adverse, and Horizontal slopes FishXing performs a backwater calculation beginning at the downstream boundary. Frontwater calculations are performed for Steep slopes, beginning at the upstream boundary. If a Steep slope culvert is backwatered (S1 curve), FishXing also performs a backwater calculation and identifies the location of the hydraulic jump (if one occurs).

Other Considerations

If only a portion of the culvert becomes pressurized, FishXing will switch between the GVF and full flow equations.

See Boundary Conditions, Rapidly Varied Flow, Headwater Calculation

Full Flow

The velocity within a full flowing culvert is calculated as:

$$V = \frac{Q}{A}$$

Where:

V = Average velocity in the culvert barrel [ft/s or m/s]
Q = Flow rate through culvert [ft^3/s or m^3/2]
A = Full cross sectional area of the flow [ft^2 or m^2]

When flowing full, the friction loss within the culvert barrel, H_f, over a given length of culvert, L, is calculated based on the friction slope, S_f:

$$H_f = S_f L$$

To calculate the friction slope, Manning's equation is rearranged into the following form:

$$S_f = \frac{n^2 V^2}{\varphi R^{\frac{4}{3}}}$$

Where:

n = Manning's roughness coefficient
φ = Constant of 1.00 for metric and 1.49 for English units
R = Hydraulic radius [ft or m]

When full flow conditions exist, FishXing uses the friction slope and culvert slope, S_o, to calculate the height of the hydraulic grade line (HGL) and energy grade line (EGL) above the culvert bottom.

$$HGL_2 = HGL_1 + (S_f - S_o)\Delta x$$

$$EGL_1 = HGL_1 + \frac{v^2}{2g}$$

If the hydraulic grade line intersects the top of the culvert, FishXing switches between full flow and open channel flow calculations.

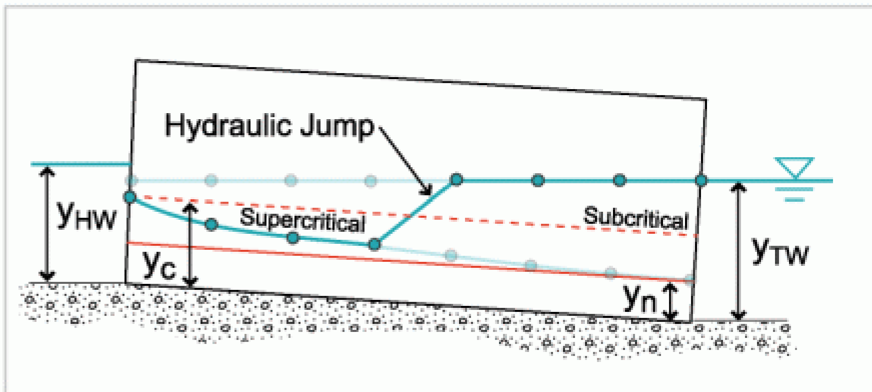
Rapidly Varied Flow

If water depth or velocity change abruptly over a short distance and the pressure distribution is not hydrostatic, the water surface profile is characterized as Rapidly Varying Flow (RVF). The occurrence of RVF is usually a local phenomenon. RVF can often be observed near the inlet and outlet of culverts, and wherever hydraulic jumps occur.

For more information on how FishXing approximates Rapidly Varied Flow please see the following topics: Inlet Contraction Velocity, Hydraulic Jump, Free Surface Outlet, Boundary Conditions, and Outlet Plunge

Hydraulic Jumps

Whenever the flow profile changes from supercritical to subcritical, hydraulic jumps will occur. A hydraulic jump represents a significant head loss that manifests in available energy for scour and creation of turbulence. Hydraulic jumps are one of the three occurrences of Rapidly Varied Flow that FishXing approximates. Hydraulic jumps are generally an undesirable condition for fish passage and erosion control.



Photos of Hydraulic Jump, Hydraulic Jump 2,

In FishXing a hydraulic jump can only occur if the following two conditions are satisfied:

1. The culvert has a steep hydraulic slope ($y_c > y_n$)

2. The tailwater depth is greater than critical depth ($y_{TW} > y_c$)

If both of these conditions exist FishXing checks for the possibility of a jump occurring within the culvert. FishXing solves the Gradually Varied Flow equations in the downstream direction (frontwater calculations) starting from critical depth at the inlet. This gives a supercritical water surface profile. Next, FishXing performs backwater calculations starting at the outlet with the water depth equal to the tailwater depth. Proceeding upstream, the backwater calculations produces a subcritical water surface profile. At any given point in the culvert there is now both a supercritical and subcritical depth. To determine which depth is correct, at each node (point) the corresponding momentum (or specific force) is calculated for both of the depths. When the upstream momentum and downstream momentum values are equal a jump occurs.

FishXing does not locate the exact location of the jump but determines the up and downstream nodes of the jump and connects sub and supercritical flow between these nodes.

The steps followed to locate the jump are summarized as:

1. Compute the upstream supercritical water surface profile by solving the Gradually Varied Flow equations from the inlet depth equal to critical depth. Calculations proceeding in the downstream direction are called "frontwater calculations".

2. Starting at the downstream boundary condition at the outlet, compute the subcritical water surface profile in the upstream direction. Calculations proceeding in the upstream direction are called "backwater calculations".

3. At each node, compute the momentum (specific force) for associated with the two depths (supercritical and subcritical).

$$M = \frac{Q^2}{g\,A} + \bar{z}\,A$$

Where:

M = Momentum or specific force

Q = Flow rate

g =Acceleration due to gravity

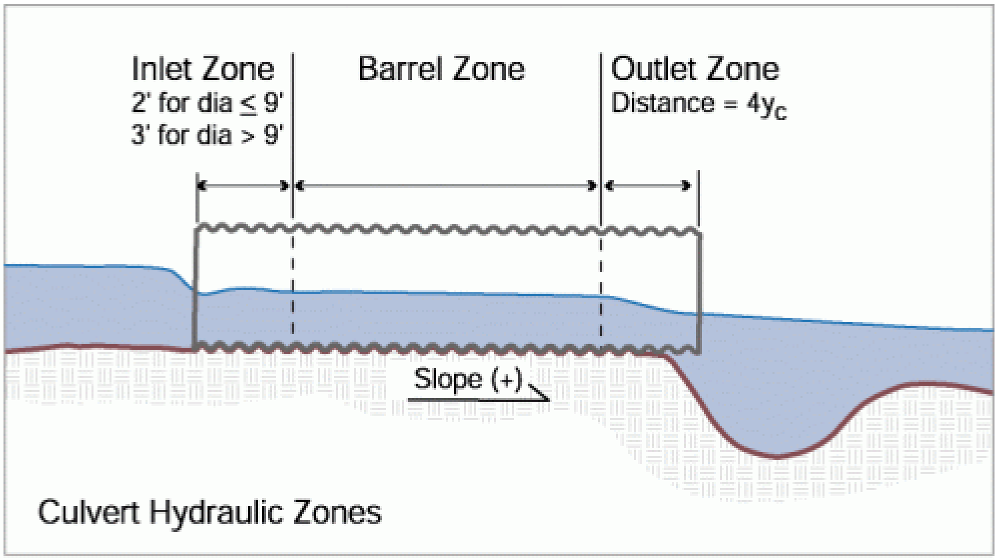
A = Cross sectional area

zbar = is the distance from the water surface to the centroid of the cross sectional area of flow.

4. Beginning at the outlet and proceeding towards the inlet, compare the momentum associated with the corresponding supercritical and subcritical depths. When the momentum associated with the subcritical profile becomes less than the momentum associated with the supercritical profile, a hydraulic jump is assumed to have occurred between the two nodes.

Inlet, Barrel and Outlet Zones

During calculations, the culvert is divided into three zones:



- **Inlet Zone** – The region within the culvert inlet where entering flows contract and then expand rapidly. FishXing reports the inlet zone as the first two nodes (points) down the culvert. For culverts with a width or diameter of 9 feet or less the inlet zone is 2 feet in length, while for culverts larger than 9 feet the inlet zone is 3 feet in length (Belhke, 1992). At this location within the culvert, FishXing calculates the Inlet Contraction Velocity.

- **Barrel** - All the nodes between the first two nodes and last two nodes in the culvert

- **Outlet Zone** - The distance from the outlet to a distance equal to $4y_c$ (four times critical depth) within the culvert. This zone consists of the last two nodes of the culvert. The area of rapidly varying flow associated with a full or partially free surface outlet will be contained within the Outlet Zone.

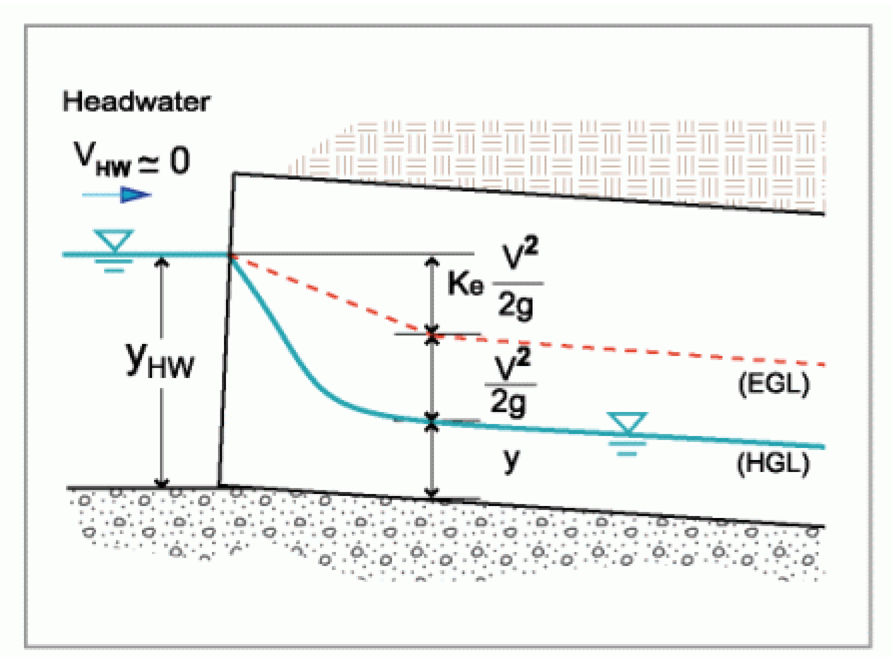
The zones also define where the inlet, barrel, and outlet Velocity Reduction Factors are applied.

For this application, the Barrel Velocity (VB) is the average cross-sectional flow in the barrel approximately one culvert diameter downstream from the inlet and represents the area immediately downstream of the inlet Contraction and Expansion zone.

See also: Inlet Head Loss Coefficient, Inlet Contraction Velocity, Velocity Reduction Factors

Headwater Calculations

The depth of water above the culvert inlet bottom is known as the Headwater Depth. This depth represents the amount of energy available to convey water through the culvert. Headwater depths are a function of the entrance shape, along with the depth and velocity immediately inside the culvert.



Headwater depths are determined by summing the energy losses associated with entrance shape, exit expansion and friction of the culvert. This is described in the basic energy balance equation:

$$y_{HW} + \frac{V_{HW}^{2}}{2g} + \Delta Z = y_{TW} + \frac{V_{TW}^{2}}{2g} + y_{\text{Friction Loss}} + y_{\text{Entrance Loss}} + y_{\text{Exit Loss}}$$

Where:

Y = Depth (ft, m)

V = Velocity (ft/s, m/s)

ΔZ = Change in elevation (ft,m)

TW = Tailwater

HW = Headwater

g = Accceleration due to gravity (ft/s^2)

In most cases the approach velocity (V) is low and the approach velocity head is neglected. Similarly the exit velocity can be neglected in the energy equation if the upstream and downstream channels are similar, reducing the Headwater calculation to:

$$y_{HW} + \Delta Z = y_{TW} + y_{\text{Friction Loss}} + y_{\text{Entrance Loss}} + y_{\text{Exit Loss}}$$

where y_{HW} is the sum of all losses and represents the difference in water surface elevation at the Outlet (headwater) and outlet (tailwater) FishXing does not include bend losses, junction losses, or grate losses.

Entrance Loss depends on the geometry of the inlet. This loss is expressed as the velocity head immediately inside the culvert reduced by the entrance loss coefficient, Ke.

$$H_L = K_e \frac{V^2}{2g}$$

Where:

H_L = Head Loss (ft)

K_e = Entrance Loss Coefficient

V = Velocity in the culvert barrel (ft/s)

g = Acceleration due to gravity

FishXing calculates the headwater depth using the following Equation:

$$y_{HW} = (1 + Ke)\frac{v^2}{2g} + y$$

FishXing calculates total headloss as the sum of the Entrance Loss, Exit Loss, and Friction Loss.

> **Note:** High exit velocities can cause downstream scour and present a barrier to fish passage so Exit Velocity should be considered in the design of culverts.

See Entrance Loss Coefficients

Inlet Contraction Velocity

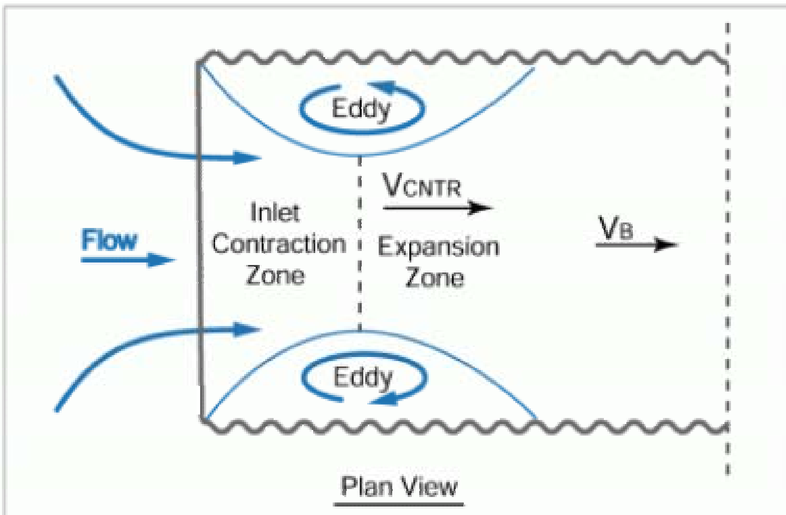


Illustration of inlet zone hydraulics, adapted from Behlke et, al. 1992.

The hydraulic environment within the inlet zone of a culvert is typically classified as rapidly varying flow. Two distinct sections exist within the inlet zone: a contraction zone where streamlines contract as the water enters the culvert and an expansion zone that exists immediately downstream of the contraction. This contraction occurs as water from the upstream channel enters into the culvert inlet. If the culvert is narrower than the channel the abrupt change in width causes flows to be constricted.

Head loss occurs as water passes through the inlet zone. The magnitude of the head-loss is dependent on the velocity within the culvert barrel and inlet geometry, which determines the appropriate entrance loss coefficient. The head-loss coefficient is a function of transition efficiency as the water enters the culvert from the upstream channel.

As the water enters the culvert, velocities increase until they reach the point of maximum contraction. In this zone there is a drop in the hydraulic grade line, which is evident by a drop in water surface. At the same time there is an increase in kinetic energy that is equal to the drop in the hydraulic grade line minus frictional losses. Just downstream of the contraction is an area of rapidly expanding flow. A large portion of the entrance headloss occurs within the expansion

The contraction zone at a culvert inlet can hinder fish passage due to the increased velocities and steeper water slope. *FishXing* approximates the maximum contraction velocity by assuming the calculated entrance headloss through the inlet zone is first converted entirely to kinetic energy, and that this gained kinetic energy is then lost in the expansion.

FishXing uses the following equation to calculate the contraction velocity, and reports it as the velocity immediately inside the culvert in the Water Surface Profile Results:

$$V_{cntr} = V_B\sqrt{1 + Ke}$$

Where:

Vcntr = Contraction velocity

Ke = Entrance loss coefficient

V_B = Average cross sectional water velocity within the culvert barrel, located at the point where the velocity contraction occurs.

For this application the Barrel Velocity (V_B) is the average cross-sectional velocity at the location of the contraction, calculated assuming gradually varied flow conditions. For calculations, the location of the contraction is defined as 2 feet (0.61 m) from the inlet for culverts 9 feet wide (2.75 m) or smaller and 3 feet (0.91 m) from the inlet for culverts larger than 9 feet (2.75 m) (Behlke, 1992). FishXing assumes the approach velocity is zero just upstream of the inlet.

See also:

Inlet Head Loss Coefficient, Continuity Equation

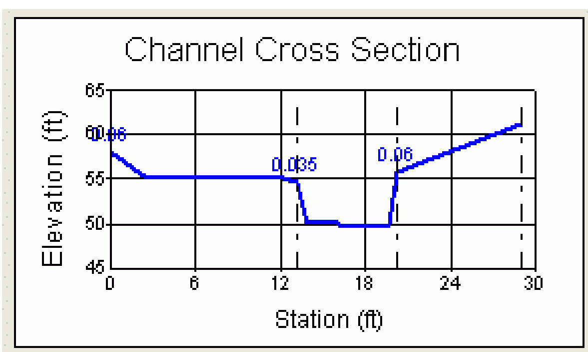
Tailwater Calculations

FishXing allows the user to define the tailwater elevation using one of three methods:

1. Constant Tailwater: Setting a tailwater elevation the remains constant as flows change
2. User Defined Tailwater Rating Curve: Inputting a rating table that relates tailwater elevation to flow.
3. Channel Cross Section: FishXing generates a tailwater rating curve based on an inputted channel cross section.

Channel Cross Section Method

The tailwater cross section method uses an inputted channel cross section to create a tailwater elevation verses flow rating table. The cross section should be located across the tailwater control below the culvert outlet. Also required is the overall channel (or water surface) slope through the cross-section and a Manning's roughness coefficient for the channel. If the cross section contains areas of different roughness, you may vary the roughness coefficients across the section. When the cross section contains multiple roughnesses, a composite roughness is calculated.



FishXing calculates the tailwater elevation - flow relationship for the cross section assuming uniform flow, and using Manning's Equation. Calculations begin with the tailwater set at the lowest elevation in the cross section and a corresponding flow equal to zero. Flow through the tailwater cross section is then calculated at regular intervals in tailwater elevation. Calculations end once the water surface encounters one of the cross section ends (whichever side is lower).

Interpolation and Extrapolation of Rating Curves

FishXing requires a tailwater elevation for every flow rate that it calculates. For both the User Defined Tailwater Rating Curve Method and the Channel Cross Section Method (which builds a rating curve) FishXing interpolates or extrapolates tailwater elevations associated with different flows. If the flow is between two calculated flows within the rating curve, FishXing uses linear interpolation to determine the corresponding tailwater elevation. If the flow is beyond the highest flow in the rating curve, FishXing uses linear extrapolation based on the last two points within the rating curve.

Rating Curve Extrapolation Graphic

Since extrapolating beyond the curve can result in substantial error, it is always best to either (depending on the Tailwater Method selected):

1. Input a rating curve that includes the entire range of flows you plan to model (User Defined Tailwater Rating Curve Method)

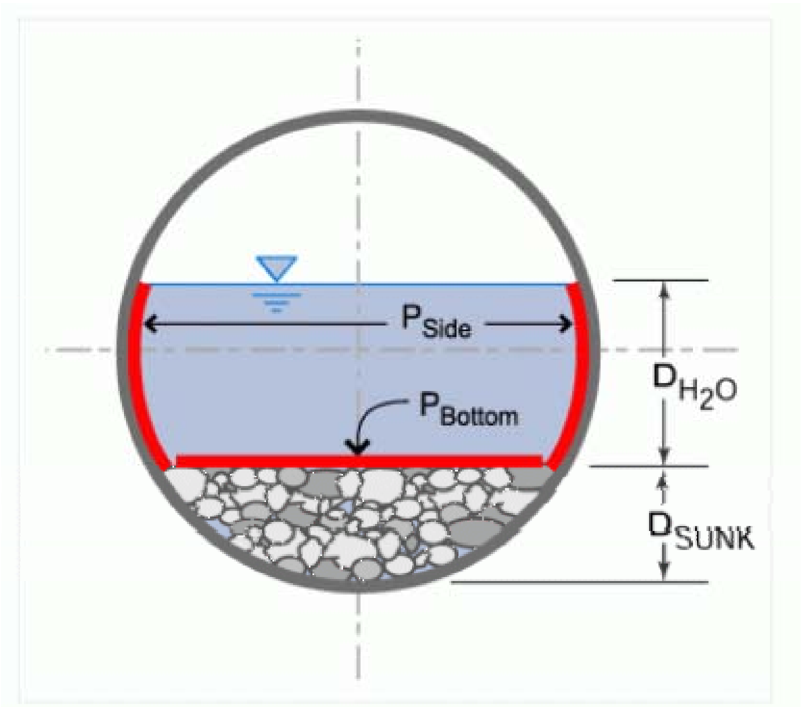
2. Enter a channel cross section that will contain all of the flows you plan to model (Channel Cross Section Method)

Composite Roughness Calculations

When a culvert or channel cross section has areas of different roughness, a composite Manning's roughness coefficient must be calculated. The composite roughness is weighted based on the wetted perimeters associated with the different roughness segments. Therefore, the composite roughness changes with changes in water surface elevation. FishXing uses composite roughness for the tailwater cross section calculations and for culverts with composite materials (such as an embedded culvert).

Composite Roughness for Culverts

FishXing allows you to input a roughness coefficient for the bottom of the culvert different than the roughness for the rest of the culvert. This applies to open bottom culverts and closed bottom culverts that are embedded. In these situations, FishXing assumes the bottom segment to be horizontal.



For culverts, FishXing uses the following form of the Horton-Einstein equation:

$$n_{composite} = \left(\frac{P_{side}(n_{culvert})^{1.5} + P_{bottom}(n_{bottom})^{1.5}}{(P_{side} + P_{bottom})} \right)^{\frac{2}{3}}$$

Where:

$n_{composite}$ = Mannings roughness coefficient for multiple materials

P_{side} = Perimeter of side material
$n_{culvert}$ = Mannings roughness coefficient of culvert material
P_{bottom} = Perimeter of bottom material
n_{bottom} = Mannings roughness coefficient of bottom material

Composite Roughness for Tailwater Cross Section

When more than one roughness value is entered for the tailwater cross section, FishXing uses the Horton-Einstein equation to compute a composite roughness:

$$n_{composite} = \left(\frac{\sum_{i=1}^{n} \left(P_i n_i^{1.5} \right)}{P_{total}} \right)^{\frac{2}{3}}$$

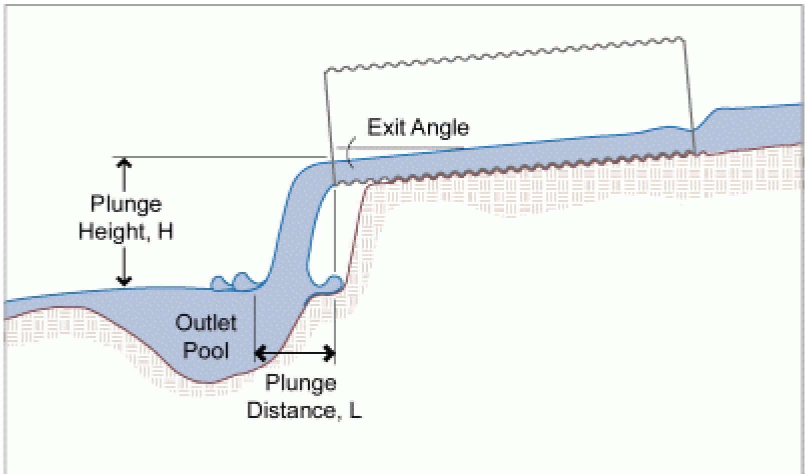
Where:

$n_{composite}$ = Mannings roughness coefficient for multiple materials
P = Perimeter of material
i = subsection of crossing

If a Darcy-Weisbach friction factor or Chezy coefficient is used instead of Manning's n, FishXing converts the alternative roughness coefficient into an equivalent Manning's n to calculate a composite roughness.

Plunging Flow

Water leaving a perched culvert has a velocity with both horizontal and vertical components. By neglecting all frictional losses, a simplified projectile equation can be applied to the exiting water. Using this equation, FishXing calculates the path of the falling water from exiting the culvert outlet until it impacts the downstream outlet pool. FishXing assumes the location in which the plunging flow impacts the outlet pool is where the fish will attempt to leap from.



The height the water plunges, H, and the horizontal distance the water travels from the outlet, L, is described by the following standard projectile equations:

$$H = V_{out}(\sin\theta)\ t - \frac{1}{2} g t^2$$

$$L = V_{out}(\cos\theta)\ t$$

Where:

H = Vertical plunge distance.

L = Horizontal plunge distance

V_{out} = Exiting water velocity at the culvert outlet [ft/s or m/s]

g = Gravitational acceleration [32.2 ft/s^2 or 9.8 m/s^2]

t = Time for the exiting water to fall from the culvert outlet to the pool [s],

θ = Angle at which the water exits the culvert outlet [degrees or radians]

Since H is known, FishXing solves for the time, t, and the horizontal plunge distance, L.

Exit Angle

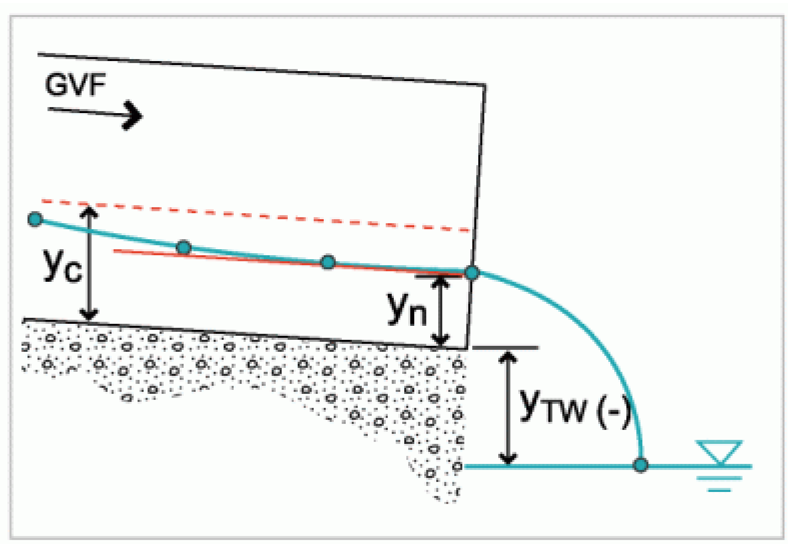
The exit angle is the angle the exiting water surface makes with the horizontal. It is calculated using the last two nodes within the culvert, which is defined as the Outlet Zone. The water surface slope at the outlet is determined by the applicable Free Surface Outlet conditions.

See Also: Defining Normal Depth, Froude Number and Flow States, Open Channel Flow, Perched Outlet

Free Surface Outlet

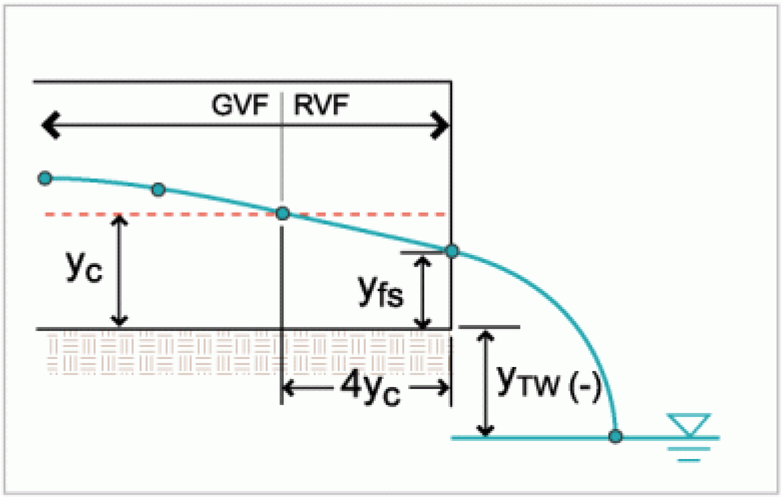
Free surface outlets, also referred to as perched or free fall outlets, exist when the tailwater does not influence the water depth within the culvert outlet. The method used by FishXing to addresses free surface outlets depends on the hydraulic slope of the culvert.

Steep Culverts



At hydraulically steep slopes (yn < yc), if the tailwater is below critical depth ($y_{tw} < y_c$) supercritical flow will occur throughout the culvert. In this case, the controlling water depth is at the upstream end of the culvert. If the tailwater depth is below the culvert outlet bottom ($y_{tw} < 0$) the culvert is considered perched. Under supercritical flow conditions, FishXing assumes the water depth at the perched culvert outlet is not influenced by the free overfall.

Non-steep Culverts



For culverts with a hydraulic slope that is not steep (instead having either a mild, critical, horizontal, or adverse slope) and having a perched culvert outlet ($y_{tw} < 0$) , the water surface profile will be on a draw-down curve as it approaches the free overfall. From where the profile crosses through critical depth to the free outfall the flow enters into a rapidly varied flow regime. Rouse (1936) examined the case of an overfall at the end of a mild slope and found that the true critical section is located at the overfall crest. The depth of this crest is a function of the wetted area at the computed critical depth, y_c:

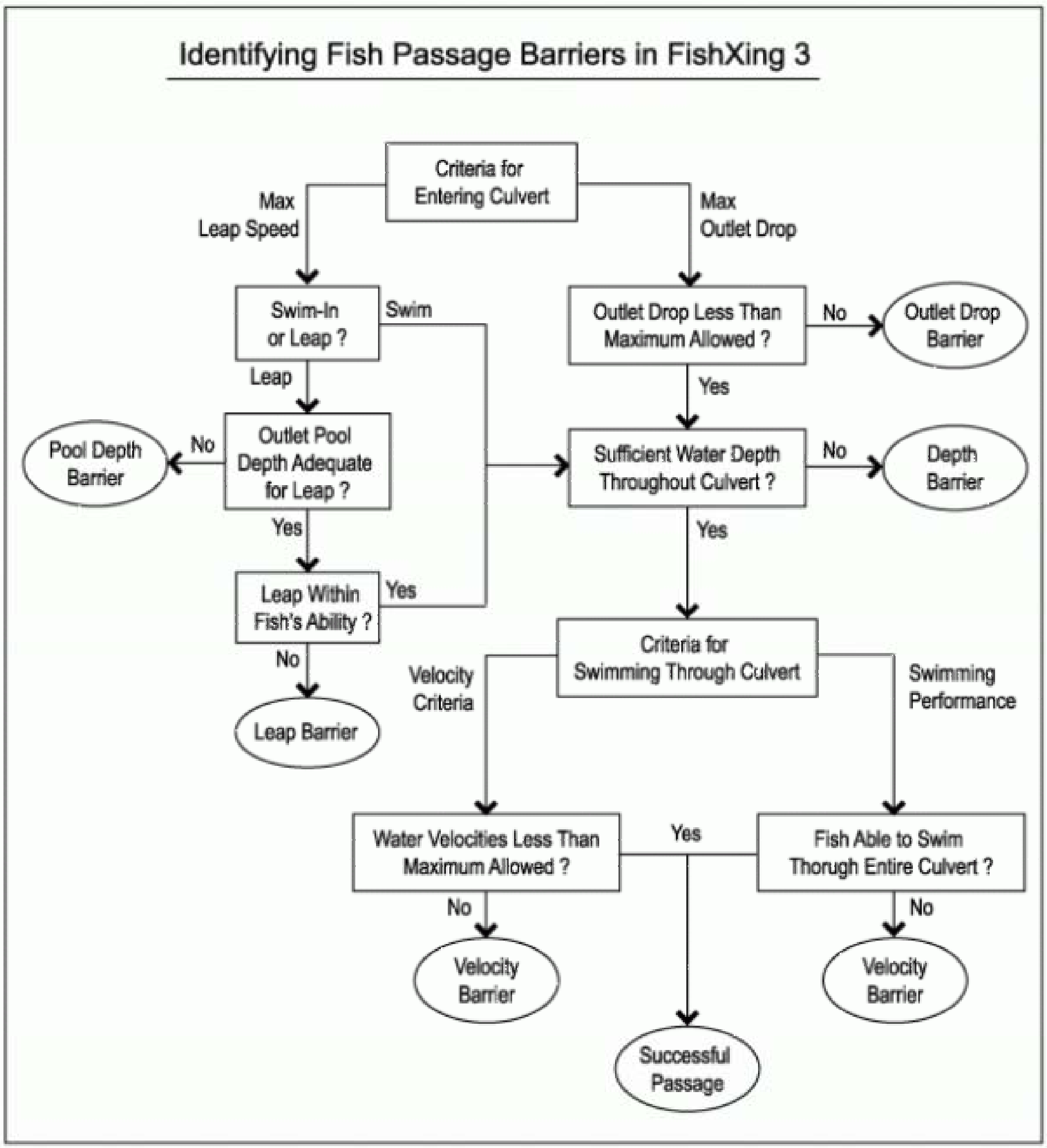
$$A_{out} = 0.71 A_c$$

The exact location of the calculated critical depth is indeterminate, as it will move upstream with increasing flow and downstream with increasing boundary roughness and surface slope. For relatively smooth rectangular channels, Rouse found this distance approximately equal to four times the critical depth ($4y_c$) upstream from the crest.

For non-steep culvert with a free overfall FishXing approximates the water surface profile near the outlet by assuming the water depth is equal to critical depth a distance of $4y_c$ upstream of the outlet. FishXing then assumes the free surface depth located at the outlet (Y_{fs}) is a function of 0.71Ac. The water surface is then assumed to be linear between y_c and y_{fs}.

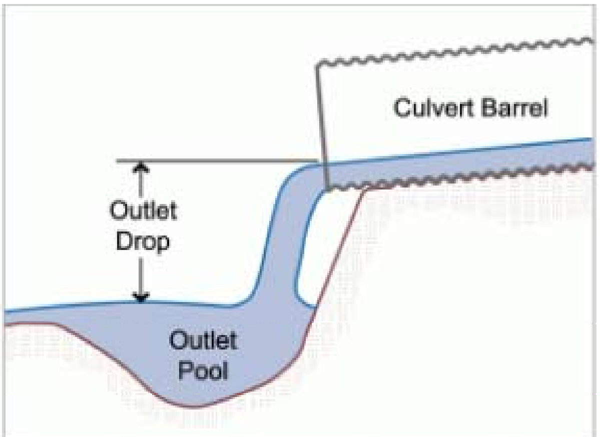
Fish Calculations Overview

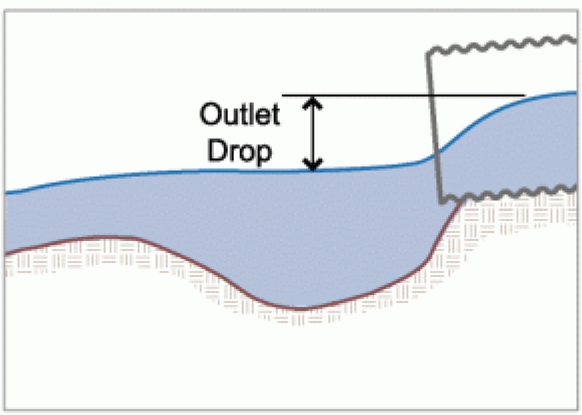
FishXing examines fish passage conditions and identifies potential barriers throughout the culvert. For example, if FishXing identifies a leap barrier it continues to examine conditions within the culvert to determine if there are additional barriers, such as insufficient depth or an exhaustion barrier.



Outlet Drop Criteria for Entering the Culvert

The outlet drop is the difference between the water surface elevation in the culvert outlet and the tailwater elevation. If the Outlet Criteria on the Fish Information section of the Input Window is set to Max Outlet Drop, FishXing compares the calculated outlet drop to the user specified Max Outlet Drop. If the Outlet Drop is greater than the Max Outlet Drop, FishXing identifies an “Outlet Drop Barrier” at that specific flow.





Entering the Culvert: Leap or Swim

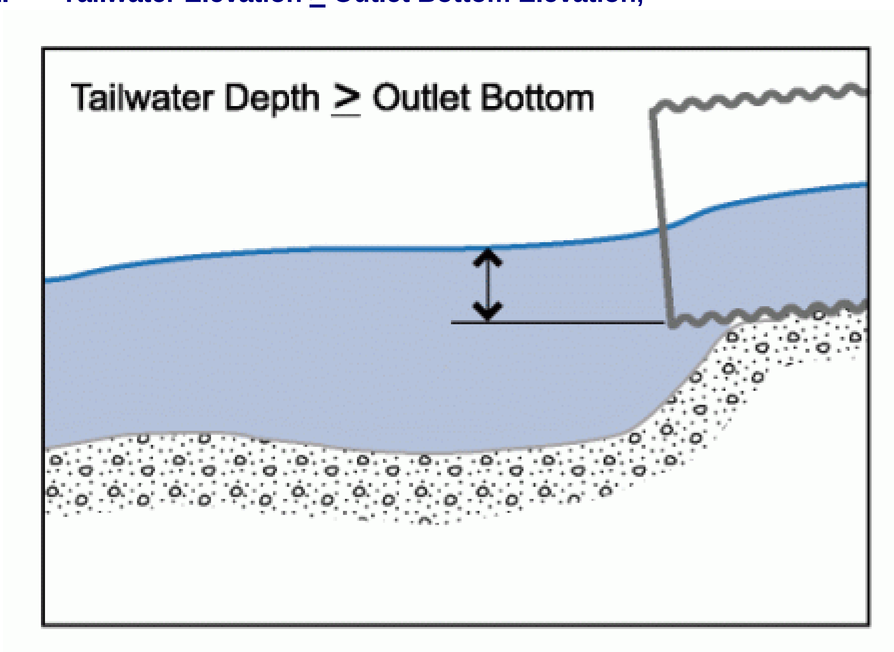
Fish will swim up rather than leap at very low falls, as observed by several researchers (Collin and Ellis 1961, Mayama 1987, Orsborn and Aaserude 1986, Stuart 1962).

FishXing allows you to evaluate passage conditions at the culvert outlet based on one of two methods, depending on which one is selected in the **Outlet Criteria**:

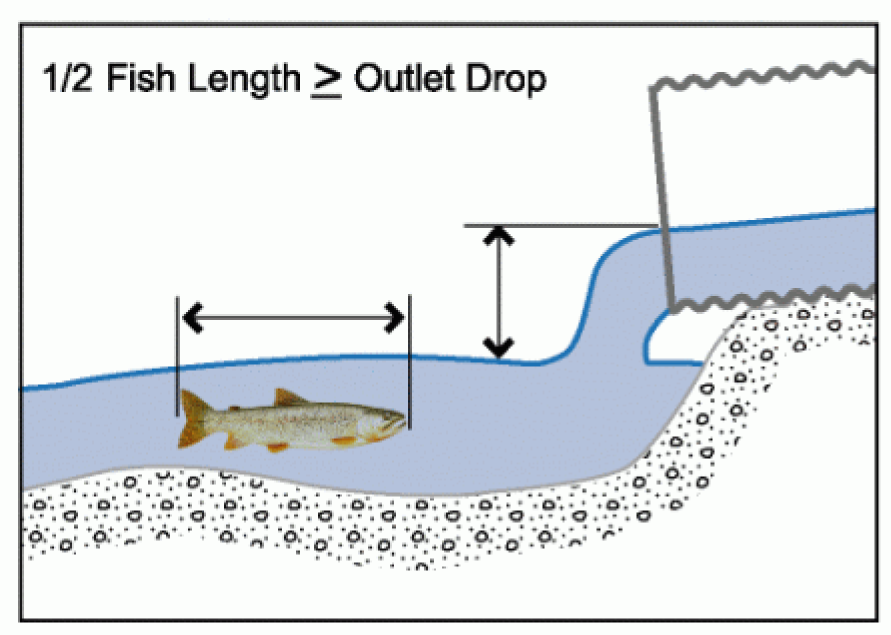
1. Maximum Leap Speed
2. Maximum Outlet Drop

When the **Outlet Criteria** is set to **Max Leap Speed**, FishXing will first determine whether the fish can swim into the culvert or if it must leap. FishXing assumes the fish is able to swim into the culvert outlet rather than leap when any of the following conditions are satisfied:

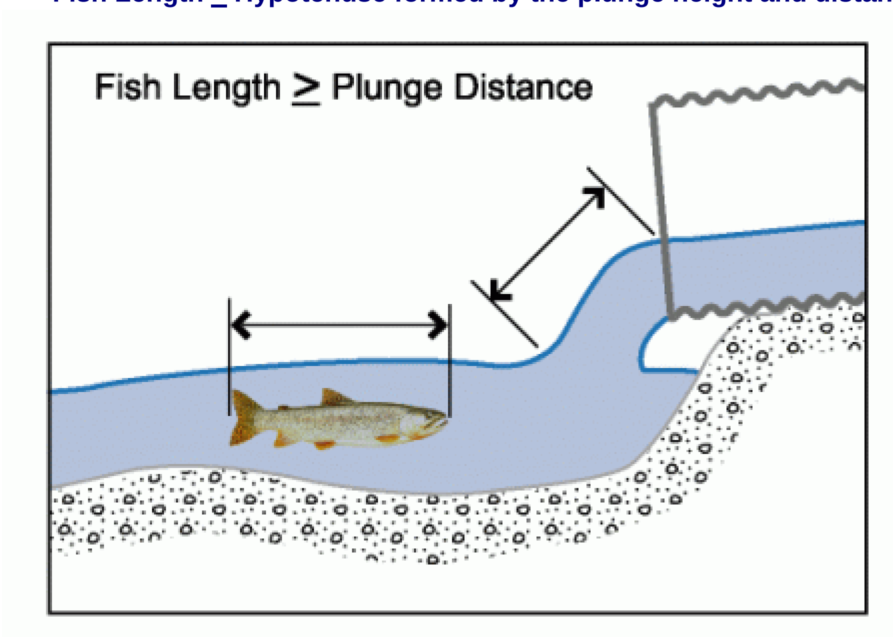
1. Tailwater Elevation ≥ Outlet Bottom Elevation,



2. ½ Fish Length ≥ Outlet Drop,



3. **Fish Length ≥ Hypotenuse formed by the plunge height and distance.**



> **NOTE:** This calculation is only used when the Outlet Criteria is set to Max Leap Speed in the FishXing Input Window. Fish that are unable to leap should have a Max Leap Speed set to zero.

See also: Leaping Calculations, Measures of Fish Length

Leaping Calculations

Leaping calculations are performed by FishXing when the **Outlet Criteria** is set to **Max Leap Speed** within the FishXing Input Window and the fish is unable to swim into the outlet.

> **Note**: If the Fish species does not leap, set the Max Leap Speed to zero. If the fish is unable to swim into the outlet FishXing reports a leap barrier at that flow.

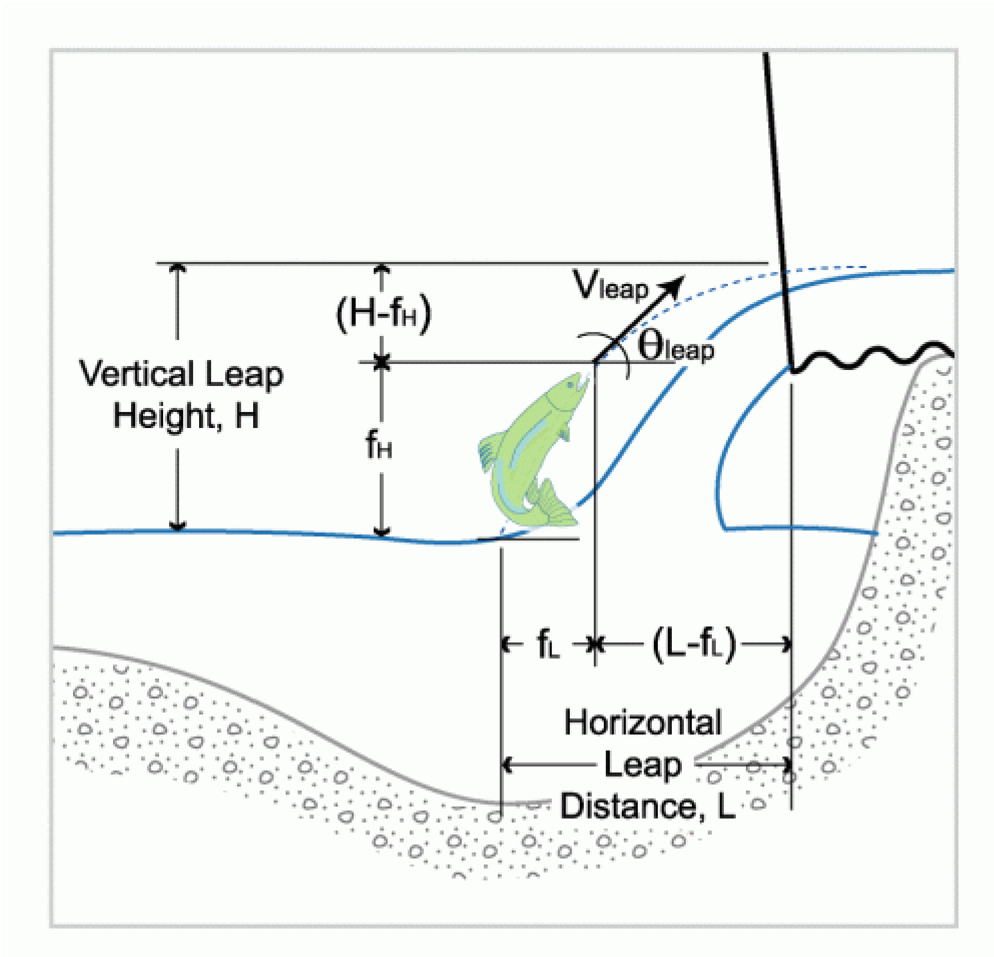
Location of Leap

When modeling leaping performance at a stream crossing, FishXing assumes the fish leaps from the location where the plunging water impacts the outlet pool. The horizontal (L) and vertical (H) distance the fish must leap is determined from the plunging water calculations.

Projectile Physics of Fish

For species that are able to leap, FishXing assumes they leap out of the water along a parabolic path that is described by standard projectile equations, similar to the equations used to describe the path of the plunging water as it exits the culvert. Since a fish primarily uses its tail for propulsion, it is able to continue propelling itself until its tail leaves the water. To account for this, FishXing subtracts the length of the fish (f) from the overall distance it must leap.

Whether a fish can successfully leap into the culvert outlet depends on the speed and direction of the fish as it exits the water. Most investigators have found that fish leaps are more successful when the fish lands horizontally at the crest of the outfall (Stuart 1962; Lauritzen 2002). Therefore, FishXing calculates the velocity (V_{leap}) and angle (θ_{leap}) the fish must leap from the outlet pool to successfully land horizontal on the water surface using the following form of the projectile equations:



$$H = V_{leap}(\sin\theta_{leap})\ t + \frac{1}{2} g\, t^2$$

$$L = V_{leap}(\cos\theta_{leap})\ t$$

Where:

H = Vertical leap distance
L = Horizontal leap distance
V_{leap} = Leap velocity
θ_{leap} = Leap angle
g = Gravitational acceleration
t = Time

Rewriting in terms of Vleap:

$$V_{leap} = \left[\frac{ag}{\sin\theta_{leap} \cos\theta_{leap}} \right]^{\frac{1}{2}}$$

$$V_{leap} = \left[\frac{a^2 g}{2\cos^2\theta_{leap}\left(a\tan\theta_{leap} - b\right)} \right]^{\frac{1}{2}}$$

Where:

$a = L - f \cos\theta_{leap}$

$b = H - f \sin\theta_{leap}$

f = Fish Length

Through an iterative process, the two equations are solved simultaneously for the two unknown variables: leap velocity (Vleap) and leap angle (θleap) required to land horizontally.

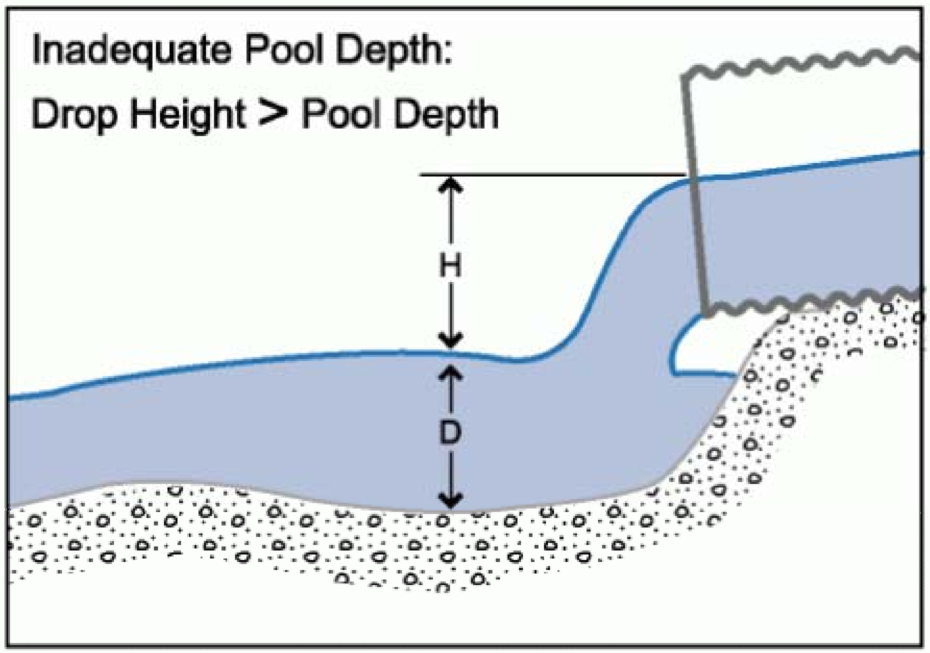
A fish unable to leap at the required leap velocity (Vleap) is unable to enter the culvert outlet. If the required leap velocity is greater than the maximum leap speed entered within the Fisheries Information section of the Input Window, the crossing is considered a leap barrier at that particular flow.

Photos of Fish Leaps

See Also: Outlet Drop Criteria, Minimum Pool Depth, Leaping Capabilities, Leaping from Plunge Pools

Minimum Plunge Pool Depth Calculations

FishXing uses a flow dependent ratio to estimate the minimum plunge pool depth at the crossing outlet needed to support fish leaping. Sufficient pool depth for leaping requires the pool depth be equal to or greater than the drop height:



$$\frac{D}{H} > 1$$

where:

D = Depth of the plunge pool

H = Water surface drop at the outlet, measured from the water surface at the culvert outlet to the water surface of the plunge pool.

If the pool depth (D) is less than the drop height (H), FishXing reports a "pool" barrier at that particular flow. The rationale for this ratio is discussed in the Leaping from Plunge Pools section.

Insufficient Depth

You must enter the minimum water depth required for the fish to be able to swim when inside the culvert. When the water depth at any location within the culvert falls below this minimum depth, FishXing will identify the culvert as containing “insufficient depth” at that particular flow. Additionally, it will report the overall length of the depth barrier in the rating tables. The Water Depth for Swimming section discusses some of the issues to consider when choosing a minimum water depth.

See also: Defining Barriers, Water Depth for Swimming, Estimating Fish Body Depth

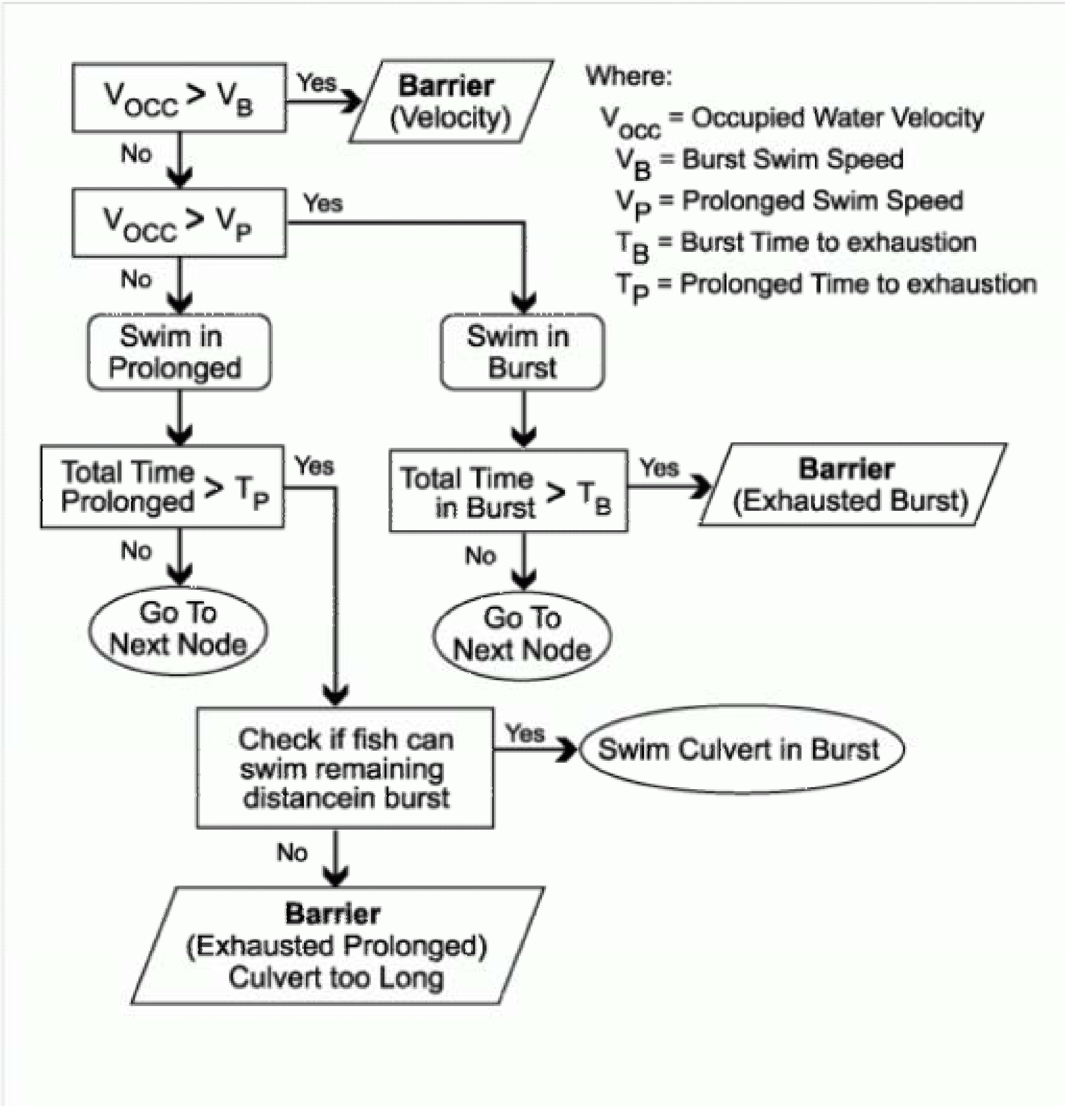
Swimming Algorithm

FishXing uses fish performance data to model a fish's ability to swim through a culvert. The model uses a constant swim speed method, which calculates the fish's speed relative to the ground by taking the difference between the fish's swim speed and the speed of the water in which it is swimming against (Vocc). A fish may fail to pass through a culvert for one of two velocity-based reasons:

(1) Water velocity exceeds a fish's maximum swim speed, or

(2) A fish becomes exhausted at either prolonged or burst speed before reaching the culvert inlet.

The culvert is divided into equally spaced segments with the segment endpoints defined by nodes. At each node swimming calculations are performed based on the following algorithm:



FishXing Swim Algorithm.

1) If occupied velocity is greater than or equal to fish's burst speed then the culvert is a velocity barrier.

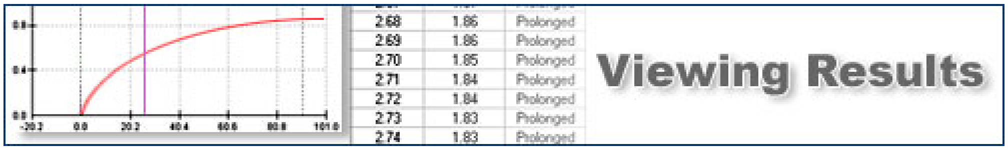
else

2) If occupied velocity is greater than or equal to fish's prolonged speed then the fish swims in burst mode.

else

3) If the fish is making adequate progress in prolonged mode, it swims through the node at prolonged speed. If not, fish swims in burst mode.

See also: Species Swimming Capabilities, Swim Categories, Fish Swimming and Swim Speed Tests, Time to Exhaustion, Fish Length and Swim Speeds



Viewing Results

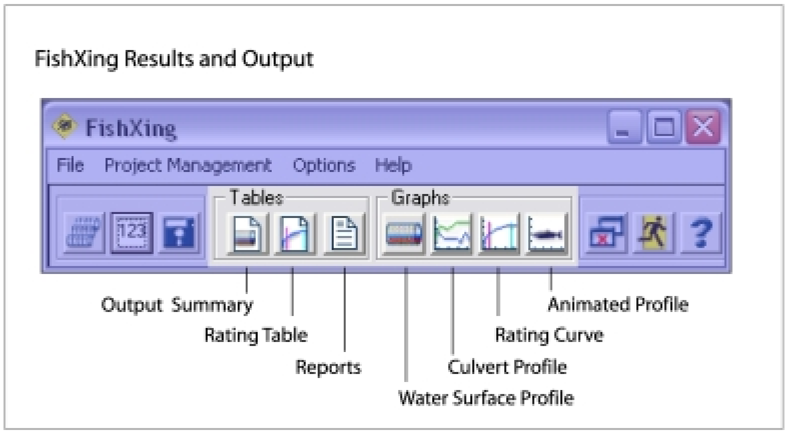
Topics:

Back to Main Topics:

Main Map Run Calculate Results Culvert Hydraulic Fish Glossary

Viewing Results

The Output Summary Window is displayed after FishXing finishes the calculations. FishXing provides a variety of ways to view and report the results. By using the **Navigation Bar** you can select from Tabular and Graphical forms of output and reports.



The results are also available through the **Graphs** and **Tables** menu bar on the Output Summary:

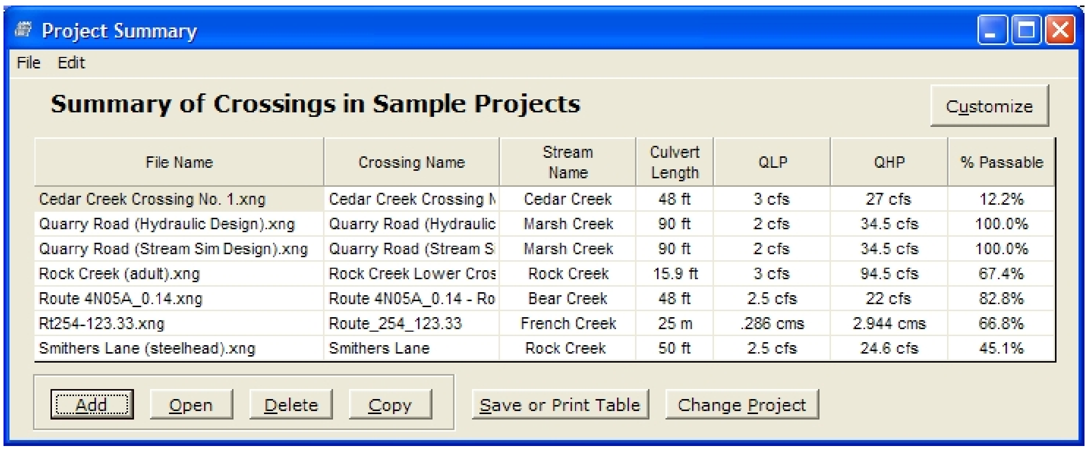
FishXing Output and Results:

- **Output Summary**
  The Output Summary Is the primary results window. It contains a summary of fish passage conditions and barriers, key hydraulic parameters for the, detailed hydraulic conditions through the culvert and a flow calculator for additional flows.
- **Rating Table and Curve**
  Provides hydraulic and passage information about the crossing with respect to flow as the independent variable.
- **Reports**
  All of the input data and output results can be printed in a customizable report form and saved as an Rich Text Format (*.rtf) file for import into spreadsheet and word processor applications.
- **Water Surface Profile**
  Graph of the culvert, Water Surface, Critical Depth, Normal Depth, Headwater and Tailwater down the length of the culvert.

- **Culvert Profile**
  Display of data down the length of the culvert. Showing hydraulic conditions and fish performance with respect to the culvert bottom.
- **Animated Profile**
  Using the numerical results of the model FishXing provides an animated "dramatization" of the hydraulics and fish performance within the culvert.

Project Summary Results

The results for each crossing file are grouped in a project and summarized in the **Project Summary**.



File Name	Crossing Name	Stream Name	Culvert Length	QLP	QHP	% Passable
Cedar Creek Crossing No. 1.xng	Cedar Creek Crossing N	Cedar Creek	48 ft	3 cfs	27 cfs	12.2%
Quarry Road (Hydraulic Design).xng	Quarry Road (Hydraulic	Marsh Creek	90 ft	2 cfs	34.5 cfs	100.0%
Quarry Road (Stream Sim Design).xng	Quarry Road (Stream S	Marsh Creek	90 ft	2 cfs	34.5 cfs	100.0%
Rock Creek (adult).xng	Rock Creek Lower Cros	Rock Creek	15.9 ft	3 cfs	94.5 cfs	67.4%
Route 4N05A_0.14.xng	Route 4N05A_0.14 - Ro	Bear Creek	48 ft	2.5 cfs	22 cfs	82.8%
Rt254-123.33.xng	Route_254_123.33	French Creek	25 m	.286 cms	2.944 cms	66.8%
Smithers Lane (steelhead).xng	Smithers Lane	Rock Creek	50 ft	2.5 cfs	24.6 cfs	45.1%

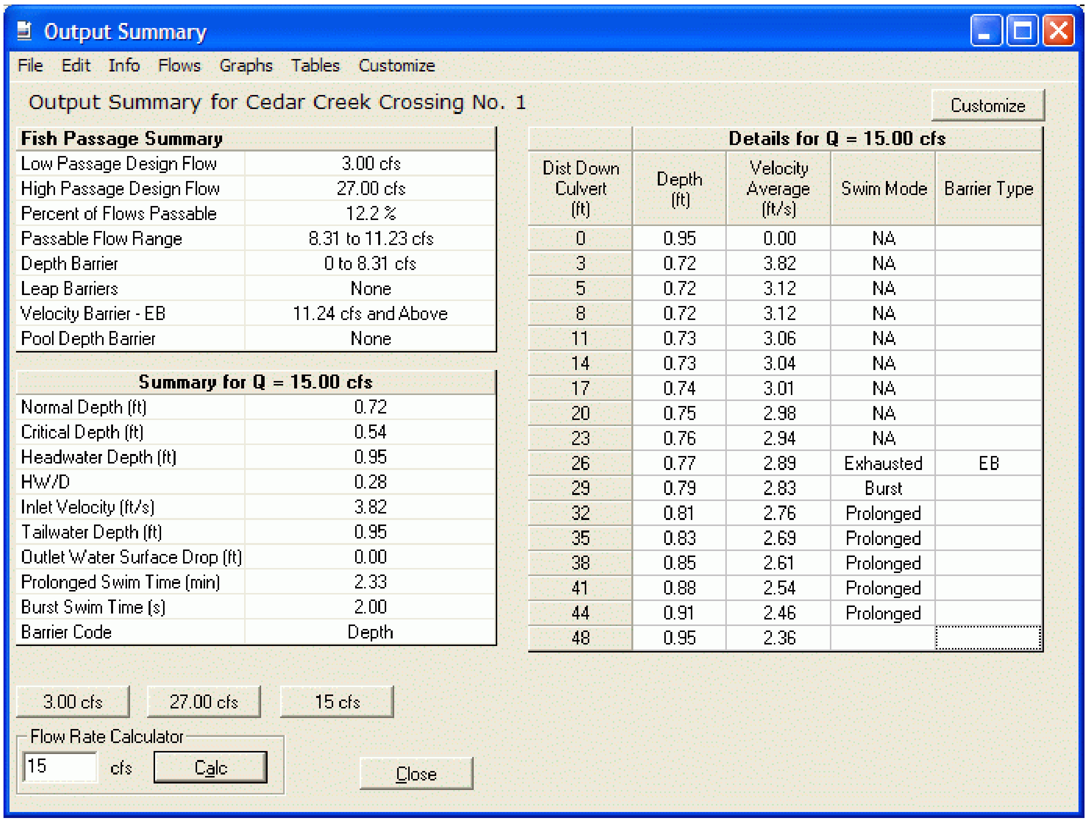
Use the **Customize** button to select from a variety of parameters including culvert descriptions and fish passage results. By clicking on the table headers the table will be sorted alphabetically according to that parameter. This summary table can be saved for export or printed using the **Save or Print Table** button at the bottom.

Fish passage result values will not be updated in the Project Summary until the crossing file is saved. So after running a particular crossing analysis save the crossing before returning to the Project Summary.

> Project Summary is also the way to open, add new and organize all of your crossings in FishXing.

Output Summary Window

The Output Summary is the first window that appears after calculations are complete and is the primary output window.



Fish Passage Summary	
Low Passage Design Flow	3.00 cfs
High Passage Design Flow	27.00 cfs
Percent of Flows Passable	12.2 %
Passable Flow Range	8.31 to 11.23 cfs
Depth Barrier	0 to 8.31 cfs
Leap Barriers	None
Velocity Barrier - EB	11.24 cfs and Above
Pool Depth Barrier	None

Summary for Q = 15.00 cfs	
Normal Depth (ft)	0.72
Critical Depth (ft)	0.54
Headwater Depth (ft)	0.95
HW/D	0.28
Inlet Velocity (ft/s)	3.82
Tailwater Depth (ft)	0.95
Outlet Water Surface Drop (ft)	0.00
Prolonged Swim Time (min)	2.33
Burst Swim Time (s)	2.00
Barrier Code	Depth

	Details for Q = 15.00 cfs			
Dist Down Culvert (ft)	Depth (ft)	Velocity Average (ft/s)	Swim Mode	Barrier Type
0	0.95	0.00	NA	
3	0.72	3.82	NA	
5	0.72	3.12	NA	
8	0.72	3.12	NA	
11	0.73	3.06	NA	
14	0.73	3.04	NA	
17	0.74	3.01	NA	
20	0.75	2.98	NA	
23	0.76	2.94	NA	
26	0.77	2.89	Exhausted	EB
29	0.79	2.83	Burst	
32	0.81	2.76	Prolonged	
35	0.83	2.69	Prolonged	
38	0.85	2.61	Prolonged	
41	0.88	2.54	Prolonged	
44	0.91	2.46	Prolonged	
48	0.95	2.36		

The **Fish Passage Summary** table gives the passage conditions for the range of flows defined by the Low and High Fish Passage flows:

- The High and Low Passage Design Flows
- Percent of the flow range that is passable (Percent Passage)
- Barriers and flow range associated for each type of barrier

The **Flow Summary Table** summarizes hydraulic conditions for the current flow:

- Normal, critical, headwater and tailwater depths
- Headwater to Diameter Ratio (HW/D)
- Inlet Velocity
- Swim times and barrier code

The **Flow Calculator** allows you change the current flow and add an additional check flow to the analysis. The active flow in the Output Summary will be the flow displayed in the Water Surface Profile and Animated Profile.

The **Profiles Table** reports the results of the hydraulic model fish passage calculations for each flow at the crossing being analyzed. Since passage is not only a function of the outlet condition FishXing allows you to view the conditions inside the length of the culvert. Each variable is calculated for the given flow along the length of the culvert at evenly spaced nodes.

	Details for Q = 15.00 cfs						
Dist Down Culvert (ft)	Depth (ft)	Velocity Average (ft/s)	Wetted Area (ft2)	Wetted Perimeter (ft)	Top Width (ft)	Hydraulic Radius (ft)	Hydraulic Depth (ft)
0	0.95	0.00	6.35	8.68	6.37	0.73	1.00
3	0.72	3.82	4.81	8.05	6.72	0.60	0.72
5	0.72	3.12	4.81	8.05	6.72	0.60	0.72
8	0.72	3.12	4.81	8.05	6.72	0.60	0.72
11	0.73	3.06	4.90	8.07	6.72	0.61	0.73
14	0.73	3.04	4.93	8.09	6.72	0.61	0.73
17	0.74	3.01	4.98	8.10	6.72	0.61	0.74
20	0.75	2.98	5.03	8.12	6.72	0.62	0.75
23	0.76	2.94	5.10	8.14	6.71	0.63	0.76
26	0.77	2.89	5.19	8.16	6.71	0.64	0.77
29	0.79	2.83	5.30	8.20	6.70	0.65	0.79
32	0.81	2.76	5.43	8.23	6.70	0.66	0.81

Customizing Tables and Graphs

Variables in the Profiles Table:

Dist. Down Culvert

The distance down the culvert, starting at the inlet, is the abscissa (x-axis) of the Output Summary Table. All of the variables are given in reference to where they are calculated along the length of the culvert. Each segment of culvert is known as a node. Calculations are made at each node and reported in the table. This variable is fixed.

Depth

The average depth of water along the length of the culvert. It is a measure of the distance from the culvert bottom to the water surface.

Critical Depth

The depth of critical flow in the culvert at this flow rate. Critical depth is the depth the water would be if inertial and gravitational forces were equal. This value will always remain constant for the entire length of the culvert.

Normal Depth

The depth of normal flow in the culvert at this flow rate. Normal Depth is the depth the water would flow if all the forces on the water were balanced and the depth remained uniform. This value will always remain constant for the entire length of the culvert. See Defining Normal Depth.

Velocity Head
Velocity Head is a measure of the available energy in the water from its velocity.

Velocity - Ave
The cross-sectional average speed of the water at any point along the length of the culvert.

Velocity - Occ
Occupied Velocity is the average water velocity reduced by the velocity reduction factors entered by the user. The FishXing model uses these velocities under the assumption that fish will swim in a zone of reduced water velocity near the edges of the culvert.

Ground Speed
The fish's speed with respect to the ground accounting for the fish's swimming speed and the speed of the flowing water.

Swim Mode
Swim mode of the Analysis Fish while in the culvert. Prolonged or Burst.

Prolonged Time
The time that the Analysis Fish spends in Prolonged Swimming Mode as measured from node to node along the length of the culvert.

Burst Time
The time that the analysis fish spends in Burst Swimming Mode (darting speed) as measured from node to node along the length of the culvert.

Barrier Type
A list of reasons why the fish may not be able to negotiate each point along the length of the culvert.

Froude Number
The Froude number, Fr, is a dimensionless value that describes different flow regimes of open channel flow. The Froude number is a ratio of inertial and gravitational forces and is used to classify flow as critical, supercritical or subcritical at a point in the pipe.

When:

$Fr = 1$, critical flow,

$Fr > 1$, supercritical flow (fast rapid flow),

$Fr < 1$, subcritical flow (slow / tranquil flow)

Specific Momentum

See: Specific Force and Momentum

Shear Stress

Shear Stress is a measure of the frictional force of flowing water exerted on the surface of the channel bed. Shear stress is a factor in determining the mobility of a given bed material.

Stream Power

Stream Power measures the work available in flowing water to move stream bed material. Stream power is a useful measure for bed mobility calculations and prediction of erosion potential.

Composite Roughness

For culverts that have a natural bottom or substrate that has a different roughness coefficient from the culvert material roughness is composited using one of three methods described in Composite Roughness Calculations.

Energy Dissipation Factor

EDF represents the amount of energy used per unit of water flowing through the culvert. This parameter is important in the analysis of baffled culverts and roughened channel culverts. EDF represents an energy threshold for the ability of fish to utilize a given volume of water.

Hydraulic Curve

Hydraulic curves, or flow profiles, classify the type of flow in the culvert based on the Water Surface slope.

Wetted Area

The cross-sectional area of water as measured perpendicular to the flow.

Wetted Perimeter

The length of channel or pipe in contact with the water as measured perpendicular to the flow.

Top Width

The width of the water surface as measured perpendicular to the flow. The top width will usually vary with stage.

Hydraulic Radius

The cross sectional area of flow divided by the wetted perimeter.

Hydraulic Depth

The wetted area of flow divided by the top width.

Bottom Elevation

The absolute elevation of the culvert bottom along the length of the culvert measured from the user's datum.

Water Surface Elevation

The absolute elevation of the water surface along the length of the culvert measured from the user's datum.

Critical Elevation

The absolute elevation of the critical water depth along the length of the culvert measured from the user's datum.

EGL Elevation

The absolute elevation of the Energy Grade Line along the length of the culvert measured from the user's datum.

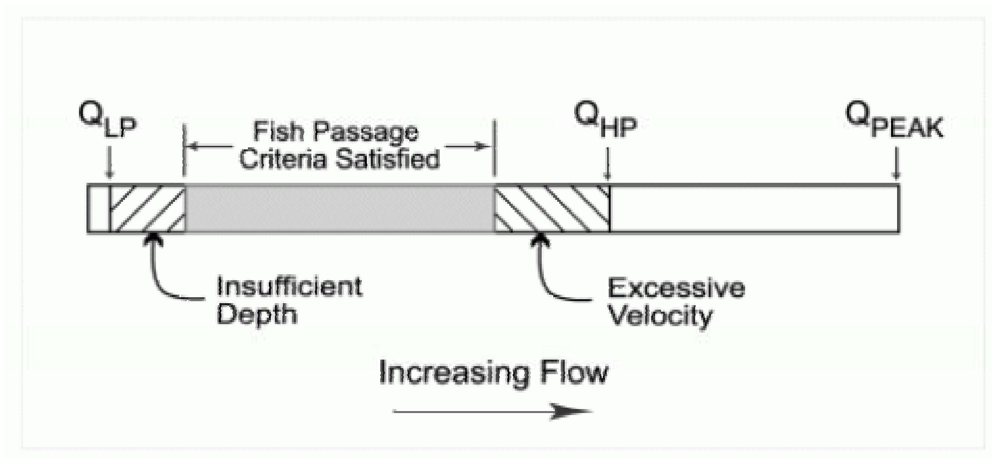
Water Surface Slope

The slope of the water surface between each node along the length of the culvert.

EGL Slope

The slope of the Energy Grade Line between each node along the length of the culvert.

Percent Passage



FishXing reports passage conditions for each culvert in a unique and insightful manner. It identifies flows in which various barrier types occur and reports the proportion of flow between QLP and QHP meeting all fish passage criteria. The **Fish Passage Summary Table** in the Output Summary Window gives the passage conditions for the range of flows defined by the Low and High Fish Passage flows:

- The High and Low passage design flows
- Percent of the flow range that is passable
- Barriers and flow range associated for each type of barrier

Fish Passage Summary	
Low Passage Design Flow	2.80 cfs
High Passage Design Flow	200.00 cfs
Percent of Flows Passable	23.7 %
Passable Flow Range	15.40 to 62.19 cfs
Depth Barrier	0 to 15.40 cfs
Outlet Drop Barriers	None
Velocity Barrier - Long	62.19 cfs and Above
Pool Depth Barrier	None

Note: Passage may also be expressed as the degree that the culvert is a barrier, which is called "**barrierity**", and is related to percent passage as (1- Percent Passage/100) .

Defining Barriers

FishXing reports the following barriers to fish passage:

Barriers are calculated based on the following decision processes:

Velocity, Exhausted Burst, and Long

For each node in the culvert:

1) If the reduced average water velocity, (average velocity * velocity reduction factor) is greater than or equal to fish's burst speed then the culvert is a VELOCITY barrier at this node. If not:

2) If the difference between the fish's prolonged speed and the reduced average water velocity, (average velocity * velocity reduction factor) is less than 0.01 ft/sec then the fish is not making adequate headway in prolonged mode and therefore swims through this node at BURST speed. If not:

3) The fish swims through this node in prolonged mode.

4) If the total time that the fish swims at prolonged speed exceeds the fish's prolonged time to exhaustion then FishXing checks to see if the fish will make it through the remainder of the culvert at burst speed before reaching its burst time to exhaustion. If so fish swims through the node at burst speed.

5) If not, the culvert is a BARRIER because it is TOO LONG (the fish is exhausted in prolonged mode).

6) If the total time that the fish swims at burst speed exceeds the fish's burst time to exhaustion the culvert is a BARRIER because the fish is EXHAUSTED in BURST mode.

Leap

If The Speed the fish must leap out of the water to successfully enter the culvert outlet is greater than its leaping ability as defined by the Max Leap Speed, a leap barrier is identified.

Drop

If the Outlet Drop (difference in elevation between the water surface at the culvert outlet and the tailwater) is greater than the Max Outlet Drop, as defined on the Crossing Input Window the culvert is a barrier at that flow due to the an excessive outlet DROP.

Depth

If the water depth anywhere in the culvert is less than the Minimum Depth as defined on the Crossing Input Window a DEPTH barrier exists at that flow. Generally the minimum depth is defined as the depth of water required to submerge the fish, see Fish Swimming more information. FishXing will notify the user of the total distance within the culvert that the depth is insufficient.

Pool

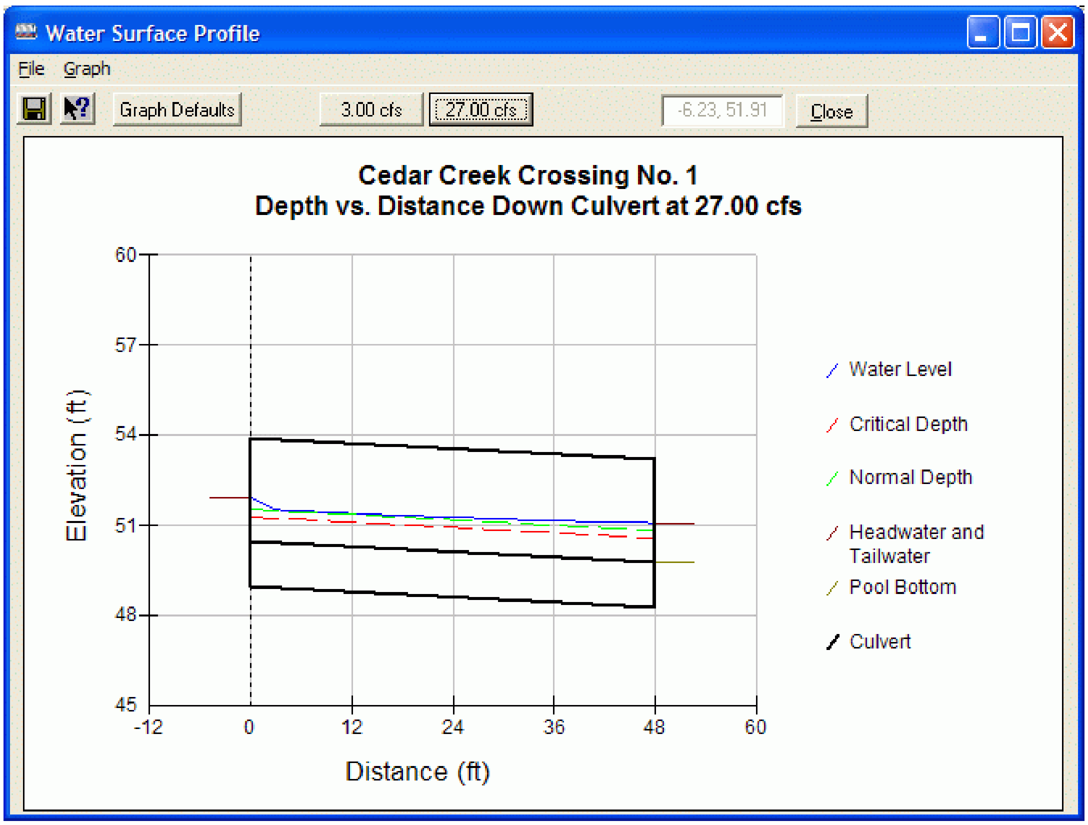
If the Outlet Pool Depth (Tailwater Elevation - Pool Bottom Elevation) is less than the Length of Fish as defined on the input screen, then it is considered to SHALLOW for leaping and is classified as a POOL barrier. This barrier criterion only applies to culverts with an outlet that requires leaping, see Fish Leaping for more info.

None

Indicates that none of the fish passage criteria was violated. The None barrier code indicates that fish passage was successful at the crossing for the given conditions and flow.

Water Surface Profile

The water Surface Profile reports the results of the hydraulic calculations graphed in the culvert. The Culvert dimensions are superimposed onto a graph with distance along the x-axis and elevation along the y-axis.



The following variables are displayed:

- **Water Level**
  Water level in the culvert modeled using gradually varied flow calculations.

- **Critical Depth**
  Depth at critical flow is the transition or control flow that represents the minimum energy in the flow with the maximum discharge for that depth. Theoretically it represents the minimum depth that water can flow through a culvert or over a boulder, log or weir.
  See also: Froude Number and Flow States

- **Normal Depth**

Normal depth is the depth of flow in a channel or culvert when the slope of the water surface and channel bottom are the same and the water depth remains constant. Normal depth only applies to the condition of uniform flow.

See Also: Defining Normal Depth, Manning's Equation

- **Headwater Elevation**

  The headwater elevation is the water surface elevation immediately upstream of the culvert.

  See Headwater Calculations for details.

- **Tailwater Elevation**

  The tailwater elevation is the water surface elevation immediately downstream of the culvert outlet. In most cases the tailwater elevation is a function of the flow as determined in the Tailwater Methods section of the input window.

  See also: Tailwater Methods, Tailwater Control

- **Outlet Pool Bottom**

  The outlet pool bottom is an input variable usually the result of a field survey. This will determine the depth of the pool and is used in leap calculations.

  See also: Minimum Plunge Pool Depth Calculations

Culvert Profiles Graph

The Culvert Profile allows you to view various parameters as they change through the culvert. The Culvert Profiles Graph is available for each of the designated Fish Passage Design Flows as well as any flow that was calculated using the Flow Rate Calculator on the Output Summary Page. A long list of variables is available by pressing the Customize button. It is recommended that only variables on similar scales be shown on a single graph so all data are displayed.

For general information see Customizing Tables and Graphs.

The following variables are available for display in the Culvert Profiles Graph.

- Distance Down Culvert
- Depth
- Critical Depth
- Normal Depth
- Velocity Head
- Velocity - Average
- Velocity - Occupied
- Ground Speed
- Swim Mode
- Prolonged Time
- Burst Time
- Barrier Type
- Froude Number
- Specific Momentum
- Shear Stress
- Stream Power
- Comp Roughness
- Energy Dissipation Factor
- Hydraulic Curve
- Wetted Area
- Wetted Perimeter
- Top Width
- Hydraulic Radius
- Hydraulic Depth
- Bottom Elevation
- Water Surface Elevation
- Critical Elevation
- Energy Grade Line Elevation
- Water Surface Slope
- Energy Grade Line Slope

Rating Table and Rating Curve

The rating table and rating curve display hydraulic variables and fish passage results with respect to a range of flow in the culvert. This allows the data to be evaluated across a wide range of flows that may be of interest in the crossing analysis. FishXing generates a table for a range of 0 cfs to 150% of the High Passage Flow (Qhp). If a higher flow is desired it is necessary to return to the Input Window and increase the High Passage Flow and re-calculate. However it should be noted that in this case the high passage flow will be incorrectly labeled in the rating curve.

See also: Customizing Tables and Graphs

Rating Table Variables

Q (analysis)

For Multiple Culvert Analyses Only: Analysis Flow Rate represents the flow in the culvert that is being analyzed for fish passage.

% Q total

For Multiple Culvert Analyses Only: Percent Q Total is the percent of the total flow in the culvert that is being analyzed for fish passage.

Q (Culvert # 1-5)

For Multiple Culvert Analyses Only: Flow in each of the culverts that are not being analyzed for fish passage.

Depth - Normal

Depth at Normal flow for range of flow rates.

Depth - Critical

Depth at Critical flow for range of flow rates.

Depth - Minimum

Shallowest Depth in the culvert for range of flow rates.

Depth – Minimum Barrel

Shallowest Depth in the culvert excluding the inlet and outlet for range of flow rates.

Depth - Inlet

Depth at first node inside the culvert inlet for range of flow rates.

Depth - Midpoint
Depth at culvert midpoint for range of flow rates.

Depth - Outlet
Depth at last node inside the culvert outlet for range of flow rates.

Depth - Tailwater
Depth of tailwater from culvert invert for range of flow rates. Negative value indicates tailwater is below the invert.

Depth - Pool
Depth of the outlet pool for range of flow rates.

Velocity - Normal
Velocity at Normal flow for range of flow rates.

Velocity – Maximum
Maximum velocity in the culvert for range of flow rates.

Velocity – Max Barrel
Maximum velocity in the culvert barrel excluding inlet and outlet for range of flow rates.

Velocity - Inlet
Velocity at the first node inside the culvert inlet for range of flow rates.

Velocity - Midpoint
Velocity at the culvert midpoint for range of flow rates.

Velocity - Outlet
Velocity at the last node inside the culvert outlet for range of flow rates.

V(occ) - Max
Maximum occupied (or reduced) velocity for range of flow rates.

V(occ) - Inlet
Occupied (or reduced) velocity at first node inside the culvert inlet for range of flow rates.

V(occ) - Midpoint

Occupied (or reduced) velocity at culvert midpoint for range of flow rates.

V(occ) - Outlet

Occupied (or reduced) velocity at the last node inside the culvert outlet for range of flow rates.

Outlet Water Surface Drop

Height of water surface drop at outlet for range of flow rates. Measured from the water surface elevation at the outlet and outlet pool water surface.

Vertical Leap Distance

Distance (height) fish is required to leap to enter the culvert outlet (same as Outlet Water Surface Drop) for range of flow rates. The Vertical and Horizontal leaping distances are predicted from projectile equations. To calculate the vertical leap distance, FishXing assumes that the fish leaps from the outlet pool water surface and lands flat on the water surface in the culvert outlet. See leaping information in Fish Performance.

Horizontal Leap Distance

Horizontal distance the fish must leap to enter the culvert outlet for range of flow rates. The Vertical and Horizontal leaping distances are predicted from projectile equations. The Horizontal Leap distance is calculated from the distance that the plunging water travels from the culvert outlet to the outlet pool. See leaping information in Fish Performance.

Required Leap Speed

Speed at which the fish must exit the water in order to successfully leap into the culvert for range of flow rates.See leaping information in Fish Performance.

Leap Angle

Angle at which the fish must exit the water in order to successfully leap into the culvert for range of flow rates.See leaping information in Fish Performance.

Prolonged Time

The time that the analysis fish spends in Prolonged Swimming Mode for range of flow rates.

Burst Time

The time that the analysis fish spends in Burst Swimming Mode (darting speed) for range of flow rates.

Length of Swim

Total length the fish swims in the culvert before either successful negotiation or failure for range of flow rates.

% Length of Swim

Percent of the total culvert length the fish swims before either successful negotiation (100%) or failure for range of flow rates.

Barrier Type

List of conditions where fish passage criteria was not met for range of flow rates. (Not available on rating curve.)

Head Loss - Inlet

Head loss at the culvert inlet for range of flow rates.

Head Loss - Total

Total head loss from the culvert inlet to outlet for range of flow rates.

Headwater Elevation

Absolute elevation of culvert headwater (referenced to user-input elevations) for range of flow rates.

Headwater Depth

Depth of headwater from culvert inlet invert for range of flow rates.

Culvert Freeboard

The difference between the height of the culvert and the headwater depth for range of flow rates.

HW/D Ratio

The ratio of headwater depth and culvert height (diameter for a round culvert) for range of flow rates.

Hydraulic Control

Is the culvert under inlet or outlet control for range of flow rates. (Not available on rating curve.)

Tailwater Elevation

Absolute elevation of the tailwater pool for range of flow rates.

Tailwater Cross Section – Max Depth

For input tailwater cross-sections only: Maximum Depth of flow at the tailwater cross-section for range of flow rates.

Tailwater Cross Section – Velocity

For input tailwater cross-sections only: Velocity of flow at the tailwater cross-section for range of flow rates.

Tailwater Cross Section – Wetted Area

For input tailwater cross-sections only: Wetted area at the tailwater cross-section for range of flow rates.

Tailwater Cross Section – Wetted Perimeter

For input tailwater cross-sections only: Wetted perimeter at the tailwater cross-section for range of flow rates.

Tailwater Cross Section – Composite Roughness

For input tailwater cross-sections only: Composite mannings roughness coefficient at the tailwater cross-section for range of flow rates. See Composite Roughness.

Slope Type

Slope type is a hydraulic parameter based on the culvert gradient and the relationship between water depth, normal depth, and critical depth. (Not available on rating curve.)

Critical Slope

The culvert slope that would result in critical flow for range of flow rates.

Water Surface Slope

Overall slope of the water surface from inlet to outlet for range of flow rates.

Shear Stress - Maximum

Maximum shear stress in culvert for range of flow rates.

Shear Stress - Inlet

Shear stress at the inlet for range of flow rates.

Shear Stress - Midpoint

Shear stress at the culvert midpoint for range of flow rates.

Shear Stress - Outlet

Shear stress at the culvert outlet for range of flow rates.

Stream Power - Maximum

Maximum stream power in culvert for range of flow rates.

Stream Power - Inlet

Stream power at the inlet for range of flow rates.

Stream Power - Midpoint

Stream power at the culvert midpoint for range of flow rates.

Stream Power - Outlet
Stream power at the outlet for range of flow rates.

EDF - Maximum
Maximum Energy Dissipation Factor in the culvert for range of flow rates.

EDF - Inlet
Energy Dissipation Factor at the inlet for range of flow rates.

EDF - Midpoint
Energy Dissipation Factor at the culvert midpoint for range of flow rates.

EDF - Outlet
Energy Dissipation Factor at the outlet for range of flow rates.

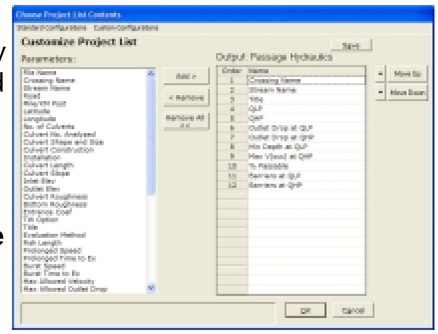
Pool Depth/Drop Height
Ratio of outlet pool depth and water surface drop height for range of flow rates.

Length of Depth Barrier
Total length of depth barrier for range of flow rates.

Customizing Tables and Graphs

All of the Graphs and Tables in FishXing can be customized for use in a variety of different analyses. The customizing procedure is similar for all of the outputs and is described below.

To customize a table or graph press the Customize Button. Select the parameter you would like to display from the Parameters list on left side of the screen and click **Add**. The parameter will be included in the Output list on the right side. The parameters in the Output list can be re-ordered by selecting the parameter and clicking the **Move Up** or **Move Down** button. Select an output parameter and click **Remove** to de-select it from the output list. When the parameters are in the desired order click **OK** to see the results.

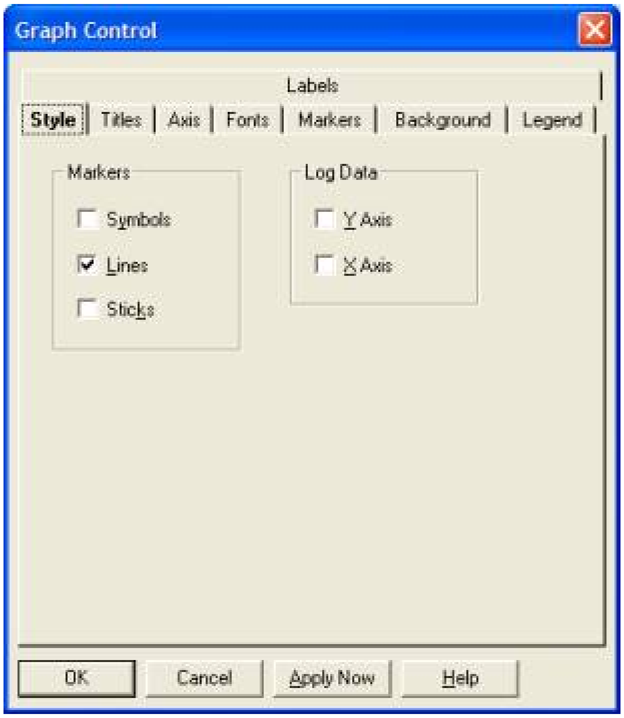


Standard Configurations

FishXing comes with certain combinations of parameters already defined for use in common applications which are listed in the Standard Configurations drop down menu. Choosing one of these Standard Configurations will change the list of parameters shown in the Output list.

Custom Configurations

After you have created a list of parameters that you wish to use repeatedly click the Save Button, name your configuration and it will be available in the Custom Configuration drop down menu.



Graph Setup

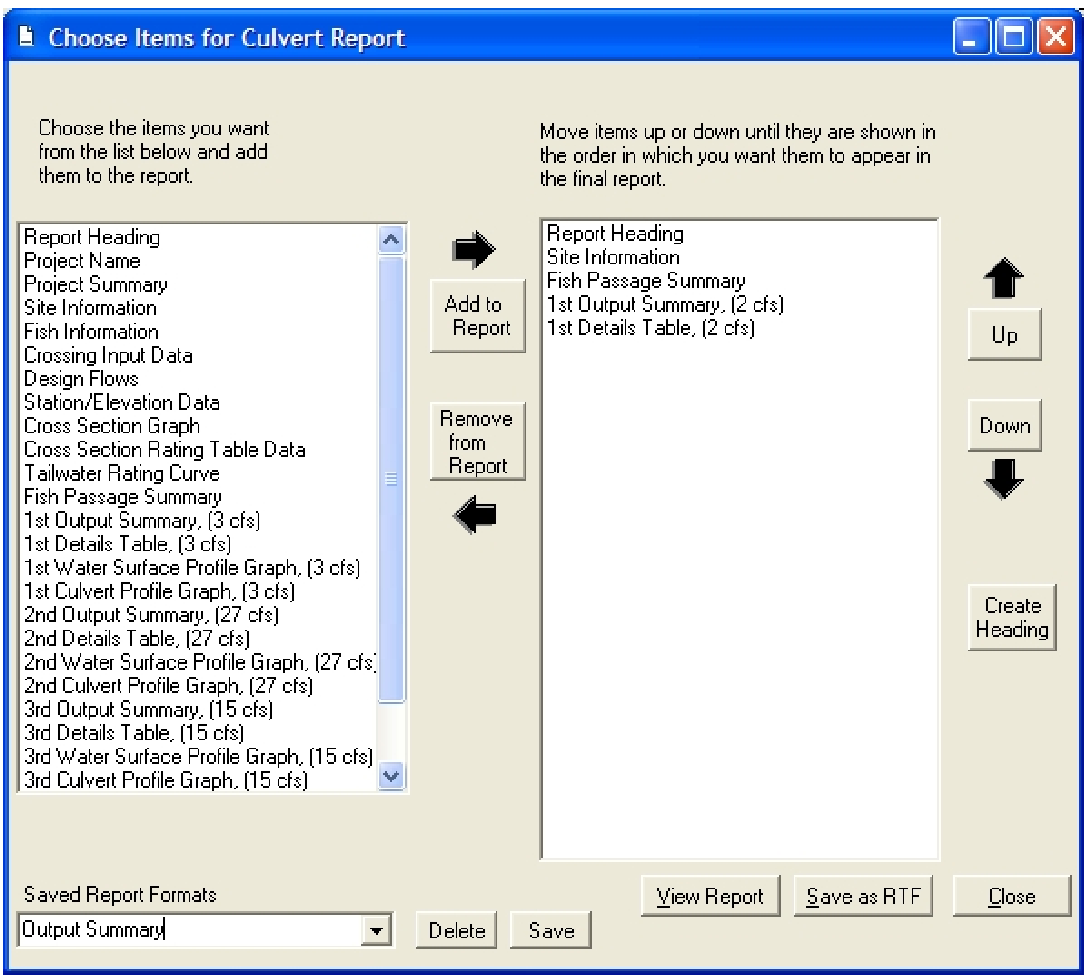
All output graphs in FishXing can be modified by right clicking on the graph. A window will appear that allows the user to change a number of graph parameters in the current view. Changes will not be applied to other graphs. The original graph layout can be restored by pressing the Graph Defaults Button.

Culvert Report

With FishXing you have the ability to create a summary report customized according to your data requirements. This custom report can include text, tables, graphs and pictures.

Choosing and arranging items for your report

When you choose Report on the Navigation Bar or Main Menu a list of items that are appropriate for this crossing will appear. You can select any of the items by highlighting the topic in the left panel and pressing **Add to Report**. An item can be selected more than once. Once items are selected they can be reordered as desired by selecting them and choosing the **Up** and **Down** buttons.



See also: Customizing Tables and Graphs

Viewing Reports

View Report – After choosing and ordering report items press View Report. This will generate a report on screen in a new window. The report cannot be edited, but several options are available for formatting:

- **Edit Headers** where you can type custom headers and footers and page numbers that will appear on each page.
- **Page Setup** where you can change the paper size, orientation, and margins.

Save as RTF – After choosing and ordering report items press Save as RTF. This will create a document in RTF (Rich Text Format) that can be edited in a word processing program. This option allows you to create reports that are fully customized, and is a good alternative when the Print View formatting is not acceptable.

Saving Report Formats

When you create a report that will be used multiple times you can save the format by choosing Save. Give the format a descriptive name at the prompt and choose Save.

Report Elements

Input

Report Heading: You can create a custom heading for the report by clicking the Create Heading button. If no custom heading is chosen the heading will just say “Crossing Report for …” and the crossing name.

Project Name: Prints the Project Name as selected in the Project Summary Window.

Project Summary: Prints the whole project summary table as it is currently configured in the Project Summary Window.

Site Information: Prints all the input information entered on the Site Information page.

Fish Information: Available when Literature or User-defined Swim Speeds are used. Prints all the information on Fish Swimming abilities shown on the Input Sheet. ***We call this Fish Information on the choice list, but the heading on the report says Biological Information…does anyone have an opinion on this?***

- Fish Length
- Minimum Water Depth
- Prolonged Swimming Speed
- Prolonged Time to Exhaustion
- Prolonged Notes
- Burst Swimming Speed
- Burst Time to Exhaustion
- Burst Notes
- Max Leaping Speed or Max Outlet Drop
- Velocity Reduction Factors

Evaluation Criteria: When Hydraulic Criteria are used, reports the criteria used in this analysis, including Maximum Allowed Water Velocity, Minimum Required Depth, Maximum Allowed Outlet Drop, Notes.

Crossing Input Data: Prints all the data associated with the culvert or culverts in the crossing. For each culvert in the crossing the following are reported.

- Culvert Shape and Size
- Material
- Installation / Countersunk Depth
- Natural Bottom Roughness Coefficient
- Length / Slope
- Culvert Roughness Coefficient
- Inlet Invert Elevation
- Outlet Invert Elevation
- Inlet Headloss Coefficient (Ke)

Design Flows: Prints Low and High Fish Passage Flow rates.

Tailwater and Cross Section Information: Depending on which Tailwater Method is selected, the report will list inputs used to determine tailwater conditions, rating curves and cross section data in table and graph format.

Output

Fish Passage Summary: Prints the Fish Passage Summary Table as shown on the Output Summary window.

1st Output Summary: Prints the Summary table for Low Fish Passage Flow rate as shown on the Output Summary window.

1st Details Table: Prints the Details table for Low Fish Passage Flow rate as entered on the Output Summary window. Any changes made to the Details Table on the Output Summary window will be reflected the in the report.

1st Water Surface Profile Graph: Prints the Water Surface Profile Graph for Low Fish Passage Flow rate as configured on the Water Surface Profile window.

1st Culvert Profile Graph: Prints the Culvert Profile Graph for Low Fish Passage Flow rate as customized and configured on the Culvert Profiles window.

2nd Output Summary: Prints the Summary table for High Fish Passage Flow rate as shown on the Output Summary window.

2nd Details Table: Prints the Details table for the High Fish Passage Flow rate as customized on the Output Summary window. Any changes made to the customization of the Details Table on the Output Summary window will be reflected in the report.

2nd Water Surface Profile Graph: Prints the Water Surface Profile Graph for High Fish Passage Flow rate as configured on the Water Surface Profile window.

2nd Culvert Profile Graph: Prints the Culvert Profile Graph for High Fish Passage Flow rate as customized and configured on the Culvert Profiles window.

If an additional flow rate was calculated with the Flow Rate Calculator on the Output Summary window, then a 3rd set of tables and graphs will be available for that flow.

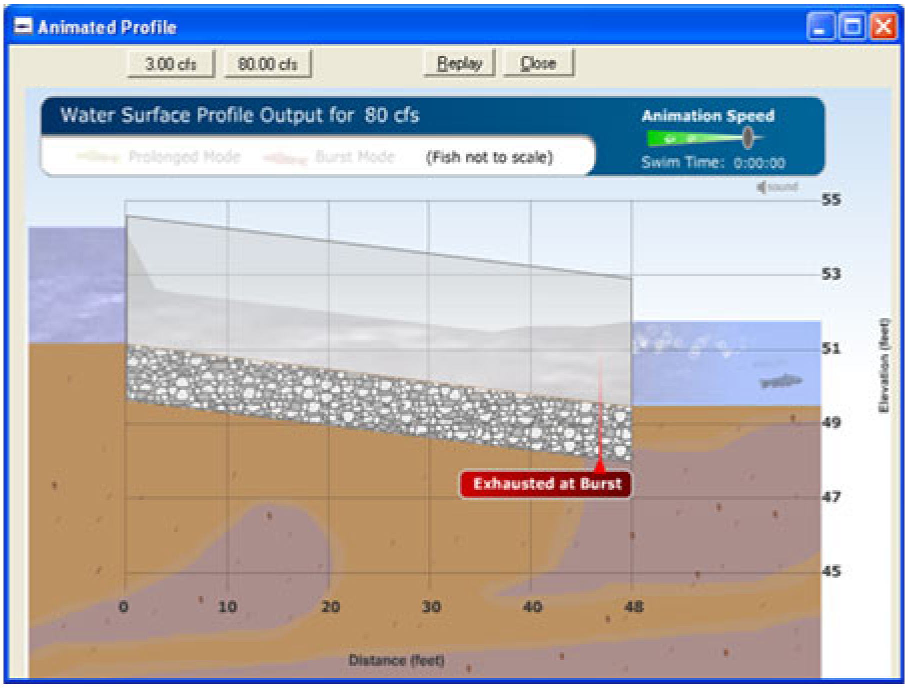
Culvert Rating Table: Prints the Culvert Rating Table as customized on the Rating Tables window.

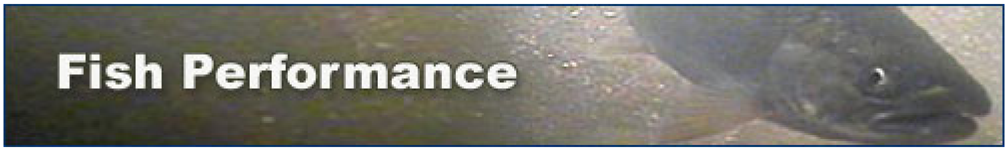
Culvert Rating Curve: Prints the Culvert Rating Curve as customized and configured on the Rating Tables window. Known bug: If the line weights or colors are reconfigured the graph may show in black and white on the report and subsequently in the Rating Curves window.

Barrier Codes: Displays a key for the codes used in output for the different type of barriers to fish passage.

Images: Displays images attached to crossing from the Site Information window.

Animated Profile





Fish Performance

Topics:

- Fish Movement
- The Analysis Species
- Swimming Capabilities
- Swim Categories
- Fish Swimming and Swim Speed Tests
- Time to Exhaustion
- Fish Length and Swim Speeds
- Measures of Fish Length
- Converting Fish Lengths
- Other Factors Affecting Swimming Speed and Leaping Capability
- Swim Speed Equations
- Occupied Velocity
- Water Depth for Swimming
- Leaping Capabilities
- Leaping from Plunge Pools
- Estimating Fish Body Depth
- Fish Passage Flows
- Guidelines for Fish Passage Flows
- Effects of Turbulence
- Fish Calculations Overview
- References

Fish Length Conversion Table

Swim Speed Table

Back to Main Topics:

Main Map Run Calculate Results Culvert Hydraulic Fish Glossary

Fish Movement

Movement by Fishes

Movement is amongst the most important of animal behaviors, because it allows animals to respond to conditions within their environment to increase growth, survival and reproductive success (Kahler et al. 2001). The scale and pattern of fish movement varies widely among species. Some of the longest and most directed movements are completed by anadromous salmonids in North America rivers or the piracema in South America as they migrate from headwater streams as young fish to the ocean and then migrate back to their natal streams as adults to spawn. Most species of stream fish do not migrate to the ocean, but instead appear to establish home ranges of various sizes and occupy those ranges for various amounts of time. Species such as smallmouth bass (*Micropterus dolomieu*) or green sunfish (*Lepomis* cyanellus) spend a majority of their time within a home pool, but do make trips to up and downstream areas (Todd and Rabeni 1989, Smithson and Johnston 1999).

The interpretation and importance of movement for these less mobile species has changed overtime. Early researchers concluded that most adult stream fishes restricted their movements to a small home range (Gerking 1959), failing to focus much attention on evidence of movement away from the home pool, with the exception of spawning runs. Researches are re-examining the premise of what is now termed the restricted movement paradigm (Gowan et al.1994), and are discovering that this paradigm is insufficient to fully define movement by stream fishes (Smithson and Johnston 1999).

Some species of resident stream fish, such as cutthroat trout (*Oncorhynchus, clarki*) were thought to spend their lives in 20 meter to 50 meter stream reaches (Miller 1957). However, recent studies have shown that most trout have relatively large home ranges (Young 1994 in Fausch and Young 1995) and at times move long distances (Hilderbrand and Kershner 2000). Bjornn and Mallett (1994) studied rainbow trout (*Oncorhynchus mykiss*), bull trout (*Salvelinus confluentus*) and cutthroat trout in Salmon River, Idaho and found that over several months many fish moved greater than 8 kilometers and some had moved greater than 40 kilometers. Hilderbrand and Kershner (2000) found that similar results for other species of trout indicate that large scale movement is a widespread pattern among resident stream salmonids.

In addition to salmonids, several other species were found to move more frequently than once believed. Lonrarich et al. (2000) concluded from their observation of 1800 marked fish (central stoneroller, *Campostoma anomalum*; striped shiner, *Luxilus chrysocephalus*; northern studfish, *Fundulus catenatus*; longear sunfish, *Lepomis megalotis* and smallmouth bass, *Micropterus dolomieu*) that movement within two Arkansas streams was a “diffusive process” with up- and downstream movement being roughly equal. Smallmouth bass moved 120 to 948 meters/day depending on water temperature (Todd and Rabeni 1989), and 100 percent of them moved out of their home pool in spring presumably to spawn. Additionally, warm water fishes that establish home ranges also spend part of their time away from their home pool; 12 percent of green sunfish (*Lepomis cyanellus*) and 14 percent of longear sunfish were recaptured away from their home pool (Smithson and Johnston 1999). The entire fish assemblage represented by eight species within Sagehen Creek, California was found to be mobile (Decker and Erman 1992). Species included Lahontan redside (*Richardsonius egregious*), Tahoe sucker (*Catostomus tahoensis*), speckled dace (*Rhinichythys osculus*), mountain sucker (*C. platyrhynchus*), mountain whitefish (*Prosopium williamsoni*), and rainbow (*Oncorhynchus mykiss*), brown (*Salmo trutta*), and brook trout (*Salvelinus fontinalis*). Warren and Pardew (1998, page 642) in studying fish passage at road stream crossing of small fishes in an Arkansas stream, found that culverts were “bi-directional barriers to fish movement in both seasons despite a range of flow conditions (e.g., bank-full flows).”

Recoloniztion studies have also been interpreted as evidence that stream fish movement is important for long-term population survival. In an Illinois stream, recolonization rates were tested following experimental removal of fishes from a 46 to 100 meter long section of stream using 18 warm water fishes [including cyprinids (minnows, shiners, chubs), catostomids (suckers), centrarchids (sunfishes and basses)]. Rapid recovery occurred in both abundance, (90 percent of fish abundance returned to predisturbance conditions in 100 to 270 hours), and species composition, (0.7 of its original composition) in 60 to 140 hours (Peterson and Bayley 1993). Other studies have also found rapid recolonization of streams providing further evidence for fish movement (Larimore et al. 1959, Hall 1972). Fish are thought to repopulate stream sections through short-term exploratory movement into and out of areas (Peterson and Bayley 1993), and through season migrations such as spawning runs (Larimore et al. 1959, Hall 1972).

Movement by Juvenile Fishes

Most studies of fish movement have focused on adult stream fishes; however, fry and juveniles also move. A summary by Gowan et al. (1994, page 2627) lists several studies that discuss well known movements made by resident stream salmonids, including many made by fry. Listed below are some of the reasons for movement cited by Gowan et al.(1994):

1. Passive fry dispersal with flow,
2. Active fry dispersal possibly mediated by social dominance,
3. Limited fry dispersal in closely juxtaposed habitats,
4. Specialized patterns of fry and juvenile dispersal in unique habitats, and
5. Movements related to ontogenetic shifts in microhabitat use, possibly to increase rate of food intake or avoid competition by habitat segregation.

Movements by juvenile coho (Oncorhynchus kitsuch), cutthroat trout and steelhead (Oncorhynchus mykiss) were found to be common, with a majority of juvenile fish moving upstream (Kahler et al. 2001). These authors also reported faster growth rates for juveniles that moved, indicating the importance of having access to up- and downstream areas.

Stream ecosystems are made of assemblages of fish species that vary in their scale and pattern of movement. Even some fishes that spend a majority of their time in relatively small home ranges do spend some time away from their home pool. Juvenile fishes also move both up- and down-stream. It appears that for stream fishes movement is a widespread phenomenon that increases their changes of survival and reproduction. For a more thorough discussion of movement of stream assemblages

Life History Cycle and Movement

According to Power et al. (1988), the ability to predict the responses of organisms to changes within their environment is dependent on an understanding of their life histories. Different life history stages often have different capabilities and needs, and use different types of habitats. The use of different types of habitats is often related to increased probability of survival. For example, stream fishes often spawn as flood waters start to rise and young are deposited in upstream or lateral habitats where predation pressure is lower than it is in downstream or mainstem rivers (Welcomme 1979). Also, by having different life history stages occupy different stream locations, the vulnerability of the population as a whole to localized disturbances is reduced (Statzner 1987). Because various life history stages of stream fishes are carried out in different locations the ability to move between habitats is important.

Even for an individual species there are regional differences associated with important life history traits, such as age or size at first reproduction or timing of spawning or downstream migrations. For many stream fishes, changes in life history stage are mediated by a combination of light, temperature or flow (Power et al. 1988). Because of the importance of understanding life history cycles when predicting responses to changes in the environment, and the possible local variability in life history cycle, local fisheries biologists are the best source of information regarding movement needs related to life history cycle.

Function of Movement

Streams are dynamic systems due to frequent disturbances such as floods or landslides, and fish habitat distribution within streams is inconsistent. Under such conditions, fish that can move between patches can recolonize disturbed areas, find new, higher quality, or less competitive habitats, or can more readily avoid predation. Also, smaller populations that are prone to extinction may be dependent on movement to sustain themselves (Schaefer 2001, Brown and Kordic-Brown 1977 in Schaefer 2001). Fish movement can also support finding critical resources that change throughout the year and throughout the life cycle of fishes. Spawning, feeding and overwintering habitats are often located in different stream reaches. In addition, habitats that are suitable for fry are often not suitable for adults so fish must move as they mature. Fish movement also allows fish to avoid unsuitable or suboptimal conditions such as seasonally dewatered areas, high stream temperatures or stream flows, or elevated pollution levels.

The movement of fishes can be affected by both the physical conditions of the stream and the composition of the fish community. In a study on the movement of three cyprinids (*Notropis boops*, *Campostoma anomalum* and *Cyprinella venusta*) current velocity, riffle length and predation threat were found to alter movement rates. Decker and Erman (1992) found that there were interspecies differences in physical and biological characteristics that were associated with movement within the Saghen Creek, California fish assemblage. Changes in abundance indicated movement into and out of the study reach. For example, temperature affected the abundance of Tahoe sucker, decreased stream discharge increased rainbow trout abundance; and breeding affected the abundance of Tahoe sucker, Lahotan redside, and possibly mountain whitefish.

Fish Movement Summary

In general, the ability to move about the stream environment is important to the survival and reproduction of fishes. Because, the scale and pattern of fish movement varies widely among species, it is important to investigate the species and their needs before analyzing a culvert for fish passage. It is also important to reconsider concepts about limited movements of juvenile and resident stream fishes. It may not be safe to assume that juvenile fish only require downstream passage or that resident stream fish's survival is solely dependent on a restricted home range.

The Analysis Species and Life Stages

It is required to select an "Analysis Fish" that represents the abilities of the fish population that will be modeled in the fish passage analysis. It is important to consider whether you are modeling the strongest swimmers or weakest individuals of a fish species.

The swim speeds and leaping abilities that are reported in the Performance Database represent a range of abilities if available, and FishXing will use the average as a default for model inputs. Similarly Hydraulic Criteria is generally based on the average abilities of a singular species of interest.

Before beginning the passage analysis, it is necessary to identify the species and life stage you will be analyzing. To provide a comprehensive assessment of fish passage at the culvert, it may be necessary to assess the passage capability of several species and life stages. FishXing uses two different approaches for evaluating fish passage conditions:

1. Biological modeling approach: Models the progress of an individual fish as it leaps into and swims through a culvert.

2. Hydraulic Criteria approach: Compares the hydraulic conditions in the culvert with criteria that must be satisfied to ensure adequate passage conditions exist.

Both methods require that a species and life stage be identified, because the analysis is based on physical (e.g., swimming speed) and behavioral (e.g., seasonal movement) attributes of specific species and life stages.

Approaches for defining the Analysis Species		
Factors Affecting Fish Passage	**Biological Modeling Approach**	**Hydraulic Criteria Approach**
Outlet Pool Depth	▪ Required Depth for Leaping	▪ Required Depth for Leaping
Entering Culvert Outlet	▪ Capable of Leaping? ▪ Leaping Speed ▪ Body Length	▪ Maximum Outlet Drop
Swimming Capabilities	▪ Swim Categories ▪ Swim Speeds ▪ Times to Exhaustion ▪ Occupied Velocities	▪ Maximum Water Velocity ▪ Occupied Velocities
Water Depth for Swimming	▪ Body Height ▪ Adequate Submergence	▪ Minimum Required Depth
Timing of Movement	▪ Low and High Fish Passage Flows	▪ Low and High Fish Passage Flows

Considerations when Choosing a Species and Life Stage for Analysis

Different species and life stages of fish have different swimming capabilities and movement needs which will determine a fishes' ability to pass through a culvert crossing.

It is possible that regulation or policy will dictate which fish species you will use in the analysis.. If, on the other hand, you need to choose which species and life stages to analyze, then there are two primary factors to consider.

1) The swimming capabilities of the species and life stages present in the stream; and

2) The time of year when passage is needed.

The Literature Swim Speed spreadsheet may be helpful in comparing the swimming capabilities of different species and life stages. The Fish Movement section discusses some factors to consider when estimating the timing of fish movements.

The range of flows analyzed in FishXing are defined by the Low Passage Flow (QLP) and High Passage Flow (QHP).When looking at a population of fish species, generally the weakest swimming fish and lifestage will determine passage at high flows while the largest fish will determine passage limitations at the lowest flows.

As stated in the Fish Movement section, adult and juvenile fish may be more active during certain time periods (such as late spring movement of juvenile coho salmon or during spawning runs of adults) or there may be certain periods when adult or juvenile fish are absent from a particular stream reach. In addition, most river systems have variable flow regimes due to seasonally variable precipitation (e.g., winter rains, spring snow melt, or summer drought). When choosing the species and life stage to analyze it is important to consider the intersection of seasonal flows with the fish's seasonal movement to determine when high flows or low flows may be limiting to fish passage through the culvert.

See Fish Passage Flows, Fish Movement, Other Factors Affecting Swimming Speed and Leaping Capability, Flow Guidelines for Fish Passage Flows

Swimming Capability

Differing swimming modes, methods of propulsion, and drag reducing effects account for the wide variation found among the swimming abilities of the world's fishes (Videler 1993, Webb 1975, 1994). Most fish swim by pushing backwards against the water with undulation of their body and their fins (Lindsay 1978). Different species of fish have different swimming modes defined by variation in these body and fin undulations (Breder 1926), examples include: anguilliform where the whole body is thrown in a wave (e.g., eels); carangiform where the body and caudal (tail) fin is thrown into a wave (e.g., pike, cod, salmon); and ostraciform where the body is held rigid and the caudal fin oscillates (e.g., cowfishes, boxfishes). Fish also have different propulsion systems due to differences in body and fin morphologies, and their drag reducing features differ (e.g., mucus, skin, and scale morphologies).

The fastest swimmers are characterized by streamlined bodies that are elliptical in cross section and have a narrow caudal peduncle. Examples of these fast swimming fish include tuna, salmonids, and black basses (*Micropterus sp.*). Fishes that are compressed laterally, such as the sunfishes (*Lepomis sp.*), have well developed maneuverability and are capable of quick bursts and turns. Some of the slowest fishes have rounded bodies and use oscraciform swimming. The swimming abilities of different fishes are often reflected in their life history traits (Castro-Santos 2002, Peake et al. 1997, Swanson et al. 1998, Taylor and Foote 1991). For example, fish completing long migrations in flowing water or that spend more time in fast moving riffles have better swimming performance than more sedentary species or species that mainly inhabit pools.

Swim Categories

Fish swimming performance has been classified into three distinct categories:

- Sustained,
- Prolonged and
- Burst.

FishXing models the latter two categories, Prolonged and Burst.

Swimming categories are based on limitations imposed by time and on biochemical processes, which supply the fuel to the muscles (Beamish 1978). The proper differentiation among swimming categories can be clearly seen when examining the relationship between time to exhaustion and swimming velocity for a particular fish. For some species, the distinction between burst and prolonged swimming and between prolonged and sustained swimming can be seen as slope changes on a graph of swimming time vs swimming velocity. For a thorough discussion of this topic that uses sockeye salmon as an example, see Brett (1964). For other species, the relationship between swimming time and swimming velocity does not include slope changes between all swimming categories (Peake et al. 1997).

Unfortunately, the literature contains inconsistent usage of terms to describe swimming categories. Before interpreting study results, it is important to clearly understand the actual definition of the swimming category used by the authors.

Sustained Swim Speed

Sustained performances are those speeds that fish can maintain for long periods (>200 minutes) without muscular fatigue (Beamish 1978). At sustained speeds, energy is supplied to slow oxidative (red) muscle fibers through aerobic processes. These fibers do not fatigue and do not have high power output (Webb 1994). Metabolic demand is matched by its supply and waste production is matched by its removal (Jones 1982). A subcategory of sustained performance is cruising speed; these speeds are used by migrating fish or fish that are negatively buoyant and must swim to maintain their place in the water column (e.g., tuna). The maximum sustained speed is the highest velocity that a fish can maintain without eventually fatiguing. Swim speeds above sustained speed fall into the prolonged or burst swimming categories.

Prolonged Swim Speed

Prolonged performances are those speeds that fish can maintain for 20 seconds to 200 minutes and ends in fatigue (Beamish 1978). The prolonged category spans the swimming speeds between sustained and burst. At prolonged speeds, energy is supplied to slow (red) and/ or fast oxidative glycolytic (pink), and /or fast glycolytic (white) fibers through aerobic and anaerobic processes, respectively. As speed increases so does anaerobic metabolism. White muscle fibers have high power output but low energy reserve, which results in eventual fatigue (Webb 1994).

Since swimming at prolonged speeds can be maintained for relatively extended periods and appears to not impose undue physical stress on the fish, these speeds are commonly used in assessment and design of culverts. Many regulatory agencies guidelines recommend using prolonged swim speeds to design or assess fish passage through culverts.

Critical Swim Speed

A sub-category within prolonged performance is the critical swimming speed, which is the maximum velocity that can be maintained by a fish for a specific period of time (Brett 1964) . This type of swimming performance is often reported in the literature and the Literature Swim Speed Table includes data derived from critical swimming speed tests. When the time between velocity increases in the critical swimming test is about one hour, the critical swimming speed approximates the speed that delineates the change from sustained to prolonged swimming, i.e., maximum sustain swimming speed (Brett 1964). More information about critical swimming speed test is provided in the Swim Speed Test section.

Burst Swim Speeds

Burst performances are the highest speeds attainable by fish and can be maintained for only short periods of time (<20 seconds) (Beamish 1978). At burst speeds, energy is primarily supplied to myotomal (body) white muscle through anaerobic processes (Webb 1994). The conclusion of short periods of burst swimming occurs as a result of the exhaustion of extracellular energy supplies or accumulation of waste products (Colvavecchia et al. 1998). Fish often use burst speeds to pass through short high velocity areas, such as the inlet or outlet of a culvert. Median and paired fins tend to power slow swimming which is supplemented and then replaced with body and caudal (tail) fin undulation swimming at higher speeds and for acceleration (Webb 1994). At burst speeds the caudal (tail) fin is expanded and made as rigid as possible (Nursall 1962). When fish swim at low speed they modulate the frequency and amplitude of their body and caudal fin undulation and at high speed they only modulate frequency (Bainbridge 1958, Webb 1971).

Recovery Time and Burst Swimming

If fish must swim in burst mode to pass through high velocity areas it is important to consider their ability to recover and perform multiple bouts of exhaustive swimming.

A fish's ability swim in burst mode may be limited in the short term (a few hours to a day) because some fish species require relatively long periods to recover from exhaustive exercise (Black et al, 1962). Additionally, some fish die after performing exhaustive exercise. For example, trout subjected to intensive exercise for six minutes had a mortality rate of 40 percent with the majority of death occurring four to eight hours post-exercise (Wood et al. 1983). Reviews of recovery from exhaustive exercise have revealed that species differences span several orders of magnitude (Milligan and Wood 1987, Nelson 1990, Boutilier et al. 1993, Keiffer 2001). For example, salmonids have high burst speeds but appear to recover relatively slowly. Paulik et al. (1957) found that coho salmon recovery from exhaustive exercise was 67 percent after three hours and full recovery occurred only after 18 to 24 hours. These fish were forced to swim until they could no longer maintain their position upstream of an electrical shock. Steelhead were able to re-perform their baseline swim speed after six hours (Paulik and DeLacy 1957).

On the other hand, juvenile Atlantic sturgeon (Acipenser oxyrhynchus) and shortnose sturgeon (A. brevirostrum) have relatively low burst speeds but recover more quickly than salmonids. Juvenile sturgeon recovered their baseline oxygen consumption rates in 30 minutes, muscle energy metabolite levels in one hour and muscle lactate levels in six hours (Kieffer 2001). It is thought that species differences in recovery rates reflect differences in ecological requirements, morphology, and behavior (Keiffer 2000).

Migrational Delays and Multiple Crossings

Anadormous fish migrating upstream to spawn do not consume food. Therefore, they have a limited energy supply with which to complete their journey to their natal stream and to spawn. Migrational delays can reduce an individual's fitness and ability to reproduce. High velocities through culverts related to seasonal high flows should be evaluated to ensure they do not exceed acceptable levels and cause migrational delays. . Migrational delays can also result from the cumulative effect of many culverts in series. The energy demands and recovery time required to pass through multiple crossings should be considered when evaluating fish passage. If fish must cross through several culverts during their upstream movements, it is important to consider their ability to perform multiple bouts of exhaustive swimming.

See **Fish Swimming and Swim Speed Tests**, Fish Calculations Overview

Fish Swimming and Swim Speed Tests

Fish Swimming performance is one of the basic FishXing model inputs and it is important to understand how swim speed estimates were developed and how accurate they might be. Most of the swim data available in the literature is derived from laboratory experiments under controlled and usually non-volitional swimming conditions.

While a thorough discussion of this topic is beyond the scope of this Help manual, the following is a brief outline of the issues involved in estimating swim speeds. More in depth discussion can be found in reviews of swimming speed tests by Beamish (1978), Cech (1990), and Hammer (1995).

Test Chambers

Beamish (1978) describes various test procedures and discusses conditions that produce variable results. Swim speed tests are usually carried out in test chambers of two basic types: in one, the chamber rotates, and in the other, water flows through a stationary chamber.

The test chamber can affect the estimate of the water velocity experienced by the fish. Rotating chambers create complex flow patterns that can affect estimates of water velocity. Where the water moves and the chamber stays stationary, the chamber is often a tube (small water volume) or flume (large water volume). Unless flow straighteners are used flow through the tube or flume can also be complex and affect the estimate of water velocity. Even when laminar flow is achieved, precise description of swimming capacity is difficult because not only does the precise location of the fish need to be monitored, but also the velocity that can be assigned to each location (Beamish 1978).

Fish Size

Another consideration when using test chambers to estimate swim speed, is the size of the fish relative to the size of the test chamber. When the fish's body occupies a significant portion of the chamber, the chamber effectively becomes narrower resulting in an accelerated flow over the body of the fish. Additionally, fish experience a higher than expected drag in an enclosed flume as compared to freestream velocity. The additional drag comes from horizontal buoyancy and solid blocking effects (Beamish 1978). Corrections for these effects have been described by Webb (1971).

Test Procedures

The test procedure can also affect the estimates of swimming speeds. For example, the length of time fish are allowed to recover from handling stress after being transferred to the test chamber has been shown to affect swimming speed. The rate and magnitude of water velocity increases also can influence test results. Hammer (1995) provides a good summary of this topic.

There are three basic types of test procedures:

1. Fixed velocity or endurance tests,

2. Increasing velocity or critical velocity tests, and

3. Volitional swimming tests that involve measuring the distance traveled against a water velocity in an open channel.

Endurance Tests

In the fixed velocity or endurance test, velocity is abruptly or gradually stepped up to the prescribed level. After the test velocity is reached, the time to exhaustion is measured. When 50 percent of the fish have fatigued, the mean maximum sustainable speed is reached (Brett 1967).

Critical Velocity Tests

In increasing velocity or critical velocity tests, the fish is subjected to increasing velocities in a series of steps (velocity increments) with each step being maintained for a specific period of time (time between increments). Brett (1964) calculated the fatigue speed or critical velocity (Ucrit) as:

$$U_{crit} = V_p + \left(\frac{t_f}{t_i}\right)V_i$$

where,

Vi = the velocity step (cm/s)
Vp = the penultimate velocity reached at fatigue (cm/s)
tf = the time lapsed from the velocity increase to fatigue (s)
ti = the time between velocity increments (s)

Hammer (1995) provides a literature review on the effect of velocity increment and the time between increments. Farlinger and Beamish (1977) demonstrated that changes in both velocity increment and time between increments have a marked effect on the swimming speed of largemouth bass (Micropterus salmoides). Hammer (1995) concludes from his review of the literature that velocity intervals shorter than 15 to 20 minutes have a marked effect on the estimate of critical velocity. However, he finds no reason for the time to be as long as the 60 minutes Brett (1964) recommended, and states that 30 minutes intervals seem to be appropriate.

It appears that following a velocity increase fish exhibit a period of restlessness and Webb (1971, in Hammer 1995) suggest that some anaerobic energy production occurs after each increase. He concludes that the time required to adjust to the higher speeds with time increments less than 20 minutes may take up a significant portion of the time at that increment and affect the results of the test. Webb (1971) further suggests that fixed velocity and increasing velocity tests measure different forms of exhaustion and should not be compared.

Volitional Swimming Tests

The last form of test involves fish swimming a measured distance against a velocity challenge. Weaver (1963, 1965) tested the ability of migrating anadromous salmonids to ascend an experimental fishway. Recently, Castro-Santos (200?) and Peake (2004) questioned the validity of swim speed estimates derived from data collected using fixed or increasing velocity tests where fish are forced to swim in enclosed tubes at prolonged speeds. Other authors have noted that fish do not swim steadily at prolonged speeds as they are forced to do in most swim speed tests. Routine swimming by fish is often unsteady. At low speeds, “stroke-and-glide” (Swanson et al. 1998), and at high speeds, “burst-and-coast” swimming behavior (Hitch and Bratty 2000) has been observed in fish. These behaviors are believed to increase endurance and reduce energy expenditure (Webb 1994 and Weihs 1974).

Some fish may not be suited to swimming steadily at prolonged speeds. Swanson et al. (1998) measured the critical swimming velocity and behavioral a kinematic limitation on swimming at submaximal velocities in delta smelt (Hypomesus transpacificus). They found that delta smelt exhibited swimming failures at velocities that corresponded to the transition between ‘stroke and glide’ swimming and continuous swimming. Delta smelt were unable or unwilling to swim steadily in the flume within the transition velocity range. They speculate that delta smelt may not swim at these speeds under natural conditions.

Peake (2004) argued that more realistic swimming speeds are generated by testing fish in a 50-meter raceway than in a respirometer tube using increasing velocity tests. He found that fish increased their swimming speed as the water velocity increased. The swimming speeds he found in the raceway were almost twice those predicted from the critical velocity tests. He speculated about the causes of the estimate differences including decreased tail beat amplitude due to confinement in the respirometer tube, but concluded that the explanations presented did not seem satisfactory and were likely caused by a combination of behavioral, physiological, and hydraulic conditions.

There is some evidence that migratory teleosts swim at a constant ground speed through a wide range of water velocities spanning both prolonged and burst swimming speeds. Swimming at constant ground speed may optimize the distance traveled in some, but not all cases (Castro-Santos 2002).

FishXing and Swim Speeds

Rather than a constant ground speed, FishXing assumes a constant swimming speed, either at their estimated prolonged or burst swimming speeds based on the water velocity. Both the validity and effect of this assumption is the subject of current study, and we expect that estimates of swimming speeds will improve over time. Most of the constant and calculated swim speed estimates in FishXing’s literature Swim Speeds Table were derived from fixed velocity or increasing velocity tests. The limitations of these tests in accurately predicting swimming speed should be understood before using this model.

Variability Between Individuals and Populations

The biological parameters and criteria used in an analysis are typically intended to represent the overall population of a specific species and lifestage. However, several researchers have commented on the wide range in swimming speeds that individuals display (Berry and Pimentel 1985, Kovacs and Leduc 1982, Mcdonald et al., 1998, and McNeish and Hatch 1978) even when the major factors affecting speeds such as species, size, life stage and stock are taken into account. McDonald et al. (1998) suggested that the individual differences were probably due to real inter-individual physiological differences. Berryand Pimentel (1985) suggest that the individual differences are probably due to different levels of motivation and stress. Because swimming speeds are variable, the species and life stage mean swimming speed may not be the best estimated to use to ensure that most of the individuals within a species and life stage can pass the culvert. It is important to consider this variability when choosing the swimming speed for the species and life stage that you will be analyzing with FishXing.

See: Time to Exhaustion, Swim Categories, Swim Speeds Table

Time to Exhaustion

The time to exhaustion is the amount of time that a fish can swim at a prescribed velocity and is typically estimated from swim speed tests. Swim tests have generally shown that, when swimming above sustained speeds, as the swimming velocity increases the amount of time the velocity can be maintained decreases. Time to exhaustion may be reported as a constant value derived in the swim test, a default value selected by FishXing Biologists, or as function of the swim speed equation.

When the relationship between exhaustion times and swim speeds has not been defined as part of a swim speed study, reasonable approximations are presumed to be 20 seconds to 200 minutes for prolonged speeds, and less then 20 seconds for burst speeds (Beamish 1978).

Determining Time to Exhaustion in Swim Speed Tests

In fixed velocity (endurance) tests, the time to exhaustion is directly measured for each velocity tested. In increasing velocity (critical) tests velocity is increased in a series of steps at specific time increments. The assumption required to use this data to assess fish passage is that the length of the time increment in the critical velocity test corresponds to the endurance time in a fixed velocity test. This assumption implies that fish are not fatigued at lower speeds, but fatigue rapidly as speeds increase (Hunter and Mayor 1986). Brett (1964) showed that for small fish fatigue curves from fixed and increasing velocity tests with 60 minute time increments have similar slopes thus supporting the validity of this assumption. However, fixed velocity tests had slightly higher endurance times than those predicted from increasing velocity tests.

Selecting Time to Exhaustion in FishXing

When you select a set of swim performance data from the Literature Swim Speeds Table a time to exhaustion will be automatically entered into the time to exhaustion field. If the swim speed study reported time to exhaustion, this data will be entered If time to exhaustion was not reported in the study, then the default is arbitrarily set at 10 seconds for burst speeds and 30 minutes for prolonged speeds. These default values are near the center and the lower end of the commonly observed time ranges associated with burst and prolonged speeds, respectively. Since FishXing generally defaults to the middle to lower end time ranges there is less chance of overestimating the time to exhaustion.

Constant Swim Speed

When using fixed swimming speeds our recommendation is to use the reported time. Entering shorter times will result in underestimating passage capabilities and entering longer times may not be valid because they are outside the range of those tested. If you enter a time to exhaustion outside the range used in the original study a warning will be displayed.

Endurance Swim Speed

On the other hand, when using equations with time as a variable, such as the Hunter and Mayor (1986) equations, it may be desirable to vary the time to exhaustion. Since swimming speed and time to exhaustion are related, lowering the time to exhaustion will increase the swimming speed. It may be desirable to run the analysis using multiple times to exhaustion within the acceptable range of values and compare passage performance.

See: Swim Speed Equations, Fish Calculations Overview

Fish Length and Swim Speeds

Swimming speeds found in the FishXing Literature Swim Speed tables are directly related to fish length. Fish length is one of the most influential factors affecting the swimming speed of fish (Beamish 1978).

Absolute Swim Speed

For most fish species, absolute swimming speed (distance per time) and fish length are positively related through all swimming categories: sustained, prolonged and burst. For example, large juvenile pallid sturgeon (fork length, 17 cm to 20.5 cm) could swim faster than small pallid sturgeon (fork length, 13 cm to 16.9 cm) in all swimming categories tested:

Swim Speed	Large Juvenile Pallid Sturgeon	Small Pallid Sturgeon
Sustained	25 cm/s	10 cm/s
Prolonged	30 cm/s	15 cm/s
Burst	55 cm/s	40 cm/s

Relative Swim Speed

On the other hand, when relative swim speeds (body lengths per time) are studied for some species the relationship between length and speed is reversed. Smaller fish generally have higher relative swim speeds than larger fish; but this relationship can be affected by temperature. For example, smaller largemouth bass were found to have higher relative prolonged swimming speeds than larger fish of this species when temperatures were near their physiological optimum, but when temperatures were lower this relationship was not apparent (Beamish 1970). Both biological processes (such as, muscle and fin size, or respiration) and the hydrodynamic properties (such as various components of drag) underlie the relationship between fish swim speed and size. Informative discussions of these topics can be found in Beamish (1978), Grey (1998), Videler (1993), and Webb (1975, 1977, 1994).

Total Length

Knowing the total length of your Analysis Species is essential for selecting an appropriate swim speed. Total fish length is one of the key parameters presented in the FishXing Literature Swim Speeds Tables and is a variable in many swim speed equations.

In certain situations, total fish length is also used in the determination of when the fish is able to swim rather than leap into a culvert outlet.

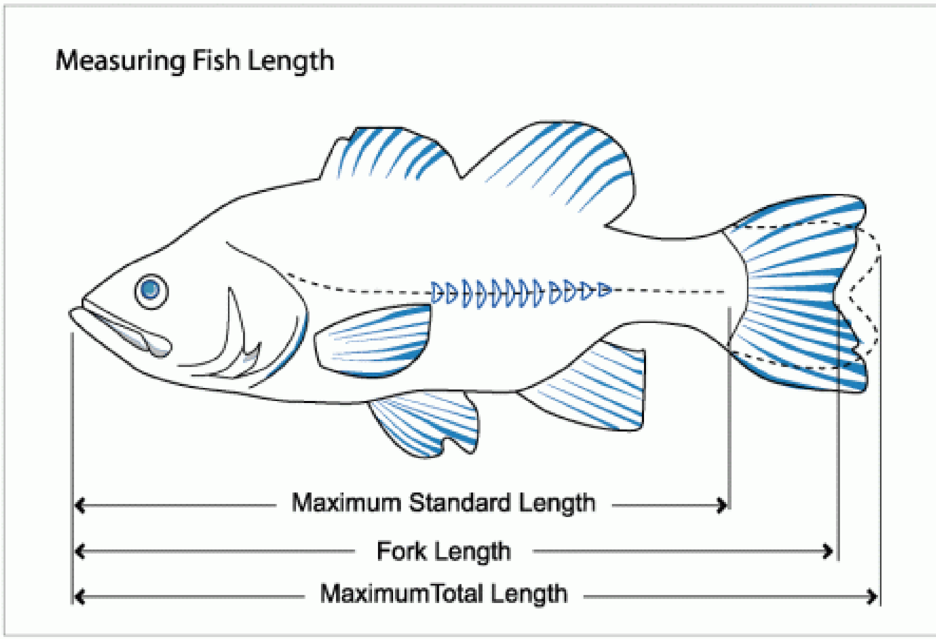
See also: Measures of Fish Length, Converting Fish Lengths, Swim Speed Equations, Entering the Culvert: Leap or Swim

See an illustration of fish length measurement.

Measures of Fish Length

Fisheries biologists use three different measures of length:

1. Total Length, **2.** Fork Length, and **3.** Standard Length.



FishXing uses total length for calculations and in reporting swimming speeds found in the literature; therefore, fish lengths entered into FishXing should be total lengths.

If only fork length or standard length is available for the analysis species, then FishXing uses a conversion factor to estimate total length. FishXing has morphometric data in the Literature Defined Swim Speed Table with conversion factors for all species found under FishXing's Literature Defined Swim Speed tab. The conversions are in the form of total length/standard length or total length/fork length and were taken from morphometric information found in Carlander (1969, 1977) or www.fishbase.com.

See an example of how the conversion factors are used to calculate total length.

Total length is defined as the measurement taken from the anterior-most part of the fish to the end of the caudal fin rays when compressed dorso-ventrally (Anderson and Gutreuter 1983).

Fork length is defined as the measurement taken from the anterior-most part of the fish to the end of the median caudal fin rays (Anderson and Gutreuter 1983).

Standard length is defined as the measurement taken from the tip of the lower jaw to the posterior end of the hypural bone (Anderson and Gutreuter 1983).

Lengths Used in FishXing: Fish Length is used in two ways within the FishXing software.

1. To determine swim speed in equations using length as a variable.

2. To determine if the fish can swim into the culvert outlet or if a leap is required.

Converting Fish Lengths

Example of conversions based on morphometric data:

In this example, we will use humpback chub, *Gila cypha.* These conversion factors are only valid for fish that have achieved their adult body form; very young fish have different body morphologies. Notice that the conversion factors are dimensionless so you can use any units of measure (Examples: feet, inches, centimeters).

Excerpt from the Morphometric Data Table:

Common name	Family	Genus	Species	BD/TL	TL/SL	TL/FL
broad whitefish	Salmonidae	Coregonus	nasus	0.232	1.165	1.099
humpback chub	Cyprinidae	Gila	cypha	0.224	1.252	1.134
humpback whitefish	Salmonidae	Coregonus	pidschian	0.196	1.142	1.078
inconnu	Salmonidae	Stenodus	leucichthys	0.174	1.146	1.080
lake sturgeon	Acipenseridae	Acipenser	fulvescens	0.118	1.186	1.096

Where: BD = Body Depth, TL = Total Length, SL = Standard Length, FL = Fork Length

1. There are three possibilities:

   a. If you need body depth and you have total length, then use the column BD/TL (body depth/total length) and the row - humpback chub = 0.224.

   b. If you have fork length and you need total length, then use the column TL/FL (total length/fork length) and the humbback chub row = 1.134.

   c. If you have standard length and you need total length, then use the column SL/TL (total length/standard length) and the humpback chub row = 1.252.

2. Multiply the length you have by the conversion factor as follows.

   a. For a humpback chub with a total length of 8.5 inches to estimate body depth:

      BD/TL x TL = BD

      0.224 x 8.5 inches = 1.9 inches body depth

   b. For a humpback chub with a fork length of 21.6 centimeters to estimate total length:

      TL/FL x FL = TL

      1.134 x 21.6 cm = 24.5 cm total length

   c. For a humpback chum with a standard length of 203 millimeters:

      SL/FL x SL = TL

      1.252 x 203 mm = 254.2 mm total length

Factors Affecting Swimming and Leaping

Fish swimming speeds are affected by a number of factors. Here, we provide a brief outline of some of the more important factors affecting swimming speeds. More comprehensive discussions on these topics can be found in the literature reviews by Beamish (1978) and Hammer (1995) and annotated bibliographies can also direct you to more in depth discussion of the various factors affecting swim speeds (Anderson and Bryant 1980, Copstead et al. 1998, Kahler and Quinn 1998, Mitchell 1973, Newbrey and Bozek 2001).

Beamish (1978) identified five biological (length, weight, condition factor, sex, and disease) and five physical (temperature, oxygen, carbon dioxide, salinity, and toxins) constraints on performance. Other authors have identified additional factors that affect swimming speed including: stock (McDonald et al. 1962), spawning status (Collins et al. 1962), run timing (Gauley and Thompson 1962), physical conditioning (Cloavecchia et al 1998; Paulik and Delacy 1958), previous exhaustive exercise (Wood et al. 1983), feeding (Farrell et al. 2001), forced vs volitional swimming (Peake 2004), pipe fullness (Slatick 1971) and light (COE 1956).

Summary of factors affecting fish swimming performance.

Topic	Effect	References
Species	Species show a wide range of performance due to differences in swimming modes, methods of propulsion, and drag reducing systems. The swimming abilities of different fishes reflect their life history traits.	Videler 1993, Webb 1975, 1994. Castro-Santos 2002; Peake et al. 1997; Swanson et al. 1998; Taylor and Foote 1991.
Length	Increases in performance with increases in length.	Topic reviewed in Beamish 1978.
Time to exhaustion	Decreases in performance with increases in swimming time that the speed is maintained.	Topic reviewed in Beamish 1978.
Weight	Increase in prolonged performance with increase in weight.	Beamish 1978; Fry and Cox 1978.
Condition Factor	Decrease in performance – due to increase in hydrodynamic drag with increased condition factor or decrease in metabolic scope for activity with increasing weight.	Beamish 1978; Vincent 1960; Green 1964.
Stage of Maturity	Not widely studied. Pink salmon study showed that gravid fish had better performance than spawning fish which were better than spawned out fish.	Williams and Brett 1987. Collins et al. 1962

Sex	Not widely studied. Male sockeye performed better than females and gravid male pink salmon performed better than gravid females. At other life stages differences between sexes were minimal.	Brett 1965; Williams and Brett 1987.
Disease	Little information on effect of bacterial infections. Performance decreases noted in Delta smelt infected with *Mycobacterium spp*. (20% reduction in Ucrit). Response to parasitic infections varied from no effect to 31 percent to 51 percent reduction in performance.	Swanson et.al. 1998. Parasitic infections reviewed in Beamish 1978.
River time – anadromous species	Decrease in performance as anadromous fish neared spawning grounds.	Paulik and DeLacy 1957. Sakowicz and Zarnecki (1962)
Strains	Various performance levels exhibited by different strains of rainbow trout.	Thomas and Donahoo 1977
Stock	Performance of salmon spawning in upstream areas were better than performance of salmon spawning in the lower river, differences were attributed to inherited differences in body form. Sockeye entering fresh water in early summer performed better than those entering in late summer. Summer Chinook performed better than spring Chinook. Anadromous Atlantic salmon performed better than landlocked Atlantic salmon.	Taylor and McPhail 1985; Gauley and Thompson 1962. Peake et al. 1997
Hatchery vs Wild	Wild fish performed better than hatchery fish.	McDonald et al. 1998a.
Feeding	Unfed fish performed better than fed fish, performance differences related to gut blood flow.	Furrell et al. 2001.
Nutrition	Increase in performance with increase in protein content of food.	Beamish et al. 1989.
Light	Downstream passage through a tunnel greatest when light provided downstream of tunnel. Increase in performance in free swimming fish when light was provided. No increase in performance in benthic (bottom dwelling) species when light was	Blahm 1963; Pavlou et al. 1972 in Hammer 1995.

	provided.	
Pipefullness	Decreases in performance with increases in pipefullness	Slatick 1971
Oxygen	Decrease in performance is associated with a threshold level of oxygen in most species.	Topic reviewed in Beamish 1978.
Carbon Dioxide	Variable response by differing species; no decrease in performance in small mouth bass (*Micropterus dolomieu*i) at CO_2 levels up to 48 mg/l; and coho salmon had decrease in performance at CO_2 levels between 2-61mg/l.	Dahlberg et al. 1968.
Salinity	Change in performance seems to be age and species dependent – it is likely that reduction in performance is proportional to energy spent inosmoregulation.	Topic reviewed in Beamish 1978.
Toxins	Decrease in performance shown in response to the various toxins.	Topic reviewed in Beamish 1978 and in Hammer 1995; Peterson 1974.
Temperature – Sustained and Prolonged Speeds	Increases in sustained and prolonged swimming speeds with increasing temperature to an optimum then decreases with increasing temperature. For warm water species maximum Ucrit found in the range of 25 to 30 C and for cold water species the range was 15 to 20 C.	Topic reviewed in Beamish 1978 and in Hammer 1995.
Temperature – Burst Speeds	Little changes in burst swimming speed with changes in temperature.	Beamish 1978; Booth et al. 1997.
Previous Training	Increase in performance with training shown for various species.	Topic reviewed in Hammer 1995; Ward and Hilwig 2004.
Exhaustive Exercise	Decrease in performance due to previous exhaustive exercise, exhaustive exercise can result in death several hours after the exercise stops.	Paulik et al. 1957; Wood et al. 1983.
Stress	Decrease in performance due to handling stress. Performance decline attributed to increased maintenance metabolic demand thus reducing active metabolic capacity.	Strange and Cesh 1992.
Forced vs Volitional Swimming	Decrease in performance in fish forced to swim.	Hinch and Bratty 2000; Peake 2004a; Peak 2004b;

Swim Speed Equations

Various authors studying a variety of fish have developed swim speed equations that relate swimming speed to fish length, or swimming speed to fish length and time to exhaustion. More recent investigations have included additional variables in their equations such as temperature or interaction terms between temperature and length and length and velocity (Peake et al. 2000). The most frequently used swim speed equations in FishXing were developed by Hunter and Mayor (1986). These authors compiled results from previously preformed swim speed test to produce a set of regression equations relating swim speed to fish length and time to exhaustion.

Hunter and Mayor (1998) Swim Speed Equation

The general form of the this swim speed equation is,

$$V = aL^{b}t^{-c}$$

where:

V = swim speed of fish relative to the water
L = length of the fish
t = time to exhaustion
a,b,c = regression constants

These equations can be selected from the Literature Swim Speed Table within FishXing. When a swim speed equation is selected, the time to exhaustion is either the time reported in the research study from which the data were derived; or if no time was reported in the study, then the default time to exhaustion is arbitrarily set at 10 seconds for burst speeds and 30 minutes for prolonged speeds.

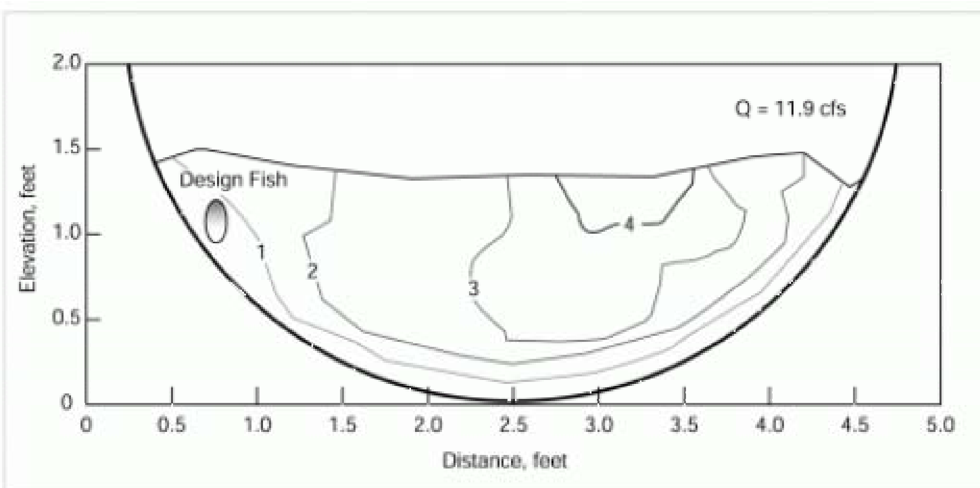
The swim speed equations utilize the length entered into the Fish Length field on the Literature Swim Speeds tab of the FishXing input window. Avoid extrapolating by making sure the entered fish length falls within the range of reported lengths used to develop the equation. If the length you entered is outside the appropriate range, a warning will appear “Out of length range” on the Literature Swim Speeds tab.

Occupied Velocity

FishXing, like other culvert models, calculates the average cross sectional water velocities. However, in many instances fish take advantage of slower velocities along the culver walls and bottom. Referred to as the occupied velocity, they are often only 10% to 50% of the average water velocity (Powers, 1997).

To account for slower velocities, FishXing offers the option of applying Velocity reduction factors (ratio of occupied velocity to average cross sectional velocity, Kocc) to the inlet zone, outlet zone, and barrel of the culvert. The use of velocity reduction factors assumes the area of reduced velocity is continuous throughout the entire zone.

Using Velocity Reduction Factors to account for occupied velocity is generally only applied to smaller fish, which have been observed using the slower water found adjacent to the larger corrugation of metal pipes.



Above is a map of water velocities in the inlet zone of a 5-foot diameter culvert. The average velocity is approximately 3.3 ft/s. Notice that smaller sized fish may be able to swim through a region of lower velocities near the culvert wall. The water velocity within this region is often referred to as the occupied velocity (Vocc).

In this example Vocc = 1.5 ft/s and Vave = 3.3 ft/s.

Kocc = Vocc/Vave = 0.45

Behlke et al. (1991) has reported velocity reduction factors ranging from 0.4 to 0.8 for juvenile salmonids and suggests the following velocity reduction factors for arctic grayling:

Inlet: Kocc = 0.8

Barrel: Kocc = 0.6

Outlet: Kocc = 0.8

Use caution when applying velocity reduction factors. These factors vary substantially and are influenced by many factors, such as the shape and roughness of the culvert, the culvert alignment with the upstream channel, outlet conditions, and the size of the fish.

Various hydraulic situations can eliminate the existence of a continuous path of lower velocities. Also, larger fish will not be able to avoid the regions of higher velocities due to there increased body size, making reduction factors inappropriate to use.

See also: Inlet, Barrel and Outlet Zones, Velocity Reduction Factors

Water Depth for Swimming

There are two issues to consider when choosing a minimum depth. The first is the point at which lack of water depth becomes a barrier to fish passage; and second is the affect that water depth has on swimming performance.

Minimum Water Depth

One depth criteria often suggested in the literature is the water depth required to fully submerge the fish species being analyzed (Powers and Orsborn 1985, Webb 1975). Full submergence is difficult to precisely define, but can be estimated as the body depth of the fish plus some additional depth to account for a number of factors that could affect passage, such as:

- Variation in individual size, behavior, and performance;
- Possible obstacles that must be passed like debris or sediment deposits; and
- The ability to move to some degree in a vertical plane for predator avoidance, or injury prevention (i.e., not being forced to contact solid surfaces).

An alternative approach is to enter the minimum depth that your analysis species will successfully swim through. Defining a minimum depth using this type of criteria may require consideration of the overall length of the culvert. It is not uncommon for some fish species (such as adult chinook salmon) to swim for short distances through depths that do not even fully submerge their bodies. However, physical and behavioral limitations may limit the distance a fish is able to swim through shallow waters. Additionally coming into contact with the culvert bottom can injure fish and perhaps affect their fitness.

In many cases, a local or Federal unit of government may have fish passage criteria or guidelines that define the acceptable minimum water depth for a particular species of fish. For example, the Department of Transportation for the State of Maine, USA, Policy and Guideline manual states that:

> "depth should be based on the target species present and either the corresponding critical depth (1.5 x the body thickness) for that species during the period of significant movement or the documented prevailing depths during periods of known movement" (Maine DOT 2002).

Maine's criteria is based on passage needs of endangered shovelnose sturgeon that experience stranding at shallower depths, as well as accommodating passage of schooling fish, such as blueback herring and alewife, that need depths greater than their body depth to move as a group.

Water depth and Swim Performance

The swim speeds presented in the Literature Swim Speeds tables were all derived from studies where the water depth fully submerged the fish being tested. Therefore, for the swim speeds found in the Literature Swim Speeds tables to be valid, the minimum depth should be the depth required to fully submerge the analysis species.

Full submergence is important because swim performance is optimal when the oxygen supply (gills) and propulsion systems (body and tail) are fully submerged (Webb 1975). Swimming is compromised in a partly submerged fish because the fish is unable to generate thrust normally produced through combined body and tail movements. In addition, when the fish's gills are not fully irrigated they can not function efficiently which results in oxygen starvation and reduced ability to maintain swimming activity (Powers and Orsborn 1985). Scale and skin injuries have also been observed when fish must contact solid surfaces.

It should be noted that while full submergence is required for the swim speeds in FishXing to be valid, the culvert might not be a depth barrier for fish species that can move upstream without being fully submerged. Adult migrating salmonids have been observed moving over shallow riffle areas and through culverts (Taylor 2004, personal communication) without being fully submerged. When the fish is not fully submerged, you will have to use your professional judgment about the length of culvert, its substrate, water depth, and water velocity to estimate whether or not the culvert is passable.

Also See: Swim Speed Equations, Swim Modes

Leaping Capabilities

Leaping Speeds

The literature pertaining to leaping capabilities by fish is limited, and often uses observed leap heights to back calculate burst swimming velocities attained prior to leaving the water (Aaserude and Orsborn 1986). The equation used to back calculate leap height is usually some form of the simple projectile equation:

$$HL = \frac{V_o^{\ 2}}{2g}$$

where,

HL = leap height

V_o = initial velocity of the fish

g = gravitational acceleration

Aaserude and Orsborn (1996) working with pacific salmonids used burst velocities of short duration to predict leap height and found that they closely matched the range of observed leap heights. Stuart (1962) and Reiser and Peacock (1985) have also stated that leaps use burst speeds of short duration. FishXing uses short duration burst velocities (5 sec burst speeds) to estimate the speed at which fish leave the water when leaping. In FishXing the Maximum Leap Speed is maximum velocity at which a fish exits the water when leaping at the culvert outlet. See the *Leaping Calculations* section to view the calculations.

Factors Affecting Leaping Success

Besides swimming speed and fall height several other factors appear to affect leaping success, including water velocity, turbulence in the take-off pool, the depth of the take-off pool, the ratio of pool depth to fall height, and where the leap is initiated.

Flow rate may affect the motivation of fish to leap at outfalls and when it does there appears to differences between species and life history stages. Stuart (1962) studying small fish (minnows, and juvenile salmon: 6-15 cm) and Lauritzen (2002) studying kokanee salmon found that passage attempts increased with flow until the flow rate exceeded the swimming capacity of the fish. Conversely, Powers and Orsborn 1985 observed that chum and coho could sometime be stimulated to move upstream by increasing the flow, but they also leaped over outfalls when the flow was reduced to just a trickle.

It seems that different species of fish and life stages may use different leaping techniques, which may lead to differing physical conditions needed to support leaping. Stuart (1962) found that minnows and juvenile salmon initiated their leaps from the surface of the water following a quick body and tail flexion that bent their bodies into a C-shape. These fish also always leaped from the standing wave created by the upwelling of water just downstream from where the falling water stuck the pool surface. On the other hand, Lauritzen (2002) found that adult kokanee salmon initiated their leaps from the bottom of the standing wave with an S-shaped curve of their bodies followed by burst swimming to the surface. These fish also mainly leaped from the standing wave. Aaserude and Orsborn (1986) found that smaller resident trout initiated their leap from the standing wave more frequently than did adult coho or chum salmon. These authors suggest that this difference may be because the upwelling presented a more influential flow condition for trout due to their smaller mass. The depth that is needed in the outfall pool is likely to be related to the leaping technique used.

The turbulence in the outlet pool will influence the fish's ability to jump. As the fish leaps it pushes against the water with its tail. In turbulent water air is entrained in the water column, and instead of the fish's tail pushing against water it pushes against air. Because air has a much lower density the fish's tail produces less thrust. In addition, fish seem to use the flow to help direct their leaps, when the water is turbulent their leaping is less directed. Turbulence in the outlet pool is a function of factors such as water velocity, and outlet pool depth in relation to the drop height.

Leaping From Plunge Pools

If a fish must leap to enter the culvert outlet, it will require a plunge pool below the culvert outlet that provides sufficient "take-off" conditions. To determine the characteristics that define a suitable plunge pool for leaping, a number of researchers have made detailed observations of leaping fish in both natural and laboratory environments.

Stuart (1962) studied leaping fish ("salmon parr and minnows") at natural waterfalls and observed that successful leaping occurred when the pool depth below the fall was 1.5 times the drop height of the falls; and that this condition resulted in a good standing wave location. He also observed that most successful leaps originated at the standing wave. At a later date, Aastrude and Orsborn (1984) did experiments in the laboratory and also found that adult pacific salmon often leapt with greater success from the standing wave. However, they also found that Stuart's observation about the D/H ratio was not generally applicable; that, in fact, the formation of the standing wave was a function of the entrained air and shape of the water jet; not the height of the falling water. These authors suggested two conditions for optimal leaping: "1) depth of penetration of the falling water (dp) should be less than the depth in the plunge pool (dpp); and 2) depth of the plunge pool must be on the order of, or greater than the length of the fish (LF) attempting to pass" (Powers and Orsborn 1985, page 42-43). Their rationale is that these two conditions will assure that the plunge pool will be stable and the depth will avoid turbulence that disorients fish and reduces the propulsive power of the fish's tail.

Lauritzen (2002) has done the most direct study on how depth of the outlet pool and height of the falls affects leaping success. He tested Kokanee salmon (*Oncorhynchus nerka*) with an average total length of 29 cm at seven pool depths (8, 15, 23, 30, 38, 46, and 66 cm) at four fall heights (0, 12, 25, and 36 cm). Fish leaping was not significantly (P>0.05) affected at the pool depth and drop heights tested. However, there was significant relationship between fish leaping and the ratio of pool depth to fall height. The ratio that best supported leaping varied between 0.6 and 1.2 depending on fall height, with higher falls having smaller ratios**.**

When the pool depth drop to less than 8 cm or was greater than 36 cm leaping ceased. A pool depth of 8 cm was too shallow to generate adequate take-off speed that were directed at the crest of the fall. At 36 cm, the pool depth was considerably lower than the bottom of the standing wave and fish would continue past the bottom of the wave, leave the current generated by the falls, and aborted the leap.

It appears that one of the conditions suggested by Powers and Orsborn's (1985) was not supported by Lauritzen's (2002) studies. Apparently, the plunge pool depth does not have to be greater then the total length of the fish attempting to pass, because the average total length of the kokanee tested was 29 cm and leaping did not stop until the pool depth was 8 cm.

Lauritzen (2002) states that the preferred fall height is dependent on the pool depth and the mean ratio of depth to height is 1.0. However he also notes that other factors besides the D/H ratio affects jumping such as the flow rate and gradient of the falls.

While it may be preferable to base the depth of the plunge pool on penetration depth of the falling water or depth of the standing wave, this information is generally not known. Instead, to determine if the pool depth is sufficient for leaping, FishXing relies on the flow dependent ratio of D/H – (maximum depth within the pool)/(total drop height measured from water surface within the culvert outlet to the pool surface).

See: Minimum Plunge Pool Depth Calculations, Entering the Culvert: Leap or Swim

Estimating Fish Body Depth

If you are using the Literature Swim Speeds tab, and you enter the average total length of the fish an estimate of the body depth will be displayed in the Comments Box. When the minimum depth entered is less than the estimated body depth of the fish a warning is displayed indicating that the fish may not be fully submerged. The Swim Speed table contains a column that is populated with body proportions of various species of fish and FishXing uses these proportions to estimate body depth from total lengths. You can access these proportions through the Literature Swim Speed table and the morphometric data table. The proportions are in the form of body depth/total length and were taken from morphometric information found in Carlander (1969, 1977) or www.fishbase.com. For an example of how the calculations are performed see: Converting Fish Lengths.

See also: Measures of Fish Length, Converting Fish Lengths, Water Depth for Swimming,

Fish Length Conversion Table

Fish Passage Flows

Maintaining fish passage through culverts during flood flows is often impracticable and unnecessary. Extreme low flow periods may also present problems for providing fish passage, and short-term barriers to movement may or may not be important to the survival of species present. It may not be necessary to provide passage at extreme low flows if fish are not attempting to move during this period or if naturally occurring stream conditions limits passage between stream reaches. For any particular species and lifestage the Low Passage Flow (QLP) and High Passage Flow (QHP) define the range of flows to be analyzed by FishXing. These are determined locally or regionally based on knowledge of movement patterns of the species present.

Some states have developed guidelines for determining Fish Passage Flows. For examples of guidelines see the “State and Agency Flow Guidelines for Fish Passage Flows” table in the Flow Guidelines for Fish Passage Flows section.

Low Flow guidelines determine the depth threshold for passage and are based on annual or migration period exceedance percentage from a flow duration curve for the 2-year, 7-day low flow.

High Flow guidelines determine the velocity threshold for passage and are typically based on annual or migration period exceedance percentage from a flow duration curve.

See also: Flow Guidelines, Reading Flow Duration Curves, Entering Fish Passage Flows

Guidelines for Fish Passage Flows

Several states have defined flows at which fish passage should be provided, except for Alaska and Idaho these requirements apply only to hydraulic designs (not stream simulation).

State and Agency Flow Guidelines for Fish Passage Flows

State / Agency	High Flow Capacity	High Fish Passage Flow	Low Fish Passage Flow
Alaska	Q_{50} or Q_{100}	"Q2d2" the flow 24 hours before or after the 2-yr flood	None
Washington	Q_{100} w/ debris	10% exceedance flow during migration period: species specific	2-yr, 7-day low flow
Oregon	Q_{100}	10% exceedance flow during migration period: species specific. Approximate by Q10% = 0.18*(Q2)+36 where Q2>44 cfs. where Q2<44 cfs use Q2	2-yr, 7-day low flow or 95% exceedance flow for migration period: species specific
NMFS SW Region	Q_{100} at HW/D =1	for adult salmon & steelhead 1% annual exceedance flow or 50% Q2. For juveniles, 10% annual exceedance flow	for adult salmon & steelhead, the greater of 3 cfs or 50% annual exceedance flow. For juveniles, the greater of 95% annual exceedance flow or 1 cfs.
California Dept. Fish & Game	Q_{100} at HW/D =1.5	standards vary from 1%-10% annual exceedance for various groups of fish	standards vary from 50%-95% annual exceedance for various groups of fish
NMFS NW Region		5% exceedance flow for period of upstream migration	95% exceedance flow during months of upstream migration
Idaho			
Maine			

Q_{100} is the peak flow equaled or exceeded on average once in 100 years. Determined based on annual peak flow data set.

10% exceedance flow during the migration period is the daily average flow that is equaled or exceeded 10% of the days in the period the selected fish species are moving. That period is usually established by the state fish and wildlife management agency. Based on period of record daily-flow data set for the migration period.

1% annual exceedance flow is the daily average flow that is equaled or exceeded 1% of the days of the year. Determined based on period of record daily mean flow data set for the entire year.

Effects of Turbulence on Fish Passage

Baffles are roughness elements added to a culvert in order to reduce water velocity to a level acceptable for fish passage. Along with reducing velocity, baffles create turbulence that in excess can create a barrier to fish passage. Turbulence represents the energy dissipated by falling water necessary to reduce velocities in the culvert. Energy dissipation is described by the Energy Dissipation Factor (EDF) and current research shows that the EDF should be between 3.0 and 4.0 ft-lb/ft3/sec to prevent sediment or debris accumulation and provide adequate passage for adult salmon.

The work that was done by Shoemaker in 1956 relates baffle dimensions to roughness in terms of the darcy friction factor (see summary of work in Appendix D of the 2003 WDFW's "Design of Road Culvers for Fish Passage" manual. Also, folks at WDFW have collected data on new baffled culverts and calculated friction factors for them.

Fish biologists classify fish into various life history forms based on where they spend part of their life cycle including, anadromous (migrate to the ocean), adfluvial (migrate to lakes), fluvial (migrate to rivers), and resident (stay within the area in which they were spawned).

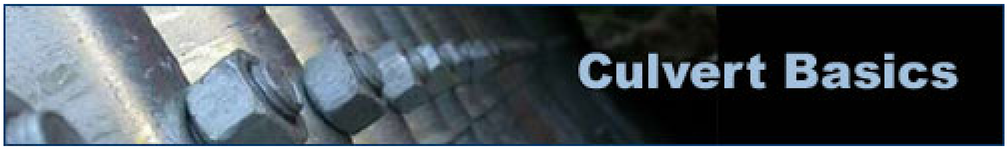
A Life history cycle is the complete series of changes in an organism from its conception to its death (Steen 1971).

Fish habitat within streams is not evenly distributed along the stream channel, instead habitat occurs in distinct patches that vary in quality and size as defined by species preferences and varying physical characteristics. Riffles and pools are examples of habitat patches which are exploited by different species or life stages that are adapted to rapid flows in riffles (e.g., flatten bodies or fast swimmers) or slower flows in pools (more rounded bodies and slow swimmers).

Caudal peduncle is the portion of the body posterior to the anal fin and anterior to the caudal (tail) fin.

The time increment in an increasing velocity test is the time between velocity increases.

Relative swim speed refers to the swimming speed of the fish relative to it length and should not be confused with the relative speed (speed fish is traveling relative to the water).



Culvert Basics

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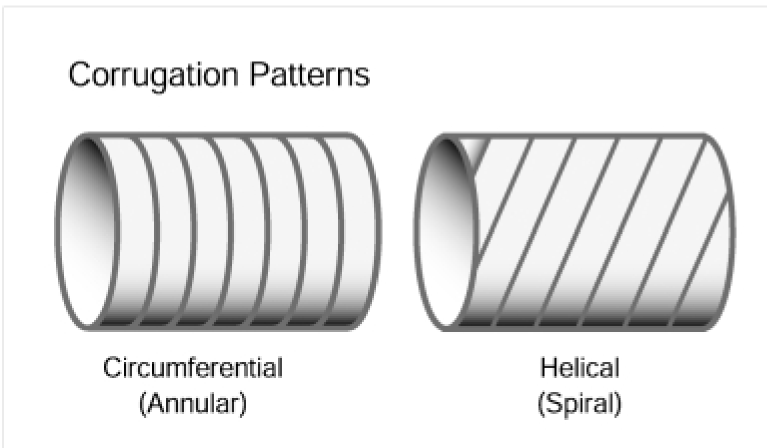
Culverts

Culverts are water conveyance structures that usually allow for continuous flow under roads and highways. Culvert design theory is largely based on the principle of conservation of energy, where discharge is a function of the flow resistance along the pipe length and the difference in tailwater and headwater levels. A pipe that is flowing full is considered “hydraulically efficient” since it is pressurized and conveying the maximum amount of water possible. For this condition to occur the upstream end of the pipe will be submerged and the downstream velocities will be higher than naturally found in the stream channel at that point.

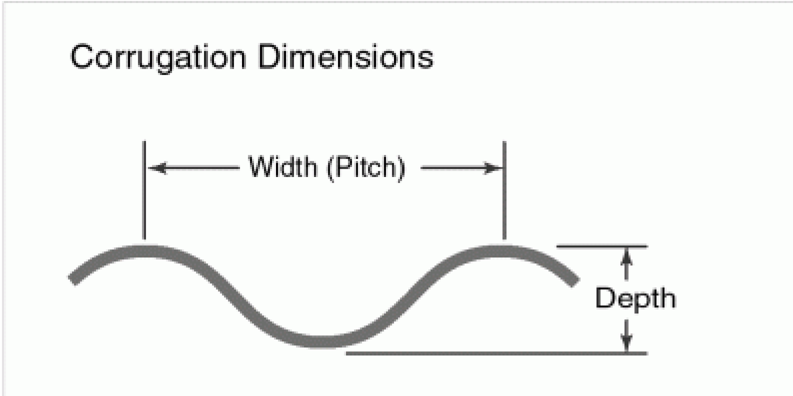
Hydraulic efficiency has been the general goal in the design of culverts for many years among highway agencies and municipalities. This allows designers to maximize conveyance while minimizing pipe size and cost. As result the impacts of culverts on aquatic species and to the geomorphic conditions of stream channels have been largely overlooked.

Corrugations

Corrugations are the undulations present in corrugated metal pipes (CMP) and structural steel plate pipes (SSP). As a Culvert Material, corrugations are added to culverts to add stiffness and increase structural strength. They have also been found to provide holding areas for juvenile fish at low flows by adding surface roughness which increases over the width and depth of standard dimensions. Corrugations can be formed in a circumferential (annular) pattern or run in a helical pattern (spiral) around the pipe. Helical corrugations tend to reduce the roughness by increasing hydraulic efficiency of flow through the pipe.



Corrugations are measured and categorized by the depth and spacing. Most CMPs under 60 inches in diameter have 2 2/3-inch x 1/2-inch corrugations. CMP greater than or equal to 60 inches in diameter typically have 3-inch x 1-inch corrugations. Structural plate pipes (SPP) and structural plate pipe arches (SPPA) often have 6-inch x 2-inch corrugations. The size of the corrugations determines the culvert roughness used in FishXing. Corrugations are measured from crest to crest (width) and valley to crest (depth).



Descriptions of different culvert materials that can be selected in *FishXing* :

Construction	Description
CMP (2 2/3- X ½-inch corrugation)	Galvanized steel or aluminum with ½ inch high corrugations, spaced 2 2/3 inches apart.
CMP (3- X 1-inch corrugations)	Galvanized steel or aluminum with 1 inch high corrugations, spaced 3 inches apart
CMP (5- X 1- inch corrugations)	Galvanized steel or aluminum with 1 inch high corrugations, spaced 5 inches apart
SSP (6- X 2- inch corrugations)	Galvanized steel plates bolted together, with 2 inch high corrugations, spaced 6 inches apart
Spiral CMP	Galvanized steel or aluminum with helical corrugations, typically ½ -inch high, spaced 2 2/3-inches apart
Concrete	Rough concrete associated most often with box culverts
PVC	Plastic with varied corrugation sizes

Culvert Materials and Construction

Culverts are generally constructed out of concrete, galvanized steel, aluminum, or PVC. The pipe material used in a project depends on cost, span, discharge, topography, soil chemistry, climate or state policy.

Structural Steel Plate (SSP), or "multi-plate" pipes are constructed of multiple plates of corrugated galvanized steel and bolted together. While time consuming to assemble they are easier to transport and are generally used for culverts that have a diameter greater than 12 feet. Large span metal arches used in fish passage projects are usually steel plate assembly.

Corrugated Steel Pipe (CSP), or Corrugated Metal Pipes (CMP) are constructed from a single piece of galvanized steel. Single pipes with a diameter greater than 12 feet usually have special traffic requirements for delivery or shipping.

Aluminum pipes are also corrugated and can be constructed as either structural plates or from a single piece of aluminum. Due to their high resistance to corrosion aluminum pipes do not develop rustlines and are often used in high corrosion environments such as saltwater applications.

Concrete (reinforced) box culverts are commonly used on county and state roads. Circular pipes that are precast in segments and grouted together are sometimes used. Circular concrete pipe does not have corrugations and is usually used for sewer applications. Concrete arches are increasing in use for new projects designed for fish passage.

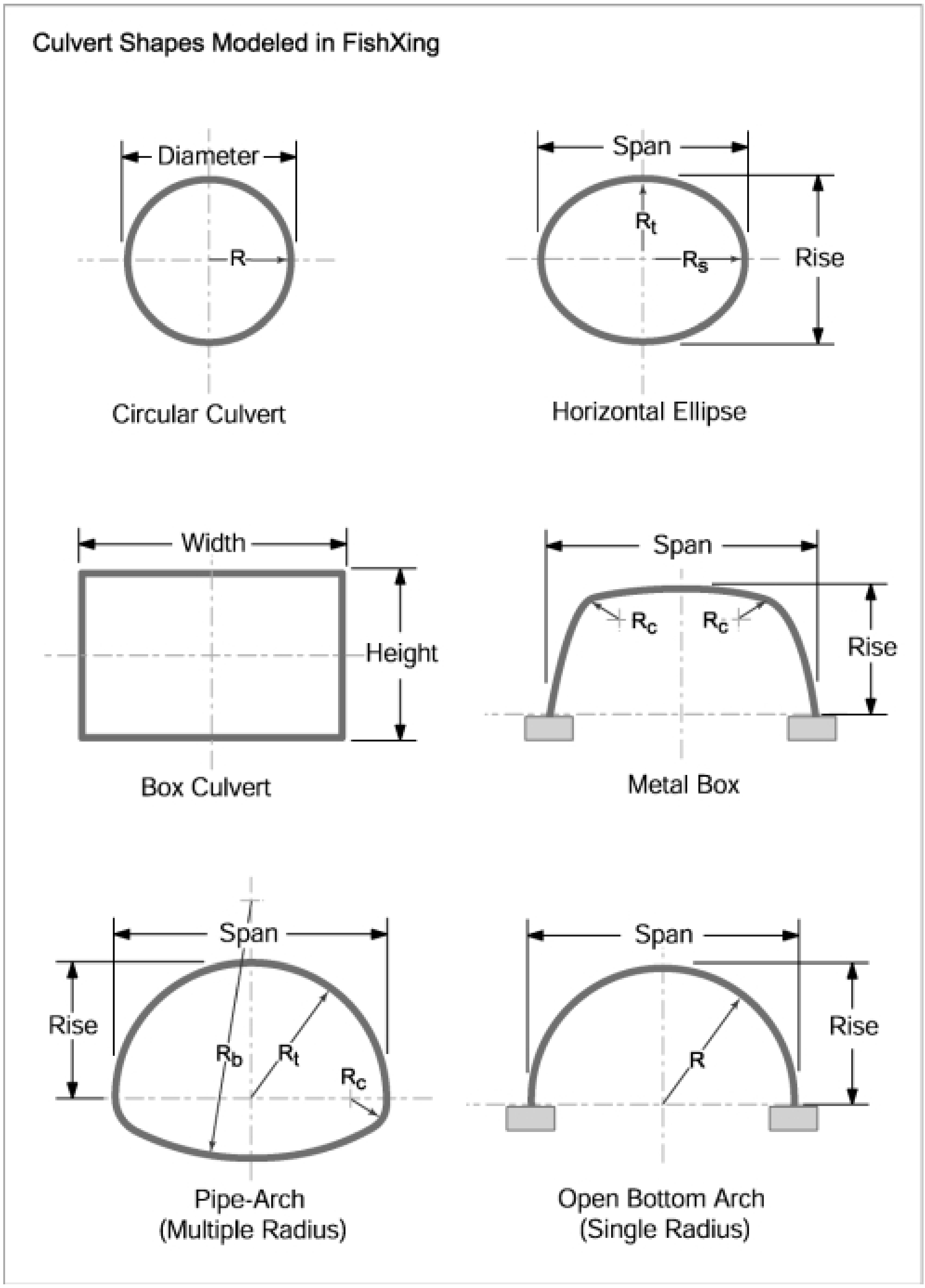
Plastic (PVC, HDPE) pipe is more commonly found in small diameter or emergency applications. Plastic pipe can be corrugated or double sided. Double sided pipe is corrugated on the outside and smooth on the inside, commonly used for irrigation and agriculture.

See also: Culvert Shapes

Culvert Shapes

The six common culvert shapes used by *FishXing* are:

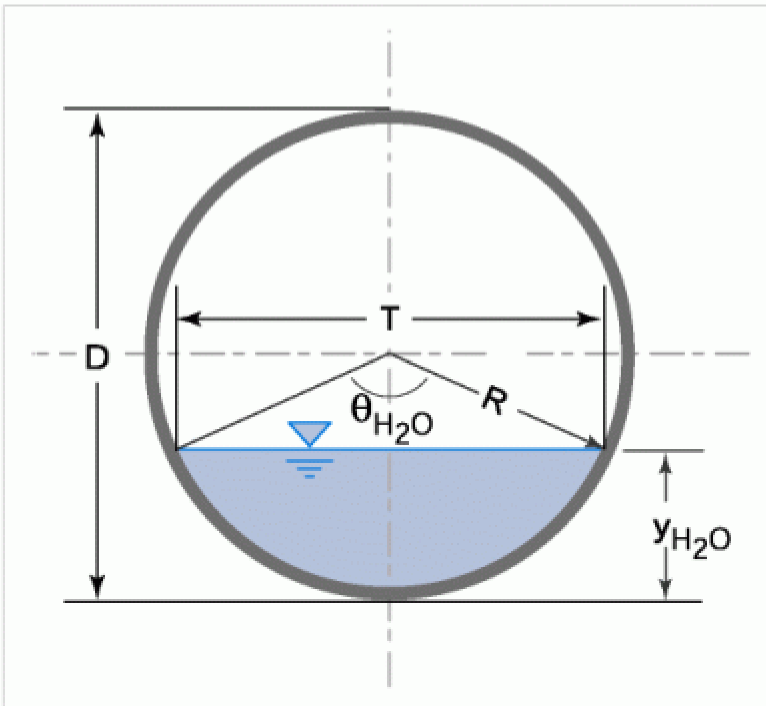
1. Circular Culvert	4. Horizontal Ellipse
2. Box Culvert	5. Metal Box
3. Pipe Arch	6. Open Bottom Arch


Culvert Shapes Modeled in FishXing
Diameter
R
Circular Culvert
Span
R_t
R_s
Rise
Horizontal Ellipse
Width
Height
Box Culvert
Span
R_c
R_c
Rise
Metal Box
Span
Rise
R_b
R_t
R_c
Pipe-Arch
(Multiple Radius)
Span
Rise
R
Open Bottom Arch
(Single Radius)

Geometry of Circular Culverts

The following equations are used in *FishXing* to calculate the wetted perimeter, top width, and cross-sectional area of the flow through a circular culvert that is not-embedded.

Definition sketch for Geometry of a circular culvert:



Equations Used in the Calculation of Circular Culvert Geometry:

$$\theta = \cos^{-1}\left(1 - \frac{y}{r}\right)$$

$$y = r(1 - \cos\theta)$$

$$A = r^2(\theta - \cos\theta\sin\theta)$$

$$P = 2r(\theta)$$

$$T = 2r(\sin\theta)$$

$$R_h = \frac{A}{P}$$

Where:

d = Diameter of culvert

r = Radius of culvert
y = Depth of water in culvert
P = Wetted Perimeter of water on the bottom
T = Top width of water surface
A = Cross sectional area of flow
R_h = Hydraulic radius

Another common method for determining culvert geometries involves the use of a table of geometric ratios developed for a partially full pipe that is not embedded. If the depth of flow is known, a ratio of depth to diameter can be used to calculate the area of flow, wetted perimeter and hydraulic radius.

Friction and Roughness of Culverts

Water flows through culverts in two basic states known as **subcritical** and **supercritical** flow, These states are controlled by the constructed slope of the channel and geometry of the culvert and fall into the category of Inlet Control and Outlet Control.

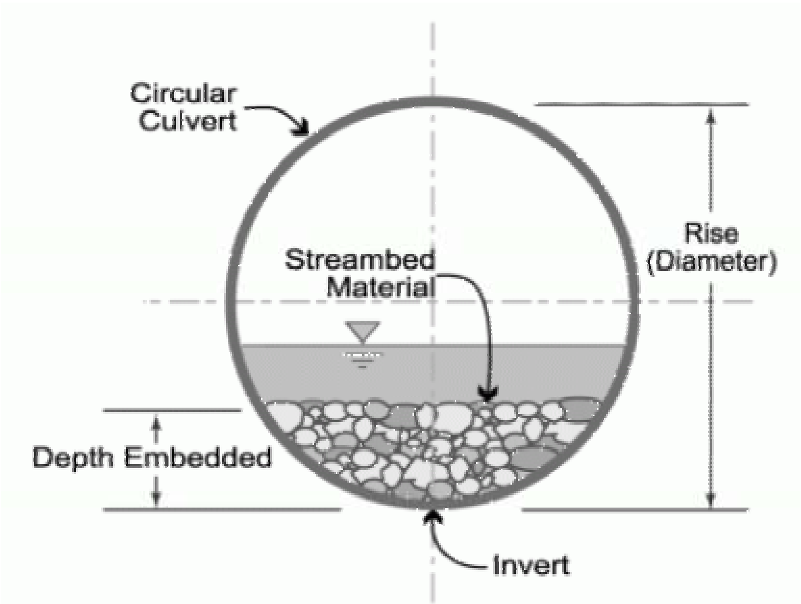
Under outlet control conditions, the roughness of the culvert will have a significant effect on the flow through the culvert. The energy loss due to the hydraulic resistance or roughness of a culvert is part of the "hydraulic price" of flow through a pipe. Two commonly used equations to describe the flow as a function roughness in a culvert are the Darcy equation and the Manning equation**.**

See also: Manning's n, Darcy Friction Factor

Embedded Culverts

Embedded culverts, also commonly known as sunken, countersunk, or depressed culverts, have their bottom placed below the streambed. This type of placement results in a culvert with natural substrate along the bottom, which increases the bed roughness resulting in lower water velocities. Embedded culverts can be circular, box, or pipe arches. Generally circular pipes are preferred since they allow for more vertical adjustment before exposing the pipe material at the bottom of the channel.

From a design and permitting perspective embedding a culvert qualifies as a streambed simulation option and eliminates the need to design for specific hydraulic criteria of an individual species of fish. There are currently few design guidelines for embedded culverts but research is ongoing. Design guidelines generally reflect the channel morphology where culvert size is based on a multiplier of the active channel or bankfull width. The sunken depth is usually 20% to 50% of the culvert diameter. Design and placement of the streambed material in the culvert and slope of the culvert requires a sufficiently long longitudinal channel profile and a bed material distribution analysis.



To evaluate embedded culverts in FishXing choose the Embedded option, specify a depth of embedment or a percent of the pipe diameter that is embedded and select a roughness factor that describes the stream bed material in the culvert. The sunken culvert option can also be used to model metal pipes with concrete-lined bottoms. Choose the Embedded option and enter the approximate depth and roughness of the concrete.

See also: Entering Embedded Culvert Data, Entering Roughness Coefficients, Roughness Factors

For additional references see:

Gubernick. R, Bates. K, Designing culverts for Aquatic Organism Passage: Stream Simulation Culvert Design. International Conference of Ecology and Transportations Proceedings , Lake Placid, NY. 2003

Gubernick. R, Clarkin. K, and Furniss. M, Site Assessment and Geomorphic Considerations in Stream Simulation Culvert Design. International Conference of Ecology and Transportations Proceedings, Lake Placid, NY. 2003

Inlet and Outlet Control

Culverts are classified according to which end controls the discharge capacity, the inlet or outlet.

Inlet Control

If water can flow through and out of the culvert faster than it can enter, the culvert is under Inlet Control. Flow capacity is controlled at the entrance by the headwater depth, cross-sectional area and type of inlet edge. Culverts under inlet control will always flow partially full and are in a state of shallow, high velocity known as Supercritical flow. Any downstream disturbance will not be propagated upstream since the flow of water is too great. The roughness, length and outlet conditions are not factors in determining capacity. Flow is therefore controlled upstream and is limited to what can enter the culvert. Culverts that have a drawdown at the inlet and a perch or hydraulic jump at the outlet are usually inlet control.

Photo: Inlet Drawdown

Outlet Control

If water can flow into the culvert faster than it can flow through and out, then it is under Outlet Control. Culverts under outlet control can flow either partially full or full. In this case water is relatively deep and slower, known as Subcritical flow and a disturbance propagates upstream. Therefore flow is controlled downstream and limited to what the pipe can carry. In this case friction and roughness in the culvert are significant in the flow through a culvert and the difference in headwater and tailwater depth represents the energy which conveys flow through the culvert.

Inlet and outlet control are set by the slope of the stream, it is not a designed feature. Generally speaking, when culverts are designed, calculations are made assuming both inlet and outlet control and comparing the headwater depth under both conditions. Designs for low headwater depths reduce pipe diameter and fill material, but risk overtopping and often result in undersized culverts when exposed to natural conditions. Conversely designs for higher headwater depths are more conservative and generally govern design.

Factors affecting Inlet and Outlet Control:

Outlet Control	Inlet Control
Headwater Depth	Headwater Depth
Tailwater Depth	n/a
Inlet Edge	Inlet Edge

Cross Sectional Area Shape	Cross Sectional Area Shape
Fall	n/a
Length	n/a
Roughness	n/a

Entrance Loss Coefficient

Inlet head loss depends on the geometry of the inlet edge. This loss is expressed as the barrel velocity head reduced by a factor known as the entrance head loss coefficient, Ke.

$$H_L = K_e \frac{V^2}{2g}$$

Where:

H_L = Head Loss (ft)
K_e = Head Loss Coefficient
V = Velocity in the barrel (ft/s)
g = Acceleration due to gravity

The entrance loss coefficient, Ke, is the head loss term of the energy equation for open-channel flow. The head loss coefficient is a measure of the efficiency of the inlet to smoothly transition flow from the upstream channel into the culvert. Although it is typically reported as a constant, it does vary with flow. Typically, reported Ke values are for near or full flow conditions. Under fish passage flows, Ke values are often substantially less.

The coefficient can range in value between 0 and 1. Larger head loss coefficients are associated with increased flow contraction in the inlet zone. Culverts having a width less than the upstream channel will constrict flow and can create a steep drop in the water surface profile at the inlet, often resulting in a velocity barrier for fish attempting to exit the culvert.

The entrance loss coefficient is a function of the flow. Coefficients are often supplied by culvert manufacturers and are for relative depths (headwater depth/culvert rise) of about 1.2, well above fish passage flows.

Attempts should be made to minimize the head loss at the culvert inlet to improve passage. Sizing the culvert large enough to avoid constricting the flow will result in a inlet head-loss coefficient of 0 for fish passage flows. Another means of reducing the head-loss at the inlet is to build wingwalls to direct the flow smoothly into the culvert.

Bates (1992) suggests that inlet coefficients should not exceed 0.7 for adult salmonid fish passage, 0.5 for sites with marginal passage conditions, and 0.2 for juvenile salmonid passage.

Entrance Loss Coefficients for Pipe or Pipe Arch Culverts

Type of Culvert and Inlet Design	Coefficient, Ke
Concrete Pipe Projecting from Fill (no headwall)	
Square cut end	0.5

Socket end	0.2
Concrete Pipe with Headwall and/or Wingwall	
Square cut end	0.5
Socket end (grooved end)	0.2
Rounded entrance (radius = 1/12 of diameter)	0.2
Concrete Pipe	
Mitered to conform to fill slope	0.7
End section conformed to fill slope	0.5
Beveled edges, 33.7 or 45 degree bevels	0.2
Side slope tapered inlet	0.2
Corrugated Metal Pipe or Pipe Arch	
Projecting form fill (no headwall)	0.9
Mitered (beveled to conform to fill slope)	0.7
Headwall or headwall with square edge wingwalls	0.5
End section conforming to fill slope	0.5
Beveled Ring	0.25
Headwall, rounded edge	0.2

Entrance Loss Coefficients for Reinforced Concrete Box Culverts

Type of Culvert and Inlet Design	Coefficient, Ke
Headwall Parallel to Embankment (no wingwalls)	
Square edged on three edges	0.5
Three edges rounded (radius = 1/12 barrel dimension)	0.2
Wingwalls at 30 to 75 degrees to Barrel	
Square edged at crown	0.4
Top corner rounded to radius of 1/12 barrel	0.2
Wingwalls at 10 to 25 degrees to Barrel	
Square edged at crown	0.5
Corrugated Metal Pipe or Pipe Arch	
Square edged at crown	0.7
Side or slope tapered inlet	0.2

Inlet, Barrel and Outlet Zones

During calculations, the culvert is divided into three zones:

- **Inlet Zone** - for culverts with a span or diameter of 9 feet or less the inlet zone is 2 feet for culverts larger than 9 feet the inlet zone is 3 feet (Belhke, 1992). FishXing reports the inlet zone as the first two nodes down the culvert.
- **Barrel** - all the nodes between the first two nodes and last two nodes in the culvert
- **Outlet Zone** - the distance from the outlet invert to a distance equal to $4y_c$ (critical depth) and is reported as the last two nodes of the culvert.

When Velocity Reduction Factors are applied they will be multiplied to the average cross section velocity in the specified zones at the nodes defining the zone.

For this application the Barrel Velocity (V_B) is the average cross-sectional flow in the barrel approximately one culvert diameter downstream from the inlet and represents the area immediately downstream of the inlet Contraction and Expansion zone.

See also: Inlet Head Loss Coefficient**, Inlet Contraction Velocity, Outlet Hydraulics,** Velocity Reduction Factors

Perched Outlet

A perched culvert is one with an outlet elevated above the downstream water surface, allowing a freefall condition (also referred to as a hanging or shotgun outlet). This condition requires migrating fish to leap into the culvert from the downstream pool.

The leap height at a perched culvert is defined as the difference between the water surface elevation of the water leaving the culvert and the water surface elevation of the pool. This height will change as the flow changes due to back water effects and depth of flow in the culvert. The depth of the outlet pool is also an important parameter that will be used to determine if the pool depth is adequate for fish leaping.

Perched culverts often result from the erosion that occurs at the outlet of an undersized culvert. Water exiting the culvert at high velocities has a high erosive potential that results in downstream scour of the channel bed and banks. The incision that occurs as a result of this scouring can be limited to the locality of the culvert and is known as local incision or can be propagated upstream due to changes in the watershed and is known as global incision. In the case of global incision the culvert may be acting as a knickpoint that can stop global incision from migrating further upstream, causing a perched condition to result.

Photo of Perched Culvert

Additional Reference: Geomorphic impacts of Culvert Replacement and Removal, J. Castro, USFWS

Tailwater Control

The water surface immediately downstream of the culvert is known as the Tailwater, often synonymous with the water surface of the outlet pool. The tailwater elevation is controlled by a geomorphic feature downstream of the outlet pool.

Often this feature is the pool tailout or riffle crest, where gravel that is scoured from the outlet pool gets deposited. In other cases the tailwater control might be a weir or grade control structure designed to backwater the culvert inlet. The tailwater control elevation also determines the residual pool depth.

In some cases there will be no outlet pool downstream and flow will be unimpeded. In this situation the channel roughness, slope and cross section shape will govern the water surface elevation downstream of the culvert.

Tailwater Control Photos

See also: Tailwater Rating Curve, Cross Section Method

Hydraulic Reference

Topics:

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Continuity Equation

One of the fundamental principles used in the analysis of uniform flow is known as the Continuity of Flow. This principle is derived from the fact that mass is always conserved in fluid systems regardless of the pipeline complexity or direction of flow.

If steady flow exists in a channel and the principle of conservation of mass is applied to the system, there exists a continuity of flow, defined as: "The mean velocities at all cross sections having equal areas are then equal, and if the areas are not equal, the velocities are inversely proportional to the areas of the respective cross sections." Thus if the flow is constant in a reach of channel the product of the area and velocity will be the same for any two cross sections within that reach. Looking a the units of the product of area (sq-ft) and velocity (fps) leads to the definition of flow rate (cfs). This is expressed in the Continuity Equation:

$$Q = A_1 V_1 = A_2 V_2$$

Where:

Q = the volumetric flow rate

A = the cross sectional area of flow

V = the mean velocity

Calculation of flow rate is often complicated by the interdependence between flow rate and friction loss. Each affects the other and often these problems need to be solved iteratively. Once flow and depth are know the continuity equation is used to calculate velocity in the culvert.

Note: This principle can be used to describe the drop in water surface at a culvert inlet. For example, when the flow is constant and the water velocity increases due to a decrease in roughness, such as through a culvert, the flow area must decrease. In the case of constant cross section geometry that change in area is reflected in a change in the water surface elevation. Q=VA, when flow is constant, as velocity increases, the flow area decreases and vice versa.

See also: Manning's Equation, Open Channel Flow

Darcy Friction Factor

The Darcy Equation is a theoretical equation that predicts the frictional energy loss in a pipe based on the velocity of the fluid and the resistance due to friction. It is used almost exclusively to calculate head loss due to friction in turbulent flow.

$$h_f = \frac{f L v^2}{2Dg}$$

Where:

h_f = Friction head loss
f = Darcy resistance factor
L = Length of the pipe
D = Pipe diameter
V = Mean velocity
g = acceleration due to gravity

The Darcy friction factor, f, is usually selected from a chart known as the Moody diagram. The Moody diagram is a family of curves that relate the friction factor, f, to Reynolds number, Re, and the relative roughness of a pipe, ε/D.

Alternatively, the Darcy friction factor is related to Manning's n through the following relationship:

$$n = \varphi R^{\frac{1}{6}} \sqrt{\frac{f}{8g}}$$

Where:

n = Manning friction factor
φ = Constant of 1.00 for metric and 1.49 for English units
R = Hydraulic Radius
f = Darcy resistance factor

Defining Normal Depth

Normal depth is the depth of flow in a channel or culvert when the slope of the water surface and channel bottom is the same and the water depth remains constant. Normal depth occurs when gravitational force of the water is equal to the friction drag along the culvert and there is no acceleration of flow. In culverts, water flows at normal depth when outside the influence of the inlet and outlet tailwater. Normal depth is undefined for culverts placed at horizontal or adverse slopes.

FishXing uses Manning's Equation to calculate normal depth at each flow based on the channel roughness, wetted area and hydraulic radius. Knowing normal depth aids in classifying the hydraulic slope of the culvert.

> **Note:** Flow at normal depth in culverts often presents the highest average velocities and shallowest depths at that flow. Using normal depth in designing for fish passage is a conservative approach, and ignores potential backwater effects that can increase the range of passable flows.

See also: Roughness Coefficients,Mannings Equation, **Geometry of Circular Culverts,** Flow Profiles

Flow Profiles

The water surface profile is a measure of how the flow depth changes longitudinally. The profiles are classified based on the relationship between the actual water depth (y), the normal depth (y_n) and the critical depth (y_c). Normal depth is the depth of flow that would occur if the flow was uniform and steady, and is usually predicted using the Manning's Equation. Critical depth is defined as the depth of flow where energy is at a minimum for a particular discharge.

Flow profiles are classified by the slope of the channel (So), y_n, and y_c. There are five slope classifications designated by the letters C, M , S, A, and H (critical, mild, steep, adverse, and horizontal) respectively.

- Mild (M) if $y_n > y_c$
- Steep (S) if $y_n < y_c$
- Critical (C) if $y_n = y_c$
- Adverse (A) if So < 0 (if slope is positive in the downstream direction)
- Horizontal (H) if So = 0

The profile is further classified according to the relative position of the actual flow depth to normal and critical depth as designated by the numbers 1, 2, and 3.

- Type 1 curve: Actual depth is greater than y_c and y_n, flow is subcritical
- Type 2 curve: actual depth is between y_c and y_n, flow can be either subcritical or supercritical
- Type 3 curve: actual depth is less than both y_c and y_n, flow is supercritical.

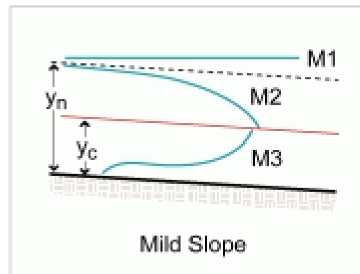
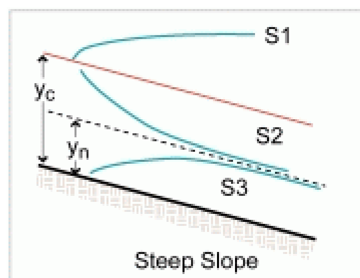
Note: While water surface profiles are influenced by the channel slope, flow profiles are also classified by the water surface slope. When the flow is uniform and steady these slopes are the same. Since critical and normal depths vary with flow, the slope classification is a function of change slopes classifications between mild, steep and critical slopes as streamflows change.

Subcritical occurs when the actual water depth is greater than critical depth. Subcritical flow is dominated by gravitational forces and behaves in a slow or stable way. It is defined as having a Froude number less than one.

Supercritical flow is dominated by inertial forces and behaves as rapid or unstable flow. Supercritical flow transitions to subcritical through a hydraulic jump which represents a high energy loss with erosive potential. When the actual depth is less than critical depth it is classified as supercritical. Supercritical flow has a Froude number greater than one.

Critical flow is the transition or control flow that possesses the minimum possible energy for that flowrate.   Critical flow has a Froude number equal to one.

Flow Profile Classification

Critical Slope is one that sustains uniform, critical flow (y_n=y_c). Critical flow is unstable and a small fluctuation in energy will shift the flow into supercritical or subcritical flow.	
Mild Slope is less than the critical slope and the normal depth is greater than critical depth (y_n>y_c). The flow is subcritical and controlled downstream. **M1** profiles are common where mild slope streams enter a pool. **M2** profiles can occur upstream of a sudden enlargement in a channel or where the slope becomes steeper.	 Mild Slope
Steep Slope is steeper than critical slope, normal depth is less than critical depth (y_n<y_c). The flow is supercritical and controlled upstream. **S1** profiles begin with rise at the upstream end, then becomes horizontal, for example where a steep channel enters a pool. **S2** is called a drawdown curve found at the downstream end of a channel enlargement.	 Steep Slope

Froude Number and Flow States

The Froude number, Fr, is a dimensionless value that describes different flow regimes of open channel flow. The Froude number is a ratio of inertial and gravitational forces.

- **Gravity** (numerator) - moves water downhill
- **Inertia** (denominator) - reflects its willingness to do so.

$$Fr = \frac{V}{\sqrt{gD}}$$

Where:

V = Water velocity

D = Hydraulic depth (cross sectional area of flow / top width)

g = Gravity

When:

$Fr = 1$, critical flow,

$Fr > 1$, supercritical flow (fast rapid flow),

$Fr < 1$, subcritical flow (slow / tranquil flow)

The Froude number is a measurement of bulk flow characteristics such as waves, sand bedforms, flow/depth interactions at a cross section or between boulders.

The denominator represents the speed of a small wave on the water surface relative to the speed of the water, called wave celerity. At critical flow celerity equals flow velocity. Any disturbance to the surface will remain stationary. In subcritical flow the flow is controlled from a downstream point and information is transmitted upstream. This condition leads to backwater effects. Supercritical flow is controlled upstream and disturbances are transmitted downstream.

Wave propagation can be used to illustrate these flow states: A stick placed in the water will create a V pattern of waves downstream. If flow is subcritical waves will appear in front of the stick. If flow is at critical waves will have a 45° angle. If flow is supercritical no upstream waves will appear and the wave angle will be less than 45°.

Note: Critical flow is unstable and often sets up standing waves between super and subcritical flow. When the actual water depth is below critical depth it is called **supercritical** because it is in a higher energy state. Likewise actual depth above critical depth is called **subcritical** because it is in a lower energy state.

Manning's Equation

One the most commonly used equations governing Open Channel Flow is known as the Mannings's Equation. It was introduced by the Irish Engineer Robert Manning in 1889 as an alternative to the Chezy Equation. The Mannings equation is an empirical equation that applies to uniform flow in open channels and is a function of the channel velocity, flow area and channel slope.

(n) Click here to view an interactive demo of Manning's Equation

Manning's Equation:

$$Q = VA = \left(\frac{1.49}{n}\right) AR^{\frac{2}{3}} \sqrt{S} \quad [U.S.]$$

$$Q = VA = \left(\frac{1.00}{n}\right) AR^{\frac{2}{3}} \sqrt{S} \quad [SI]$$

Where:

- Q = Flow Rate, (ft^3/s)
- v = Velocity, (ft/s)
- A = Flow Area, (ft^2)
- n = Manning's Roughness Coefficient
- R = Hydraulic Radius, (ft)
- S = Channel Slope, (ft/ft)

Under the assumption of uniform flow conditions the bottom slope is the same as the slope of the energy grade line and the water surface slope. The Manning's n is a coefficient which represents the roughness or friction applied to the flow by the channel. Manning's n-values are often selected from tables, but can be back calculated from field measurements. In many flow conditions the selection of a Manning's roughness coefficient can greatly affect computational results.

Note: Manning's Equation can be rearranged to solve for slope (S), which is termed the friction slope, (Sf). The friction slope is part of the gradually varied flow used to solve for the water surface profile through a culvert.

Manning's n Values

Reference tables for Manning's n values for Channels, Closed Conduits Flowing Partially Full, and Corrugated Metal Pipes.

Manning's n for Channels (Chow, 1959).

Type of Channel and Description	Minimum	Normal	Maximum
Natural streams - minor streams (top width at floodstage < 100 ft)			
1. Main Channels			
a. clean, straight, full stage, no rifts or deep pools	0.025	0.030	0.033
b. same as above, but more stones and weeds	0.030	0.035	0.040
c. clean, winding, some pools and shoals	0.033	0.040	0.045
d. same as above, but some weeds and stones	0.035	0.045	0.050
e. same as above, lower stages, more ineffective slopes and sections	0.040	0.048	0.055
f. same as "d" with more stones	0.045	0.050	0.060
g. sluggish reaches, weedy, deep pools	0.050	0.070	0.080
h. very weedy reaches, deep pools, or floodways with heavy stand of timber and underbrush	0.075	0.100	0.150
2. Mountain streams, no vegetation in channel, banks usually steep, trees and brush along banks submerged at high stages			
a. bottom: gravels, cobbles, and few boulders	0.030	0.040	0.050
b. bottom: cobbles with large boulders	0.040	0.050	0.070
3. Floodplains			
a. Pasture, no brush			
1.short grass	0.025	0.030	0.035
2. high grass	0.030	0.035	0.050
b. Cultivated areas			
1. no crop	0.020	0.030	0.040
2. mature row crops	0.025	0.035	0.045
3. mature field crops	0.030	0.040	0.050

c. Brush			
1. scattered brush, heavy weeds	0.035	0.050	0.070
2. light brush and trees, in winter	0.035	0.050	0.060
3. light brush and trees, in summer	0.040	0.060	0.080
4. medium to dense brush, in winter	0.045	0.070	0.110
5. medium to dense brush, in summer	0.070	0.100	0.160
d. Trees			
1. dense willows, summer, straight	0.110	0.150	0.200
2. cleared land with tree stumps, no sprouts	0.030	0.040	0.050
3. same as above, but with heavy growth of sprouts	0.050	0.060	0.080
4. heavy stand of timber, a few down trees, little undergrowth, flood stage below branches	0.080	0.100	0.120
5. same as 4. with flood stage reaching branches	0.100	0.120	0.160
4. Excavated or Dredged Channels			
a. Earth, straight, and uniform			
1. clean, recently completed	0.016	0.018	0.020
2. clean, after weathering	0.018	0.022	0.025
3. gravel, uniform section, clean	0.022	0.025	0.030
4. with short grass, few weeds	0.022	0.027	0.033
b. Earth winding and sluggish			
1. no vegetation	0.023	0.025	0.030
2. grass, some weeds	0.025	0.030	0.033
3. dense weeds or aquatic plants in deep channels	0.030	0.035	0.040
4. earth bottom and rubble sides	0.028	0.030	0.035
5. stony bottom and weedy banks	0.025	0.035	0.040
6. cobble bottom and clean sides	0.030	0.040	0.050
c. Dragline-excavated or dredged			
1. no vegetation	0.025	0.028	0.033
2. light brush on banks	0.035	0.050	0.060
d. Rock cuts			
1. smooth and uniform	0.025	0.035	0.040
2. jagged and irregular	0.035	0.040	0.050

e. Channels not maintained, weeds and brush uncut			
1. dense weeds, high as flow depth	0.050	0.080	0.120
2. clean bottom, brush on sides	0.040	0.050	0.080
3. same as above, highest stage of flow	0.045	0.070	0.110
4. dense brush, high stage	0.080	0.100	0.140
5. Lined or Constructed Channels			
a. Cement			
1. neat surface	0.010	0.011	0.013
2. mortar	0.011	0.013	0.015
b. Wood			
1. planed, untreated	0.010	0.012	0.014
2. planed, creosoted	0.011	0.012	0.015
3. unplaned	0.011	0.013	0.015
4. plank with battens	0.012	0.015	0.018
5. lined with roofing paper	0.010	0.014	0.017
c. Concrete			
1. trowel finish	0.011	0.013	0.015
2. float finish	0.013	0.015	0.016
3. finished, with gravel on bottom	0.015	0.017	0.020
4. unfinished	0.014	0.017	0.020
5. gunite, good section	0.016	0.019	0.023
6. gunite, wavy section	0.018	0.022	0.025
7. on good excavated rock	0.017	0.020	
8. on irregular excavated rock	0.022	0.027	
d. Concrete bottom float finish with sides of:			
1. dressed stone in mortar	0.015	0.017	0.020
2. random stone in mortar	0.017	0.020	0.024
3. cement rubble masonry, plastered	0.016	0.020	0.024
4. cement rubble masonry	0.020	0.025	0.030
5. dry rubble or riprap	0.020	0.030	0.035
e. Gravel bottom with sides of:			
1. formed concrete	0.017	0.020	0.025

2. random stone mortar	0.020	0.023	0.026
3. dry rubble or riprap	0.023	0.033	0.036
f. Brick			
1. glazed	0.011	0.013	0.015
2. in cement mortar	0.012	0.015	0.018
g. Masonry			
1. cemented rubble	0.017	0.025	0.030
2. dry rubble	0.023	0.032	0.035
h. Dressed ashlar/stone paving	0.013	0.015	0.017
i. Asphalt			
1. smooth	0.013	0.013	
2. rough	0.016	0.016	
j. Vegetal lining	0.030		0.500

Manning's n for Closed Conduits Flowing Partly Full (Chow,1959).

Type of Conduit and Description	Minimum	Normal	Maximum
1. Brass, smooth:	0.009	0.010	0.013
2. Steel:			
Lockbar and welded	0.010	0.012	0.014
Riveted and spiral	0.013	0.016	0.017
3. Cast Iron:			
Coated	0.010	0.013	0.014
Uncoated	0.011	0.014	0.016
4. Wrought Iron:			
Black	0.012	0.014	0.015
Galvanized	0.013	0.016	0.017
5. Corrugated Metal:			
Subdrain	0.017	0.019	0.021
Stormdrain	0.021	0.024	0.030
6. Cement:			
Neat Surface	0.010	0.011	0.013
Mortar	0.011	0.013	0.015
7. Concrete:			
Culvert, straight and free of debris	0.010	0.011	0.013
Culvert with bends, connections, and some debris	0.011	0.013	0.014
Finished	0.011	0.012	0.014
Sewer with manholes, inlet, etc., straight	0.013	0.015	0.017
Unfinished, steel form	0.012	0.013	0.014

Unfinished, smooth wood form	0.012	0.014	0.016
Unfinished, rough wood form	0.015	0.017	0.020
8. Wood:			
Stave	0.010	0.012	0.014
Laminated, treated	0.015	0.017	0.020
9. Clay:			
Common drainage tile	0.011	0.013	0.017
Vitrified sewer	0.011	0.014	0.017
Vitrified sewer with manholes, inlet, etc.	0.013	0.015	0.017
Vitrified Subdrain with open joint	0.014	0.016	0.018
10. Brickwork:			
Glazed	0.011	0.013	0.015
Lined with cement mortar	0.012	0.015	0.017
Sanitary sewers coated with sewage slime with bends and connections	0.012	0.013	0.016
Paved invert, sewer, smooth bottom	0.016	0.019	0.020
Rubble masonry, cemented	0.018	0.025	0.030

Manning's n for Corrugated Metal Pipe (AISI, 1980).

Type of Pipe, Diameter and Corrugation Dimension	n
1. Annular 2.67 x 1/2 inch (all diameters)	0.024
2. Helical 1.50 x 1/4 inch	
8" diameter	0.012
10" diameter	0.014
3. Helical 2.67 x 1/2 inch	
12" diameter	0.011
18" diameter	0.014
24" diameter	0.016
36" diameter	0.019
48" diameter	0.020
60" diameter	0.021
4. Annular 3x1 inch (all diameters)	0.027
5. Helical 3x1 inch	
48" diameter	0.023
54" diameter	0.023
60" diameter	0.024
66" diameter	0.025
72" diameter	0.026
78" diameter and larger	0.027
6. Corrugations 6x2 inches	
60" diameter	0.033
72" diameter	0.032
120" diameter	0.030
180" diameter	0.028

Open Channel Flow

The analysis of flow patterns of water surface shape, velocity, shear stress and discharge through a stream reach falls under the heading Open Channel Flow.

Open Channel Flow is defined as fluid flow with a free surface open to the atmosphere. Examples include streams, rivers and culverts not flowing full. Open channel flow assumes that the pressure at the surface is constant and the hydraulic grade line is at the surface of the fluid

Steady and unsteady flow depend on whether flow depth and velocity change with time at a point. In general if the quantity of water entering and leaving the reach does not change, then the flow is considered steady.

Steady flow in a channel can be either Uniform or Non-uniform (varied).When the average velocities in successive cross sections of a channel are the same, the flow is uniform. This occurs only when the cross section is constant. Non-uniform flow results from gradual or sudden changes in the cross sectional area.

Uniform flow and varied flow describe the changes in depth and velocity with respect to distance. If the water surface is parallel to the channel bottom flow is uniform and the water surface is at normal depth. Varied flow or non-uniform flow occurs when depth or velocity change over a distance, like in a constriction or over a riffle. Gradually varied flow occurs when the change is small, and rapidly varied flow occurs when the change is large, for example a wave, waterfall, or the rapid transition from a stream channel into the inlet of a culvert.

See also: Continuity Equation, Gradually Varied Flow

Shear Stress

Shear Stress (τ) is a measure of the force of friction from a fluid acting on a body in the path of that fluid. In the case of open channel flow, it is the force of moving water against the bed of the channel. Shear stress is calculated as:

$$\tau = \gamma \, D \, Sw$$

Where:

τ = Shear Stress (N/m^2, □□)

γ = Weight Density of Water (N/m^3, lb/ft)

D = Average water depth (m, ft)

Sw = Water Surface slope (m/m, ft/ft)

Note: Bed load movement and sediment transport is a function of Shear Stress. When the drag force of flowing water against a rock is greater than the gravitational force holding it in place it begins to move.

Vertical changes in water velocity produces shear forces that are parallel to the bed. These shear forces acting on the bed of a channel generate shear stress, which initiate bedload movement. The magnitude of these stresses is a function of water surface slope, channel geometry and flow

The moment where the directive forces (shear forces) overcome restrictive forces (inertia, friction) is known as the moment of incipient motion and is the threshold of particle entrainment. The shear stress at this threshold is known as the critical shear stress (τ*).

Specific Force and Momentum

Conservation of linear momentum provides a third principle, in addition to continuity of mass and conservation of energy, that is used to solve open channel flow problems.

The momentum principle states that all forces acting on a system result in a change of momentum in the system. For fluid flow those forces include; pressure in the downstream direction, weight in the downstream direction, pressure in the upstream direction, and friction in the upstream direction. The momentum at a cross section can be defined as the product of mass flow rate and the velocity.

$$\text{Momentum} = (\text{Mass flow rate}) \times (\text{Velocity})$$

The expression of momentum is a function made up of two terms: The momentum of flow passing through a channel section per unit time per unit weight of water and the second is the force per unit weight of water. The sum is known as Specific Force:

$$M = \frac{Q^2}{g\,A} + \bar{z}\,A$$

Where

M = specific force,

Q = flow rate,

A = cross sectional area of flow,

zbar = distance from the water surface to the centroid of the cross sectional area of flow

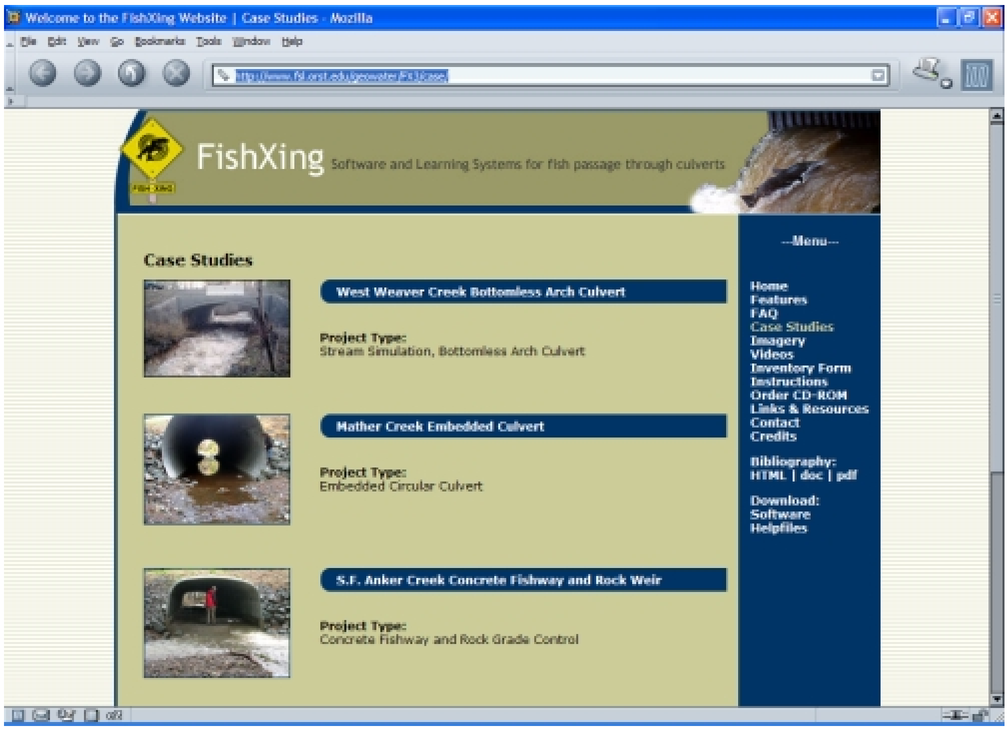
Momentum principles can be applied to situations that deal with a high loss of internal energy, like hydraulic jumps, which cannot be evaluated with the energy principles alone.

Case Studies

Example culvert replacement projects for fish passage can be viewed at the following website:

http://stream.fs.fed.us/fishxing/case/index.html

Click to view in a new browser window:



Glossary

A . B . C . D . E . F . G . H . I-L . M . N . O . P . Q . R . S . T . U . V . W-Z

A

Active Channel Stage: The active channel or ordinary high water level is an elevation delineating the highest water level that has been maintained for a sufficient period of time to leave evidence on the landscape, such as the point where the natural vegetation changes from predominantly aquatic to predominantly terrestrial or the bank elevation at which the cleanly scoured substrate of the stream ends and terrestrial vegetation begins.

Adfluvial: Produced by river action; occasionally used in reference to fish that mature in lakes and migrate upstream into tributaries to spawn.

Alviens: Newly hatched fish with the yoke sack still attached.

Anadromous Fish: Fish such as salmon and some trout that are born in fresh water rivers and tributaries, migrate downstream, mature in the ocean, and return to fresh water to spawn.

Apron: A hardened surface (usually concrete or grouted riprap) placed at either the invert of the culvert inlet or outlet to protect structure from scour and storm damage. Aprons often produce shallow depths with high velocities, creating barriers to upstream fish movement.

Aquatic Ecosystem: The total community of living species and its interrelated physical and chemical environment that is directly related to the functions of a particular water drainage.

Arch: An open bottomed road stream crossing structure usually formed of bolted structural plates.

Armoring: Protective covering, such as rock, vegetation, or engineered materials used to protect stream banks, fill or cut slopes, or drainage structure outflows from flowing water energy and erosion.

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B

Baffles: Wood, concrete or metal panels mounted in a series on the floor and/or wall of a culvert to increase boundary roughness and thereby reduce the average water velocity in the culvert.

Bankfull Stage: Corresponds to the stage at which channel maintenance is most effective, that is, the discharge at which the stream is moving sediment, forming or removing bars, forming or changing bends and meanders, and generally doing work that results in the average morphologic characteristics of channels. The bankfull stage is most effective or is the dominate channel forming flow, and in many streams has an approximate recurrence interval of 1.5 years (Dunne & Leopold 1978).

Bedload: Sand, silt, and gravel, or soil and rock debris rolled along the bottom of a stream by the moving water. The particles of this material have a density or grain size which prevents movement far above or for a long distance out of contact with the streambed under natural flow conditions.

Bottomless-arch: See Open Bottom Arch

Breaks-in-slope: Steeper sections within a culvert. As culverts age they often sag as the road fills settles.

Bridge: A structure, including supports, erected over a depression or an obstruction, such as water, a channel, road, trail, or railway, and having a deck for carrying traffic or other moving loads.

Bridge Load Rating: The bridge capacity measured in tons of Gross Vehicular Weight (GVW). Bridge capacities are rated at two load levels.

Burst Speed: The highest speed a fish can swim for a short time.

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C

CFS: Cubic feet per second.

CSP: Corrugated steel pipe. Pipe barrel is comprised of a single sheet of material.

CMP: Corrugated metal pipe. Pipe barrel is comprised of a single sheet of material.

Cofferdam: Temporary enclosure built in a water course and pumped dry to permit work on a structure by separating the work from the water.

Corrugations: Refers to the undulations present in CSP and SSP culvert material. Corrugations provide surface roughness which increases over the width and depth of standard dimensions.

Critical Depth: Depth of flow at which specific energy is a minimum; depth in a conduit at which maximum flow will occur if the conduit is at critical slope, the water is flowing at critical velocity, and an adequate supply of water exists.

Critical Flow: A condition existing at critical depth where the sum of the velocity head and static head is a minimum.

Critical Slope: The slope at which maximum flow will occur at minimum velocity; the slope equal to loss of head per foot resulting from flow at a depth giving uniform flow at critical depth.

Cross Drain: A ditch relief culvert or other structure or shaping of the traveled way designed to capture and remove surface water from the traveled way or other road surfaces.

Crown: Surface shaping of the roadway with the high point in the middle causing surface runoff to flow both towards the uphill shoulder or ditch and the downhill shoulder.

Cruising Speed: The speed a fish can swim for an extended time.

Culvert: A specific type of stream crossing, used generally to convey water flow through theroad prism base. Typically constructed of either steel, aluminum, plastic, or concrete. Shapes include circular, oval, squashed-pipe (flat floor), open bottom arch, square,or rectangular.

Culvert Entrance: The downstream end of a culvert through which fish enter to pass upstream.

Culvert Exit: The upstream end of a culvert through which a fish exit to pass upstream.

Culvert Inlet: The upstream end of a culvert through which stream flow enters.

Culvert Outlet: The downstream end of a culvert through which stream flow discharges.

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D

Design Discharge: Flow quantity expected at a point in a channel resulting from the design storm.

Design Frequency: The recurrence interval for a hydrologic event used for structure design purposes.

Design Life: Length of time of service for a facility without major repair.

Debris Plugging: Reduction in flow capacity of a road stream crossing drainage structure or ditch relief pipe due to blockage by woody materials.

Diversion Potential: The possibility, caused by a road, for streamflow to leave its established channel.

Drawings: The documents, including plan and profile sheets, cross sections, diagrams, layouts, schematics, descriptive literature, illustrations, schedules, performance and test data, and similar materials showing details for construction of a transportation facility.

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E

Embedment: The depth to which a culvert bottom is buried into the streambed. It is usually expressed as a percentage of the culvert height or diameter.

Erosion: The detachment and subsequent transport of soil particles by water, wind, or ice.

Exceedance Flow: n percent exceedance flow is the flow that is equaled or exceeded n percent of the time.

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F

Fish Habitat: Conditions essential for fish life including sufficient water quality and quantity, spawning, nursery, and rearing areas, and food supply.

Fish Passage: The ability of both adult and juvenile fish to move both up and down stream.

Fishway: A structure for passing fish over vertical impediments. It may include special attraction devices, entrances, collection and transportation channels, a fish ladder, and exit.

FishXing: (pronounced “Fish Crossing”)A computer software program developed by the Forest Service and cooperators. FishXing models culvert hydraulics (including open-bottom structures) and compares the predicted values with data regarding swimming and leaping abilities and minimum water depth requirements for numerous fish species.

Flood Frequency: The frequency with which a flow has the probability of being equaled or exceeded. For example, a "100-year" frequency flood refers to a flood discharge of a magnitude likely to occur on the average of once every 100 years or, more properly, has a one-percent chance of being equaled or exceeded in any year. Although calculation of possible recurrence is often based on historical records, there is no guarantee that a "100-year" flood will occur at all within the 100-year period or that it will not recur several times.

Flood Frequency Analysis: A procedure for identifying the magnitude of flow, i.e., the N year precipitation event, that will be equaled on an average of every N years. In the case of a 20-year event, there is a 5% chance that it will be equaled during any given year.

Floodplain: The area adjacent to the stream built by the river in the present climate and inundated during periods of high flow.

Flood Prone Zone: The area corresponding to the modern floodplain, but can also include river terraces subject to significant bank erosion. For delineation, see definition for floodplain.

Flow Duration (or Annual Exceedance Flow): A flow duration curve is a cumulative frequency curve that shows the percentage of time that specified flows are equaled or exceeded. Describes the natural flow characteristics of a stream by showing the percentage of time that a flow is equal to or greater than a given value during a specified period. Flow exceedance values are important for describing the flow conditions under which fish passage is required as applied annually, monthly, or to the migration period.

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G

Gradient Control Weirs: Stabilizing weirs constructed in the streambed to prevent lowering of the channel bottom.

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H

HW/D: Headwater to Diameter Ratio is a measure of the depth of water at the inlet of the culvert. HW/D < 1 describes a culvert with a headwater depth below the top of the culvert inlet, HW/D = 1 is the condition in which the headwater at the inlet is equal to the culvert diameter, and HW/D >1 is when the headwater depth exceeds the culvert diameter. In this condition, flow entering the culvert is under pressure and water is "ponding" at the inlet. D represents diameter for circular pipes and rise or height for arch or box culverts.

Head: The force per unit area exerted by a column of liquid at a height above a depth (and pressure) of interest. Fluids flow down a hydraulic gradient, from points of higher to lower hydraulic head.

Headcutting: Erosional process moving upstream from the location of initial downcutting.

Headwater elevation: The depth of water above the upstream side of the culvert. This depth represents the amount of potential energy available to convey water through the culvert.

Hydraulic Capacity: The maximum amount of flow that a stream crossing can convey at a specific headwater depth.

Hydraulic Controls: A location within the channel that controls the water depth and velocity upstream. For example, the tailwater control below a culvert may be a hydraulic control influencing hydraulic conditions within the culvert.

Hydraulic Gradient: Pressure gradient, or a line representing pressure or piezometrichead in a pipe flowing full, or the water surface in open channel flow.

Hydraulic Jump: An abrupt transition in streamflow from shallow and fast (supercritical flow) to deep and slow (subcritical flow).

Hydraulic Radius: The ratio of area of flow to wetted perimeter.

Hydrograph: Plot depicting discharge of water versus time for a stream, including surface, subsurface, and base flows.

Hydrology: The water of the earth and air; its flow, distribution, characteristics, and actions.

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I

Invert: The part of a culvert below the spring line that represents the lowest point in the internal cross section. Also the stream bed or floor within a structure or channel.

Inlet: Upstream entrance to a culvert.

Inlet bottom: Measured in the center of the culvert inlet for both standard and embedded (sunken) culverts. If the culvert is embedded, this should be the elevation of the natural bottom at the inlet and not the elevation of the culvert inlet invert.

Inlet Control: Culvert configuration for which the cross sectional area of the barrel and headwater depth are the primary controls on culvert capacity. Generally occurs in steeper culverts that are not backwatered.

Inlet Invert: Location at inlet, on the culvert floor where an elevation is measured to calculate culvert slope.

Invert: The part of a culvert below the spring line that represents the lowest point in the internal cross section. Also the stream bed or floor within a structure or channel.

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J

Juvenile: A young fish.

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M

Manning's Formula: An equation for determining flow quantity given hydraulic radius, cross sectional area of flow, slope (for uniform flow), and a coefficient of roughness.

Maximum Average Water Velocity in Culvert: The highest average water velocity for any cross-section along the length of the culvert, excluding the effects of water surface drawdown at the culvert outlet.

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O

Open Bottom Arch: A type of culvert with rounded sides and top attached to concrete or steel footings set below stream grade. The natural stream channel and substrate run through the length of the culvert, providing streambed conditions similar to the actual stream channel.

Ordinary High Water Mark: The mark along the bank or shore up to which the presence and action of the water are common and usual, and so long continued in all ordinary years, as to leave a natural line impressed on the bank or shore and indicated by erosion, shelving, changes in soil characteristics, destruction of terrestrial vegetation, or other distinctive physical characteristics.

Outfall: The outlet end of a culvert.

Outlet: Downstream opening of a culvert.

Outlet Bottom: Measured in the center of the culvert outlet for both standard and embedded (sunken) culverts. If the culvert is embedded, this would be the elevation of the natural bottom at the outlet and not the elevation of the culvert outlet invert.

Outlet Control: Culvert flow in which the cross sectional area of the barrel, inlet configuration, amount of headwater or ponding, tailwater in the outlet channel, and slope, roughness, and length of barrel are of controlling importance to hydraulics of flow.

Outlet Invert: Location at outlet, on the culvert floor, where an elevation is measured to calculate culvert slope.

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P

Passage Flow: Range of flows for fish migration. The passage flows define the range of flows analyzed by FishXing. See also Qhp and Qlp.

Peak Flow: The greatest discharge in a given channel from a given precipitation event.

Perching: The development of falls or a cascade at a culvert outfall because of downstream erosion.

Perched Outlet: A condition in which a culvert outlet is suspended over the immediate downstream pool, requiring a migrating fish to leap into culvert.

Pipe-arch: A type of culvert with a flat bottom and rounded sides and top, usually created by shaping or squashing a circular CSP or SSP pipe.

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Q

Qhp: Stream discharge (in cfs) at high passage flow. For adult salmonids, in California defined as the 1 percent exceedance flow (the flow equaled or exceeded 1 percent of the time) during the period of expected migration.

Qlp: Stream discharge (in cfs) at low passage flow. For adult salmonids, in California defined as the 90 percent exceedance flow for the migration period.

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R

Recurrence Interval: Also referred to as flood frequency, or return period. It is the average time interval between occurrences of a hydrological event of a given or greater magnitude. For example, a flood event with a two-year recurrence interval has a 50 percent chance of being equaled or exceeded in any given year.

Resident Fish: Fish that spend their entire life in a limited range of habitats, such as fresh water.

Reynolds Number: A nondimensional coefficient used as a dynamic scale of flow. Interpreted as the ratio of inertial forces to viscous forces in a fluid (inertial forces/viscous forces).

Riffle Crest: See "tailwater control".

Riparian Area: The area containing moist soils and hydric vegetation along and interacting with a stream comprised of two ecosystems, riparian and aquatic, sometimes depicted by a measured width.

Risk: The chance of failure.

Roads: For purposes of these guidelines, roads include all sites of intentional surface disturbance for the purpose of vehicular or rail traffic and equipment use, including all surfaced and unsurfaced roads, temporary roads, closed and inoperable roads, legacy roads, skid trails, tractor roads, layouts, landings, turnouts, seasonal roads, fire lines, and staging areas.

Rust line: A line defined by the top of the corroded metal that forms in the bottom of steel culverts. The rust line is useful as an indicator of base high flows.

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S

SSP: Structural steel plate. Pipe diameter is comprised of multiple sheets of material which are usually bolted together.

Salmonid: Any fish belonging of the family Salmonidae including whitefish, grayling, salmon, and trout.

Scour: Underwater erosion of a stream bottom or bank or at a drainage structure outflow.

Section 10 and 404 Regulatory Programs: The principal federal regulatory programs, carried out by the US Army Corps of Engineers, affecting structures and other work below mean high water. The Corps, under Section 10 of the River and Harbor Act of 1899, regulates structures in, or affecting, navigable waters of the US as well as excavation or deposition of materials (e.g., dredging or filling) in navigable waters. Under Section 404 of the Federal Water Pollution Control Act Amendments (Clean Water Act of 1977), the Corps is also responsible for evaluating application for Department of the Army permits for any activities that involve the placement of dredged or fill material into waters of the United States, including adjacent wetlands.

Slope: The rise divided by the run in stream channels and culverts.

Soffit: The bottom of the top of a pipe, the uppermost point on the inside of a pipe. The crown is the uppermost point on the outside of the pipe wall.

Spawning Bed: A habitat used by fish for producing or depositing eggs.

Spring line: The line of the outer most points on the side of a culvert. For circular pipes it the line one half the diameter above the invert. Also, the maximum horizontal dimension of culvert or conduit.

Stream Crossing: Any human-made structure generally used for transportation purposes that crosses over or through a stream channel including a paved road, unpaved road, railroad track, biking or hiking trail, golf-cart path, or low-water ford. A stream crossing encompasses the structure employed to pass stream flow as well as associated fill material within the crossing prism.

Subcritical Flow: Slower and deeper flowing water in which gravitational forces (potential energy) dominate, and are greater than inertial forces.

Supercritical Flow: Faster and shallower flowing water that is usually associated with a hydraulically steep, smooth surface. In supercritical flow, inertial forces exceed gravitational forces. Sometimes referred to as rapid or “shooting flow.”

Sustaining Speed: The swimming speed a fish can maintain for several minutes.

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T

Tailwater Control: The channel feature that determines the water surface elevation immediately downstream of the culvert outlet. The location controlling the tailwater elevation is often at the riffle crest immediately below the outlet pool. Tailwater control is also the channel elevation that determines residual pool depth.

Tailwater: Natural stream or channel just downstream of a culvert or hydraulic structure. The hydraulic response of the downstream water level to discharge from the culvert affects the capacity of the culvert system.

Tailwater depth: The water depth immediately downstream of the culvert as measured from the invert of the outlet.

Thalweg: The line connecting the lowest or deepest points along a streambed.

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V

Vented Ford: A crossing where the road grade is above the stream channel bottom and all of the water passes through the structure during periods of low flow. During floods, most of the flow overtops the structure. The openings through the structure may be corrugated metal pipe, concrete pipe, concrete box culverts, or treated timber.

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W

Waters of the United States: Currently defined by regulation to include all navigable and interstate waters, their tributaries and adjacent wetlands, as well as isolated wetlands and lakes and intermittent streams.

Waterbar: Combination of ditch and berm installed perpendicular or skew to road centerline to facilitate drainage of surface water, sometimes non-driveable and used to close the road.

Watershed: An area or region bounded peripherally by ridges or divides such that all precipitation falling in the area contributes to its watercourse or water body.

Weir: a) A notch or depression in a levee, dam, embankment, or other barrier across or bordering a stream, through which the flow of water is measured or regulated; b) A barrier constructed across a stream to divert fish into a trap; c) A dam (usually small) in a stream to raise the water level or divert its flow. Active Channel Stage: The active channel or ordinary high water level is an elevation delineating the highest water level that has been maintained for a sufficient period of time to leave evidence on the landscape, such as the point where the natural vegetation changes from predominantly aquatic to predominantly terrestrial or the bank elevation at which the cleanly scoured substrate of the stream ends and terrestrial vegetation begins.

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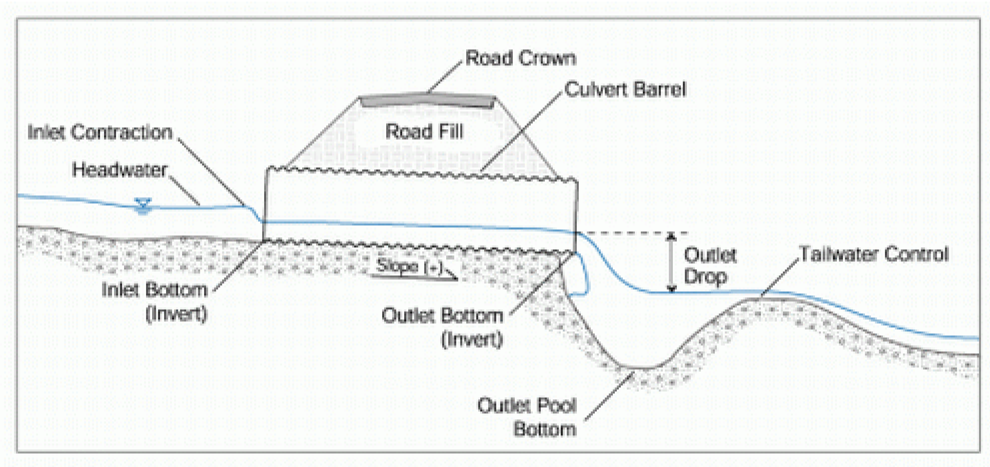
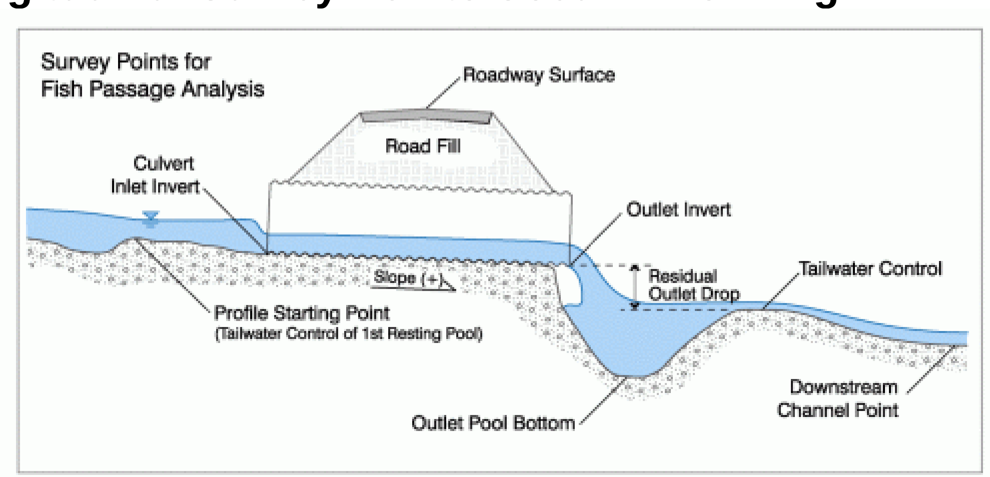
Culvert Definition Sketch



Longitudinal Survey Points Used in FishXing



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