ABSTRACT

GARDNER, ANGELA NICHOLE. Fish Passage through Road Culverts. (Under the direction of Dr. Greg Jennings).

The North Carolina Department of Transportation (NCDOT) has regulations requiring road crossings to facilitate Aquatic Organism Passage (AOP). Due to a current inability to prove that AOP will not be inhibited, acquiring permits for the design and construction of culverts has become difficult. Often, bridges costing up to three times as much must be built in their place. To improve the design of culverts and the feasibility of obtaining a permit, this study determined the maximum swimming speed that can be sustained by a fish for a period of ten minutes. This speed, known as the critical velocity, is equivalent to traversing a 100m culvert. The critical velocities were determined for the following fish species native to the piedmont of North Carolina: *Nocomis leptocephalus, Lepomis auritus, Etheostoma nigrum, Lepomis macrochirus, Noturus insignis, Notropisprocne.* The fish were collected by electrofishing from local streams. After resting for 12 to 18 hours the fish were placed in a flume and allowed to accommodate at a resting velocity of 20cm/s. The velocity was then increased by 10cm/s every ten minutes, while returning to the resting velocity for five minutes between each step. The critical velocities for each species were 85.56cm/s, 43.89cm/s, 67.76cm/s, 37.05cm/s, 48.67cm/s, 61.42cm/s respectively. Based on the data collected in this experiment, it is recommended that the maximum velocity in a culvert be kept under 55cm/s for 90% of the fish migration period. A Microsoft Excel model was created based on the results. The model uses the critical velocities as guidelines for maximum flow rates in the hydrologic design of culverts. Using the model in addition to

other hydrologic design models can aid in the design of culverts that do not impede fish passage.

FISH PASSAGE THROUGH ROAD CULVERTS

By

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To my family: for keeping me grounded while letting me dream big,
And for being my biggest fans.

To my best friends: for keeping me sane in times of stress,
For making me laugh when times were tough,
And for joining me in the adventure of life.

Biography

Angela Nichole Gardner was born in North Springfield, Virginia to Sandra and James Gardner in May 1982. She is the middle of three girls, with Kellie being the eldest, and Jenny being the youngest. After a brief stay in Jacksonville, Florida, the Gardner family returned to Springfield where they would stay for the remainder of Angela's childhood.

The fall of 2000 would bring Angela to Blacksburg, Virginia for her first year at Virginia Tech. Years of playing outside and enjoying the outdoors would inspire Angela to pursue a major in Biological Systems Engineering studying soil and water conservation. After completing her Bachelors of Science, Angela realized there was still much more she wanted to learn in her field. Her passion for stream restoration and stormwater engineering led her to the Masters of Science program in the department of Biological and Agricultural Engineering at North Carolina State University. She began her degree in the fall of 2004, focusing on stream restoration. She completed her Masters of Science in the spring of 2006, and she plans to work as a consultant in an engineering firm focusing on stream restoration.

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1.0 Introduction

1.1 Ecological Connectivity

In periods of rapid development the need for a new infrastructure often overshadows concerns of potential environmental impacts. Streams have been straightened and channeled through pipes, and culverts have been sized without considering impacts on fish migration. As a result there has been a deterioration of freshwater habitat, and the endangerment of many fish species (Bond et al. 2003). In recent years a movement towards restoring freshwater ecosystems previously devastated by human impacts has begun.

In the restoration process of freshwater systems it is important to consider the effects of ecological connectivity. Ecological connectivity refers to the ability of a landscape to support the movement of energy, organisms, and materials (Bates et al. 2003). This can include the migration of fish, movement of sediment and debris, and the capacity of a stream to handle changes in hydrology. With regards to fish passage and road culverts, it is the linkage between the upstream and downstream reaches.

The process of restoration can be maximized by focusing on these linkages, specifically the effects on fish dispersal and colonization (Bond et al. 2003). The ability of fish and other aquatic organisms to disperse is essential for their survival. Dispersal gains them access to spawning habitats, prey, escape from predators, and the "maintenance of populations in areas unsuitable for reproduction," (Warren et al. 1998).

Each fish species requires specific habitat conditions for spawning. These habitats are often located in the upper stream reaches. Fry hatched in the upper reaches have access to the entire downstream watershed for rearing. During the rearing process juvenile fish can use nearly every segment of a stream environment (Bates et al. 2003).

When a culvert is installed, not only is habitat lost in that specific area, but oftentimes fish can not navigate through the culvert, effectively cutting off access to the upper stream reaches. This fragmentation in the landscape ecology can isolate fish populations, which increases susceptibility to genetic change and the risk of extinction due to chance events (Venner Consulting and Parsons Brinkerhoff 2004). When a barrier is present, individual exchange is blocked among populations, thus eliminating genetic diversity and the ability of one population to support a waning population nearby. This can both delay and prohibit the recovery of fish assemblages following disturbance from culvert installation (Warren et al. 1998)

Wildlife issues are gaining more importance on state Department of Transportation (DOT) agendas. Possible improvements for culverts, culvert retrofits, and roadway crossings are being examined to reduce impacts on wildlife passage. A survey conducted in 2002 shows that 17 of 50 state DOTs are beginning to consider wildlife crossings in the roadway design process. However, few of the 17 have wildlife crossing policies. The same survey shows that 9 of 50 state DOTs have made modifications to existing culverts in order to improve ecological connectivity across roads; however, only 4 states have monitored the crossings to ensure the desired results were reached (Venner Consulting and Parsons Brinkerhoff 2004).

1.2 Culverts

1.2.1 Definition of a culvert

The purpose of a culvert is to carry water under a road embankment. Culverts vary in shape and size and can be as long as 100m (328ft). Circular culverts are the most common; however, they can also be elliptical, rectangular or shaped as an arch, and are made with a variety of materials (Ead et al. 2002).

A culvert is a rigid body that is set into an ever changing stream environment. Changes in land use due to urbanization can create an unstable watershed. As runoff volume increases, the streams actively degrade in order to accommodate higher flows. Culverts are unable to adapt to the degrading streams and instead become barriers to fish movement. The most common reasons culverts become barriers are excessive outlet drops, high water velocity within the culvert, turbulence within the culvert, accumulation of sediment and debris, and an inadequate water depth within the culvert (Bates et al. 2003). In addition to these barriers, the absences of refuge pools at either end of the culvert prevent fish from acquiring the rest necessary to traverse the obstacle. Scour pools located at the culvert outlet as well as midchannel bars upstream of the culvert can also be a sign of velocity barriers within the culvert (Bates et al. 2003). Some culverts are only seasonal barriers, acting as barriers during periods of low flow. All of the aforementioned barriers hinder the movement of adult fish but are often more detrimental to both juveniles and smaller fish species. (Toepfer et al. 1999).

1.2.2 Retrofitting Culverts

When considering fish passage conventional hydraulic designs procedures have to be altered. One option is designing or retrofitting culvert fishways. A culvert fishway is defined as any culvert with special features to make it passable by fish (Rajaratnam et al. 1991). These features attempt to break up the culvert into a series of cells and bays, creating resting places along the culverts length and barrier velocity at the baffles or slots created by the baffles (Ead et al. 2002). It is assumed that fish will use their burst speed to get past the velocity barriers, and then use their prolonged speed to travel in the pools along the areas of lower velocity (Rajaratnam et al. 1991).

There are several types of fishways commonly used including an offset baffle system (OB), spoiler system (SPB), side baffles, slotted-weir baffle (SWB), weir baffle system, circular culvert fishways (CFW), Alberta fish weir (AFW), and the Alberta fish baffle (AFB). These fishways can be installed in streams with gradients up to 12 % (Robison et al. 1999). In an OB there is a baffle pointed diagonally upstream on one side of the culvert and a shorter baffle perpendicular to the culvert on the other side making a small slot between the baffles. The SB design has multiple baffles running along the length of the culvert in the direction of the water flow. The baffles are generally spaced at four times the height and are a length of 2.375 times the height. A SWB has a weir spanning the length of the baffle with a small slit in the middle of the weir. This type of baffle can also be made without a slit, causing water to build up behind the baffle and then pass over, creating a large pool (Robison et. al 1999).

Weirs and baffles can be welded to the culvert or attached by bolts. They can be made of a variety of materials including wood, concrete and metal plates (Robison et al.

1999). Flow equations for many of these baffle systems can be found in *Hydraulics of culvert fishways IV: spoiler baffle culvert fishways* by N. Rajaratnam et al. (1991), and also in *Generalized Study of Hydraulics of Culvert Fishways* by S.A. Ead et al. (2002). Flow calculations are based on the height, width and flowrate going through the baffle system.

The advantages of a baffle system are that they require less oversizing than buried culverts and are less expensive than bridges and large open bottomed culverts. Also, baffle systems can be installed in areas where the stream grade is at or near the bedrock. They are generally used on streams with slopes up to 12%, which would generally require a bridge. Although fishways and baffles have been designed to improve fish passage through culverts, there are many problems which have made baffles fall to one of the last options in the design process for fish passage at road crossings. Baffles have a much larger failure rate than oversized culverts and bridges. They are prone to clogging with debris and sediment and can rip out and cause damage to the culvert itself. Also, they can disrupt the boundary layer, which is a layer in the water profile directly above the stream bed with the lowest velocities. Baffles can also impede the ability of juvenile fish to traverse the culvert. It is also difficult to install prefabricated baffles into culverts, because settling can cause the baffles to pop out, and the damage can then cause culvert failure (Robison et al. 1999).

1.2.3 Culverts verses Bridges:

A bridge is defined as a structure spanning the entire width of a stream, which sits on abutments and/or piers (Robison et al. 1999). In multiple state manuals regarding fish passage, bridges are selected as the best design alternative. They change stream habitat and flow regime the least, and bridges are preferred most in regards to natural resource protection. Bridges do not tend to create the same flow problems that culverts do (Fitch 1996). Despite being ecologically friendly, bridges cost as much as three times more to build, and ten times more to maintain than culverts (Fitch 1996). The amount of money budgeted for fish passage problems is limited. Constructing bridges in place of every culvert not meeting fish passage guidelines would greatly limit the amount of work that could be done to combat this problem (Robison et al. 1999). In Oregon and Massachusetts alone there are over 10,000 and 28,500 road crossings, respectively, that affect fish bearing streams (Venner Consulting and Parsons Brinkerhoff 2004). For this reason it is important to come up with a culvert design that is hydrologically feasible.

In choosing between a bridge and a culvert for a specific site it is important to consider the geometry of the stream and other topographical features. Channel slope can play a major role in choosing a culvert or a bridge. Culverts are best used when they can be installed at the slope of the streambed or at less than a 3% slope (Fitch 1996). When the stream gradient ranges from 5-8% ,the cost of the culvert becomes comparable to the cost of a bridge for that stream (Robison 1999). In general bridges become economical as the stream size increases (Robison 1999). In *The Design of Road Culverts for Fish Passage*, Bates (2003) suggests that when a stream width exceeds 6.1m (20ft) or there is frequent movement of large debris, a bridge is the best design alternative. Another source suggests that culverts should only be used on small streams with a channel width of less than 3.05m (10ft), because when the design includes multi-plate structures the cost becomes comparable to a bridge (Robison et al. 1999).

Most research articles and state design manuals list their order of preference for stream crossing options in the same order. Oregon, Washington, Maryland, and Virginia all state that the use of baffles on newly installed culverts should be discouraged, and cement aprons should not be used on culverts (Bates 2003, Fitch 1996, Robison 1999). The Oregon restoration guide has the following design table with advantages and disadvantages for each crossing type, listed in descending order of preference (Table 1.1).

Table 1.1: Stream crossing structural options for fish passage

Type	**Advantage**	**Disadvantage**
Bridge	Best alternative (for minimum ecological impact)	Most Costly alternative
Open Bottom Culvert	Good Alternative if properly sized	Expensive and difficult to install
Sunken and Embedded Culverts	Same slope as stream and same stream characteristics	Difficult to install compared to non-buried culvert
Flat Culverts	Least cost alternative	Difficult to get this passage flat and limited to <0.5% slope
Outlet Backwater Culvert	Low cost alterative (≤4% slope)	Installation of effective, stable weirs for passage can be tricky
Weir/baffle Culverts	Less expensive compared to bridges and open bottom culverts	Have a legacy of failure due to debris and sediment clogging and securing baffles
Fords	Low cost (limited use)	Can only be used for low traffic areas and large gravel apron needed on both sides of stream

Source: Oregon Dept. of Fish and Wildlife (1999)

1.3 Regulations to facilitate AOP at road crossings

1.3.1 Standards and Regulations

There are both Federal and State regulations regarding the building of culverts and their effects on water bodies. In the US Army Corps of Engineers (USACE) document entitled *Final Regional Conditions for Nationwide Permits* effective May 12th 2002 under Section II, number 5, the construction of culverts is discussed. It requires that measures be taken in the installation process to ensure the safe passage of aquatic organisms. For the 20 North Carolina counties under the Coastal Area Management Act (CAMA), culverts must be buried at least 0.3m (1ft) below the stream bed. This is also true for all culverts greater than 1.2m (4ft) in diameter. For culverts with a diameter less than 1.2m (4ft) the invert must be buried to a depth of at least 20 percent of the culvert diameter.

Nationwide Permit (NWP) # 14 (Road Crossings) discusses aquatic life movements in part five of the General Conditions section. It states that

> *No activity may substantially disrupt the necessary life-cycle movements of those species of aquatic life indigenous to the waterbody, including those species that normally migrate through the area, unless the activity's primary purpose is to impound water. Culverts placed in streams must be installed to maintain low flow conditions.* *p3*

Similarly in the North Carolina Division of Water Quality (NC DWQ) General Certification Conditions (GC3375), Section 9 discusses the placement of culverts in streams to allow for low flow passage of fish unless it can be proven to the DWQ that it would be impractical. It also requires the design of road crossings to maintain equilibrium in the stream, causing neither aggration or degration.

Part 11.a under the General Conditions of NWP #14 discusses endangered species. It states that no NWP will be authorized to an activity that could possibly threaten an animal identified under the Federal Endangered Species Act (ESA). This includes altering their habitat in such a way that would disrupt their life-cycle. A detailed report must be given listing species and habitats that may be affected and the degree to which they will be affected. In North Carolina a species of specific concern is the endangered Cape Fear Shiner (*Notropis mekistocholas*). There are also many endangered mussels in the state of North Carolina which travel up and downstream by attaching themselves to fish.

North Carolina's administrative codes for surface waters and wetlands are listed in the "REDBOOK", effective August 1st, 2004. Section 15A NCAC 02B .0231, b.5.d of the code addresses the movement of aquatic fauna in wetland habitats. Endangered species are addressed on the state level in section 15A NCAC 02B .0110. Regulations can be found in their original context in Appendix B.

1.3.2 North Carolina State BMP Manual

The North Carolina Department of Transportation (NCDOT) published a manual entitled *BMP's for Construction and Maintenance Activities* in August of 2003. Section 4.2 in this manual outlines the expectations in the procedures of installing pipes and culverts from the site erosion control to the site cleanup. The following guidelines are listed in this section of the manual regarding AOP through pipes and culverts. The following passages are excerpts from these guidelines.

4.2.7. Install the pipe/culvert per the NCDOT standards and specifications, and any specified permit conditions. Note that the pipes and culverts shall be buried a minimum depth below the existing streambed, as defined below, in order to allow for aquatic organism passage during low flow conditions. Variance may be obtained by the DEO to allow for deviations in pipe burial depths due to bedrock, steep gradients in the stream channel, existing head cutting, potential for drainage of upstream wetlands, or other concerns. *p 28*

4.2.8 Stream pattern dimension and profile shall be maintained by pipe/culvert installation

- *A 4-foot (1.22m) diameter pipe/culvert installed in a 2-foot (0.61m) wide stream may require baffles in order to maintain aquatic organism passage during low flow conditions.*
- *Pipe size should at least match stream width wherever possible, but a 2-foot (0.61m) wide culvert installed on a 4-foot (1.22m) wide stream may also need baffles to reduce velocities.*
- *Two 48 inch (1.22m) pipes installed in a 10-foot (3.05m) wide stream would require that one pipe be installed at a lower elevation, and in alignment with the low flow stream channel elevation so that AOP is maintained during low flow conditions.*
- *The low flow pipe should be aligned with the deepest part of the stream channel, so that flow is maintained during low flow conditions.*

p 29-30

The protocol for NCDOT projects as listed in the manual requires that a species survey must be conducted for each site along with a habitat evaluation. The impacts of the project on habitat must be determined and the future effects on habitat must be as well.

1.3.3 Acquiring Permits

Appendix E of the NCDOT manual is entitled *Environmental Permits and Certifications.* This section focuses on the 404 Nationwide permit, covering topics including maintenance, bank stabilization, temporary construction access, dewatering, and road crossings. The 404 Nationwide permit number 14 covers road crossings. The BMP Manual states that,

> *"This permit authorizes activities for the construction, expansion, modification, or improvement of linear transportation crossings (e.g. highways, railways, trails, etc.) in jurisdictional waters and is subject to specific acreage and linear limits. Authorization for public linear transportation projects in non-tidal waters, excluding non-tidal wetlands adjacent to tidal waters, is provided if the discharge does not cause the loss of greater than ½ acre (0.2 hectare) of jurisdictional waters. Authorization for public linear transportation projects in tidal waters or non-tidal wetlands adjacent to tidal waters is provided if the discharge does not cause the loss of greater than 1/3 acre (0.13 hectare) of jurisdictional waters and the length of fill for the crossing does not exceed 200 linear feet (60.96m)."*

Specific permits for culvert installation can be found at the USACE website: http://www.saw.usace.army.mil/wetlands/Permits.html

The trout waters of western NC and coastal waters of eastern NC require additional and stricter permits. In recent years there has been an increasing difficulty in acquiring the necessary permits to build culverts at road crossings. The permits require that AOP guidelines be met, but there are not any quantitative guidelines to follow to prove that this has been done. As a result bridges have to be built in their place. The guidelines are not species specific and are often adapted from other states guidelines. Virginia's research and guidelines are based on trout species. Their research concluded that the flow velocity should not exceed 1.2 m/s (3.94 ft/s) under normal flow conditions. Also, the minimum depth of flow should be 9 cm (3.54 in), and the maximum outfall height should be 10cm (3.94 in) (Fitch 1996). Yet even Virginia's guidelines are not complete. They lack guidelines for installing bridges or culverts on high gradient streams (Fitch 1996)

The dominant group of fish that has been studied is the salmonids. With most of the research being done in the pacific northwestern part of the United States, the current research and reflects species specific to that region. Also, the majority of research done on the limitations of fish passage has been on anadromous fish. With the majority of North Carolina's waterways providing habitat for nonanadromous fish, it is important to create new guidelines and regulations that reflect their limitations.

1.3.4 Developing Regional Criteria

A *National Inventory and Assessment Procedure* was developed in 2003 by the USFS San Dimas Technology and Development Center. The procedure explained in this manual is intended to be nationally applicable. It develops a consistent method for identifying road crossings that impede AOP in streams which is outlined in Figure 1.1.

When a stream does not resemble a natural channel, it is important to refer to regional screens that define a species' ability to leap into and traverse road crossing structures. These regional screens create a quick and consistent process of determining the degree of impediment for each crossing structure.

To develop a regional screen, a list of species must be selected. "The ideal crossing is one that passes all aquatic organisms and terrestrial species that require stream or streamside zones to move (Clarkin et al. 2003)." In that case, it is important to select species representative of all those in the area. In creating this list it is also important to consult both state and federal regulatory agencies and other interested parties that may have an input on species of concern. After reviewing any available literature on the species listed, species, groups, or life stages which have the greatest limitations in mobility should be selected for the regional screen.

A range of limiting velocities and outfall heights should be developed for each species. These ranges serve as guidelines, and the ranges should be field tested to see what portion of the range should be used for classification purposes.

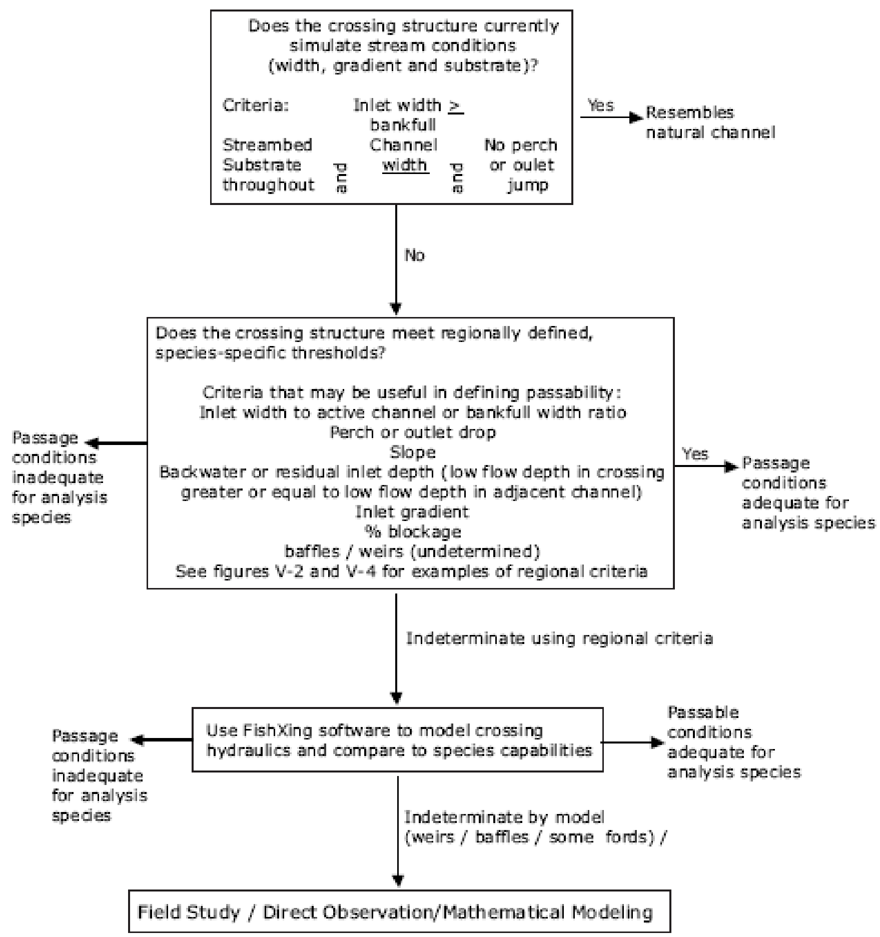


Figure 1.1: Algorithm for identifying road crossings that impede AOP. (Clarkin et al. 2003)

When it cannot be determined whether the road crossing is a barrier or not, the assessment procedure recommends the use of a public domain hydraulic model called FishXing. The model was developed to help engineers and biologists evaluate culvert design based on fish passage. Version 2.2 is available for download at http://www.stream.fs.fed.us/fishxing/ in English and Spanish. Information on data collection to support the program, case studies, and other resources are available at this website. Some of the features of this program as listed on their website are the model:

- *Allows for comparison of multiple culverts designs within a single project.*
- *Calculates hydraulic conditions within circular, box, pipe-arch, open-bottom arch, and embedded culverts.*
- *Contains default swimming abilities for numerous North American fish species.*
- *Contains three different options for defining tailwater elevations.*
- *Calculates water surface profiles through the culvert using gradually varied flow equations, including hydraulic jumps.*
- *Outputs tables and graphs summarizing the water velocities, water depths, outlet conditions, and lists the limiting fish passage conditions for each culvert.*

Figure 1.2 shows an input screen for a culvert being evaluated by the program. It is separated into fish information, culvert information, migration period of concern, and hydraulic criteria. The program will supply the default swimming speed for the species chosen and calculate the water surface profiles based on the flows. A regional screen created for the Piedmont of North Carolina would not only help the assessment procedure of current culverts, but the swimming abilities of local fish could be added to the databank of FishXing for future use.

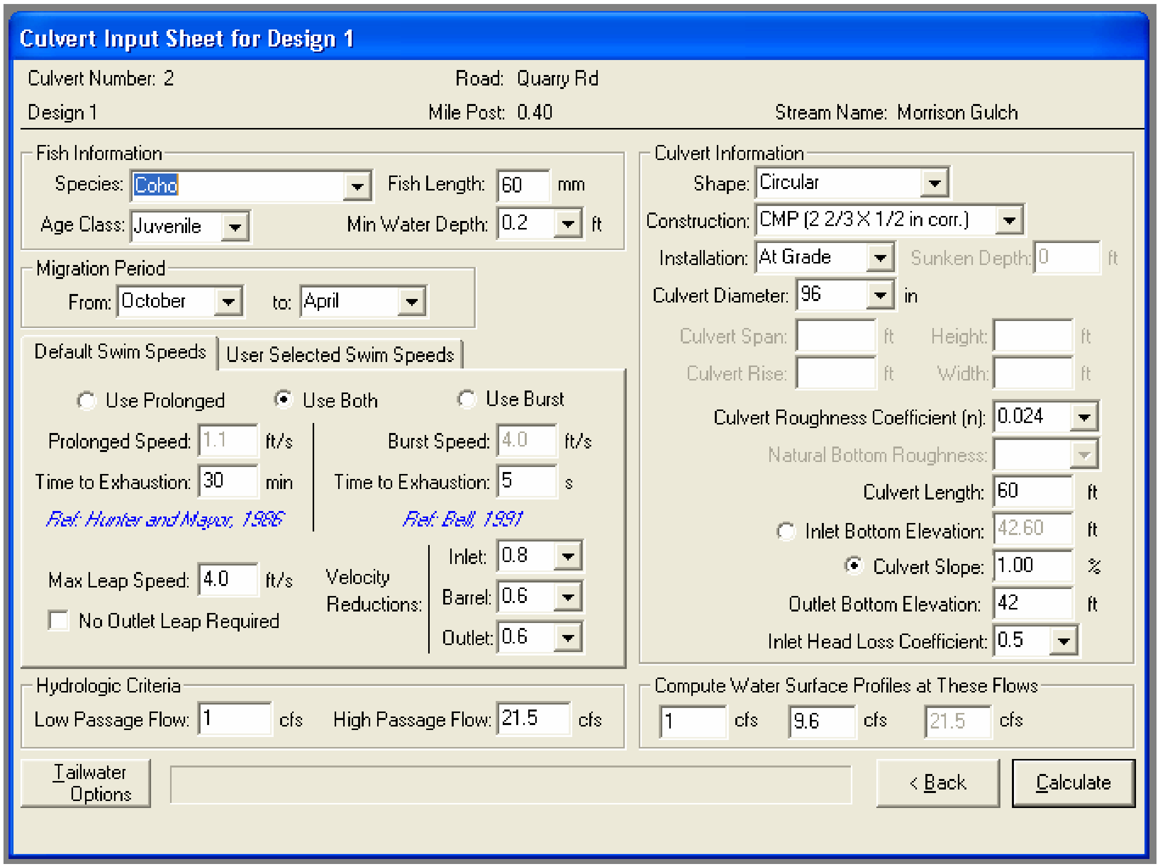


Figure 1.2: Culvert information input sheet in FishXing

1.4 Research in the Pacific Northwest

1.4.1 Rebuilding and protecting the Salmonid population

Washington and Oregon are among the leaders in pursuing proper design of road culverts out of concern for migratory fishes. The salmonid populations are important to the area for both recreational and economic reasons, as well as being part of local history. Both states are among the few in the country to have published manuals or guidebooks on the design of road culverts for fish passage. Washington State's manual was developed as a part of their Aquatic Habitat Guidelines (AHG) Program. This program began in 1999 to help in "the promotion, protection, and restoration of fully functioning marine, freshwater, and riparian habitat through comprehensive and effective management of activities affecting Washington's aquatic and riparian ecosystems (WDFW 2006)." Agencies contributing to the development of the program and manual include the Army Corps of Engineers, the Washington Department of Natural Resources (DNR), Interagency Committee for Outdoor Recreation (IAC), United States Fish and Wildlife Service (USFWS)

Washington State's guidebook entitled *Design of Road Culverts for Fish Passage* published in 2003 outlines three options for the design of road culverts: The no-slope design option, hydraulic design option, and stream simulation design option.

1.4.2 No-Slope Design Option

The no-slope design option is the first choice for a culvert when it is applicable for a site. A no-slope culvert can be installed as a new or a replacement culvert, but cannot be a retrofit. They can be installed when the stream gradient is less than three percent, and passage is needed for all species. This design is the simplest, requiring the least amount of site surveys and engineering calculations. The manual defines a no-slope culvert as follows:

- *"Width equal to or greater than the average channel bed width at the elevation the culvert meets the streambed.*
- *A flat gradient*
- *The downstream invert is countersunk below the channel bed by a minimum of 20% of the culvert diameter or rise.*

- *The upstream invert is countersunk below the channel bed by a maximum of 40% of the culvert diameter or rise*
- *The possibility of upstream headcut has been taken into account, and*
- *There is adequate flood capacity." (Bates 2003)*

With the width equal to or greater than the channel bed, the deposit of bed material and sediment within the culvert is not hindered. After some time a thalweg may form within the culvert. The manual states that the diameter of the culvert must be at least 1.25 times the channel bed width. Although this option may ensure a greater number of species could pass through it is often the most expensive, with culverts being much larger than those designed with the hydraulic design option.

1.4.3. Hydraulic Design Option

The hydraulic design option is based on the properties of open channel flow hydrology. The design is constrained by the swimming abilities of local fish species, and velocities within the culvert are limited to those that can be traversed by the target species chosen. This design option can be used for retrofits, replacements, and new culverts in a stream with a low to moderate gradient.

The first step in a hydraulic design is determining the fish passage requirements. The species and life stages of concern must be identified for the area of culvert installation. The design should be based on the weakest fish of concern. Table 1.2 is taken from the design manual and shows an example of species design criteria based on the length of the culverts. The velocity limitations for each fish are compared to the average velocity within the cross section of the culvert. This estimate is conservative because it does not take into account areas of lower velocity along sides and bottom of the culvert where weaker fish could swim. The hydraulic design must meet velocity requirements at least 90% of the time during fish migration season where anadromous fish are the species of concern.

Table 1.2: Fish passage design criteria from WDFW design manual, 2003.

	Adult Trout >6in (150mm)	Adult Pink or Chum Salmon	Adult Chinook, Coho, Sockeye, or Steelhead
Culvert Length	Maximum Velocity (fps)		
10 - 60 ft	4.0	5.0	6.0
60 - 100 ft	4.0	4.0	5.0
100 - 200 ft	3.0	3.0	4.0
Greater than 200 ft	2.0	2.0	3.0
	Minimum Water Depth (ft)		
	0.8	0.8	1.0
	Maximum Hydraulic Drop in Fishway (ft)		
	0.8	0.8	1.0

The next step is determining the length of the culvert. This is dependent on the velocity requirements for fish. The length of the culvert is related inversely to the velocity that a fish can swim against.

The manual lists four options for hydraulic analysis in this order of preference: stream gauging, continuous-flow simulation model, local regression model, and regional regression model. Design hydrology can be separated into two sections: high fish-passage design flow and low fish-passage design flow. The high fish-passage design flow is the flow exceeded ten percent of the time for each species. The low fish-passage design flow is used to calculate the minimum water depth within the culvert. This design flow is often determined by using the two-year seven-day low flow.

The size, material, and slope of the culvert must then be selected in order to meet the velocity and depth requirements already calculated. The use of Manning's equation (Schwab et. al 1993) is the most commonly used method to calculate the flow rate through the culvert based on the material, slope, and geometry.

$$Q = 1.49AS^{1/2}R^{2/3}/n = VA \tag{1.1}$$

Where
- Q = Discharge, ft^3/s
- S = Slope, ft/ft
- R = Hydraulic Radius, ft
- A = Cross Sectional Area
- n = Roughness Coefficient (Mannings n)

In culvert design, channels can be artificially roughened in order to decrease the velocity changes within the culvert. A study done by Michael Fitch for Virginia in 1996 suggested casting the bottom of culverts to mimic the roughness of stream bottom. Based on Manning's equation there should theoretically be no change in velocity within the culvert if this is done. Washington's manual suggests a mix of rock and sediment to be built into the culvert to achieve channel roughness. This roughness creates various flow patterns which provide both migration paths and rest areas for fish. Very little research has been done on the effectiveness of these artificially roughened channels.

1.4.4 Stream-Simulation Design Option

Chapter six of the manual discusses the stream-simulation design option. In a stream simulation design, the goal is for the bed of the culvert to be formed in such a way that the stream's natural processes are created or maintained. The idea is that "if fish can migrate through the natural channel, they can also migrate through a man-made channel that simulates a stream channel (Bates 2003)." When applying this theory, there is no longer need to consider specific target species and their velocity and depth limitations. This design option can be used for both new and replacement culverts on moderate to high graded streams. The slope ratio must be less than 1.25, and if it is greater the hydraulic design option should be used. The stream simulation option is best applied where ecological connectivity is a critical issue, and passage is needed for all fish species.

Any material can be used for this type of culvert; however, bottomless culverts tend to be the best because the native bed material can remain in place. The size of the culvert should be greater than or equal to the bed width of the stream. The manual gives the following equation for the minimum width of the bed in a given channel:

$$W_{culvert\ bed} = 1.2 * W_{channel} + 2 \qquad \text{(in feet)} \qquad (1.2)$$

The culvert will be filled with material and sediment similar to that which is in other parts of the channel. When designing a culvert bed for a stream in equilibrium, the streambed itself can be used as a reference for design. If the channel is aggrading or degrading then a reference reach should be used for the design. The two suggested methods to use in bed design are the Unit-Discharge method, and the Paleohydraulic Analysis method. Both of these methods will aid in the development of the sediment mix by calculating average particle sizes.

1.5 Passive and active methods of finding physical limitations of fish

1.5.1 Passive and Active Methods

There are two methods for determining the physical limitations of fish. The passive method for studying fish passage and movement makes use of mark and recapture studies. In such studies a group of fish is captured downstream of the culvert.

These fish are then tagged or marked in some way as to identify them later. After a set time, fish are then recollected upstream of the culvert. The flow conditions during the set time period are recorded along with the number, size, and species of fish that were able to pass through the culvert. This test gives some idea as to what flow conditions fish are able to pass through.

Active methods for testing fish limitations require a laboratory set up, where fish are inserted into a current, and their behavior is recorded as the current increases. Active studies offer more precision for the physical measurement of individuals and ensure that every individual is accounted for. Active studies are more intensive and time consuming.

There are three types of speed that have been defined by biologists to describe the swimming behavior of fish: prolonged speed, sustained speed, and burst speed. Studies often focus on one or more of these speeds. Prolonged swimming speed encompasses those velocities which can be maintained for periods of 20 seconds to 200 minutes, but eventually cause fatigue in the fish. Sustained swimming speed is defined as a speed maintainable for longer than 200 minutes without inducing muscular damage (Winger et al. 2000). Aerobic metabolism is used by the body during sustained speed in order to fuel red muscle fibers (Peake et al. 2000). Burst speed is used for periods less than 15-20 seconds, and is fueled by an anaerobic process utilizing the white muscle fibers in fish (Peake 2000). Burst speeds are often used to traverse short distances very quickly.

Defining the critical velocity of a fish is often the goal of both passive and active studies. The critical velocity is “the maximum sustained speed a fish can maintain for 10 minutes which is considered comparable to the passage velocity of fish through long culverts up to 328 ft (100m) (Clancy and Reichmuth 1990)." A 100m culvert is used as the average length of a long culvert.

1.5.2 Mark Recapture Studies

In an experiment performed in Arkansas by Melvin Warren Jr. and Mitzi Pardew in 1998, nine culverts were studied to analyze their impact as barriers to small-stream fish movement. Four specific culvert designs were selected: fords, open box bridges, cylindrical culverts, and a solid concrete slab. The goals of the study were to determine if velocity and water depth in the culvert affected fish movement, if fish movement varied among the four culvert types, and if the type of culvert had any relation to species diversity. The average water velocity in the culvert, the water depth, and the length of the structure was recorded for each culvert. Fish were captured, marked, and then released downstream of the culverts. An average of 302 fish were marked per site in the spring, and 424 in the summer. Of the fish marked, 26 species and 8 families were represented. On average, 18% of the fish were recaptured in the spring and 21% in the summer.

The results of the study showed the highest rate of fish crossing through the natural reaches as well as the fords. There was little difference in migration between the fords and open box structures. No fish were able to navigate the concrete slab, and the cylindrical culverts proved to be a significant barrier to fish movement. Warren and Pardew (1996) reported that "culvert and slab crossings reduced overall fish movement, diversity of movement, and movement of fish families relative to natural reaches." The change in hydrology through the culvert was proportional to the severity of the resulting barrier. As a result of the study, a maximum velocity of 30-40cm/s (1-1.3 ft/s) is the recommended design standard for a 100m culvert.

A study done by David A Belford and William R. Gould in 1989 examined the passage of four trout species through six different round, corrugated-metal culverts in Bozeman, Montana. In the study fish were caught by trapping and electrofishing and forced to move upstream through culverts by barriers placed on the downstream end of a culvert. Velocities and water depths were recorded for each culvert, along with diameters and culvert slopes. Fish that traveled through the culvert were caught upstream and their body length, weight, and sex were recorded. Non-linear regression relationships were formed for each species in relation to combinations of bottom velocity and culvert length. Results were very similar for all four trout species, and design suggestions can be given based on the regression relationships for rainbow trout. This relationship shows that for culvert lengths up to 10m (32.8 ft) fish could navigate bottom velocities up to 0.96 m/s (3.15 ft/s). As the length of the culvert increases, the maximum velocity the fish can navigate decreases. Based on the relationship, a maximum velocity for a 100m (328 ft) culvert is 0.67m/s (2.2 ft/s).

1.5.3 Research on Active Methods

In an experiment performed by D. R. Jones, J.W. Kiceniuk, and O. S. Bamford in 1974, the critical speed of 17 species native to the Mackenzie River system was evaluated. Five of these species including the burbot, broad whitefish, mountain whitefish, Arctic char, and Arctic cisco were examined in the laboratory. After collection and delivery to the laboratory, the fish were deprived of food for 24 hours before they were used in the experiment. During the experiment fish were placed in an 8.9 cm-diameter (0.29ft) tube which utilized a closed circuit respirometer. The fish were allowed an initial settling period of 10 minutes before the current flowing through the tube was increased in 10 minute increments. The velocity was increased until the fish became exhausted, in which case the last ten minute period the fish completed was considered the critical velocity. A fatigue test was also performed, where the fish were placed in the tube and after a period of one hour at the resting velocity of 10cm/s (0.33 ft/s) the velocity was increased to 60-90% of the critical velocity. The velocity was then kept constant and the time to fatigue was recorded, with the maximum time of 100min.

The results showed a significant correlation between the body length of fish and their critical velocity in six of the species. The values for critical velocity ranged from 42.5 – 100.2 cm/s (1.39-3.29 ft/s). The fatigue tests did not show a significant correlation between swimming speed and the time to fatigue. For the longnose sucker, burbot, and pike the highest maintainable speed was 60% of the critical velocity, and for the char and grayling it was 80%.

Another experiment was performed by S. Peake, R. S. McKinley, and D. A. Scruton in 2000 to measure the swimming performance of a wild population of walleye (*Stizostedion vitreum*). The results were then used to predict water velocities that allow fish passage through culverts. Fish were collected and held in an outdoor tank before use. The fish were deprived of food for at least 48 hours before use in the experiment. A Blazka respirometer was used for the study. Fish were placed in the device and allowed to acclimate for a period of four hours at 0.10cm/s (0.003 ft/s). Velocity was then increased by 0.10cm/s (0.003 ft/s) every hour until fatigue occurred. The walleye were considered to be exhausted when they were pinned to the back screen for longer than five seconds. The results of the test were used to estimate the critical velocity. The following equation was developed to illustrate the linear relationship between sustained swimming ability and fork length and can be used to estimate maximum sustained velocities for walleye's 0.18-0.66 m (0.59-2.17 ft) long at temperatures from 5.8-20.5 ºC (42.44-68.9 ºF)

$$Ucrit_{60}\ (m/s) = 0.124 + 0.68\ \text{fork length (m)} + 0.0052\ \text{Temperature (ºC)} \qquad (1.3)$$

It was found that the critical velocities were only slightly higher than $Ucrit_{60}$ found in the above equation. An equation for prolonged performance was also developed from the study. It shows that prolonged speed also increases linearly with fork length, and water temperature. This equation can be used for walleye's 0.18-0.67 m (0.59-2.2 ft) long at temperatures from 6.0- 19.0 ºC (42.8-66.2 ºF)

$$Ucrit_{10}\ (m/s) = 0.263 + 0.72\ \text{fork length (m)} + 0.0120\ \text{Temperature (ºC)} \qquad (1.4)$$

The Active methods experiments had many procedures in common. The fish were generally deprived of food for at least 24 hours. (Peake et al. 2000, Jones et al. 1974, Winger et al. 2000) This ensured that they were in a post-absorptive state. The fish were given a minimum time of five minutes to acclimate to the current (Peake et al. 2000, Jones et al. 1974, Toepfer et al. 1999). Also, the flow was increased in steps, generally around 0.10m/s (0.33 ft/s) (Peake et al. 2000). Mesh was often put at the entrance and exit of the flume. The entrance mesh would regulate turbulent flow, and the exit mesh would catch fish that became exhausted (Toepfer et al. 1999, Whoriskey and Wootton

1986). A variety of methods were used to encourage fish to swim if they fell back on the mesh. Some were prodded with a glass rod (Whoriskey and Wootton1986), while other used electrodes placed at the end of the flume (Winger et al. 2000).

1.6 Selecting fish species for the experiment

1.6.1 Choosing fish species

The first step in choosing the species for developing a regional screen is to select the geographic region of concern. In this project the piedmont of North Carolina was selected. Fish abundance charts found in Edward Menhinick's The Freshwater Fishes of North Carolina were used to select a basic list of species to choose from. Species that were the most abundant were placed on the list. The North Carolina Division of Water Quality (NC DWQ) then provided a list of possible species (Table 1.3), highlighting those of specific concern to them. The NC Wildlife Resource Commission (NC WRC) suggested studying a shiner similar to the Cape Fear shiner, the Redbreast sunfish, and the Carolina darter. The goal was to find species of a variety of morphologies to discover the differences in their performance. A final list of species was chosen based on the input received by the regulatory commissions, the species abundance charts for the North Carolina Piedmont, and the ease the NC DWQ had in collecting certain species in streams local to Raleigh, NC.

Table 1.3: List of possible species for the experiment provided by the NC DWQ

	Species
1	Redfin pickerel
2	Roseyside dace
3	Highback chub
4	Bluehead chub
5	Creek chub
6	Creek chubsucker
7	Satinfin shiner
8	Spottail shiner
9	Redlip shiner
10	Greenhead shiner
11	Whitemouth shiner
12	Swallowtail Shiner
13	White shiner
14	Crescent shiner
15	Highfin shiner
16	Rosefin shiner
17	Pinewoods shiner
18	Sandbar shiner
19	Striped jumprock
20	Blacktip jumprock
21	Margined madtom
22	Pirate perch
23	Speckled killfish
24	Redbreast sunfish
25	Green sunfish
26	Warmouth
27	Pumpkinseed sunfish
28	Fantail darter
29	Johnny darter
30	Tessellated darter
31	Carolina darter
32	Piedmont darter
33	Chainback darter

1.6.2 Selected Species

Six species were chosen for this experiment to aid in the development of a regional screen: the Bluehead Chub (*Nocomis leptocephalus*), Redbreast Sunfish (*Lepomis auritus*), Johnny Darter (*Etheostoma nigrum*), Bluegill (*Lepomis macrochirus*), Margined Madtom (*Noturus insignis*), and the Swallowtail Shiner (*Notropisprocne*).

The Bluehead Chub, shown in Figure 1.3, is in the cyprinidae family. It was chosen to represent chubs for the experiment. The Virginia Tech College of Natural Resources Virtual Aquarium describes it as having a stocky body, and very large head tubercles on breeding males. It has a subterminal mouth, pointed snout, and small to medium eye. The sides of the body are an olive green color, and the dorsal and tail fins are orange to orange red. Only the breeding males have a blue head. An average adult is 70-160 mm (0.2-0.52 ft). They generally live in cool rocky streams, and are often pool dwellers. They feed on insects and plants

Source: http://faculty.virginia.edu/vcafs/education.html
Figure 1.3: Bluehead Chub

The Redbreast Sunfish (Figure 1.4) is in the centrarchidae family. It was chosen for its importance to the NC DWQ and NC WRC. It is also a species easy to collect. The Virtual Aquarium describes it as having a very deep compressed body. The earflap is dark and very long. The mouth is medium and terminal, and the eye is quite large. The males can have a bright red belly, and often blue iridescent markings can be found on the snout. Orange and yellow-orange spots can be found on the bars. The caudal fins are rounded out to a point, and the pectoral fin is also rounded. The average adult body length is 90-185 mm (0.3-0.61 ft). The Redbreast is found in warm streams of low gradients, often in the pools and along the edges of the stream. They feed on insects, crayfish, and other arthropods. Often they are fished recreationally for food.

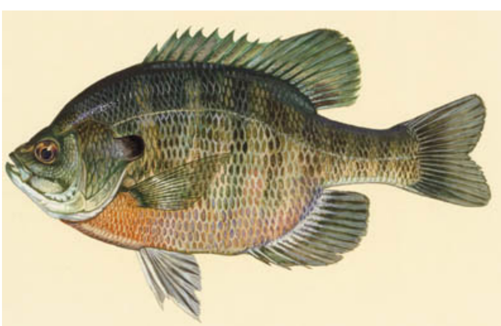
Source: http://www.cnr.vt.edu/efish/families/redbreastsun.html

Figure 1.4: Redbreast Sunfish

The Johnny Darter, shown in Figure 1.5, is in the percidae family, with large pectoral fins, high dorsal fins, and a rounded tail fin. Both the dorsal and tail fins are translucent with dark speckles. The body is long and slender, with the eyes being nearly at the top of the head. The mouth is terminal and the nose is blunt. There are diamond shaped black spots running the length of the body. The body is tan with a gold-green iridescence. The average length of an adult Johnny is 30-40 mm (0.1-0.13 ft). Its habitat is in warm streams over either gravel, sand or silt. It can be found in small riffles, pools, and runs. It eats insects and other invertebrates. The Johnny is tolerant of pollution, and serves as prey to many important game fish.

Source: http://www.agriculture.purdue.edu/fnr/afs/puafsx.html
Figure 1.5: Johnny Darter

The Bluegill, shown in Figure 1.6, is another member of the centrarchidae family. The Virtual Aquarium describes it as having a very deep and compressed body with a small terminal mouth. It has a dark earflap that is smaller than that of the Redbreast. There is a dark spot near the rear of the second dorsal fin which aids in the identification of the Bluegill. The blue/blue-green sides have dark vertical bars running down them. The average body size for adults is 80-220 mm (0.26-0.72 ft). The Bluegill resides in pools of low to moderate gradient streams. It feeds on small aquatic terrestrial insects and plants. This fish is a popular sport fish.



Source: http://aged.ces.uga.edu/2004cds/cd1/Hot_Potatoes/Fish_Identification/Natural_Resources_Fish_ID.htm
Figure 1.6: Bluegill

The Margined Madtom is in the ictaluridae family. As shown in Figure 1.7, it looks like a small catfish. The Virtual Aquarium describes the body as being mildly elongated and compressed posteriorly, with a straight pectoral spine. The head is broad and depressed, with an inferior mouth. There are white barbels around the mouth, and brown ones elsewhere. Some of the fins have dark markings on the tips. The pectoral fins and spine can be sharp to the touch. The average body length of adults is 80-120mm (0.26-0.39 ft). The Margined Madtom resides in water bodies from large creeks to large rivers of low to moderate gradient. The majority of their diet is insect larvae, however they are also known to eat small fish and terrestrial insects. The spotted species, similar to the Margined Madtom, is endangered.

Source: http://www.cnr.vt.edu/efish/families/marmadtom.html

Figure 1.7: Margined Madtom

The Swallowtail Shiner, shown in Figure 8, is in the Cyprinidae family. The Virtual Aquarium describes it as having a slender elongated body, with a subterminal or slightly inferior mouth, and a slightly pointed or rounded snout. The dorsal fin begins along the back have of the pelvic fin base. The Swallowtail is a pale yellow color and has a darker blue stripe running the length of its side. The fins are somewhat yellow in color, and there is a small black spot at the base of the tail fin. The average length of adults is 40-55 mm (0.13-0.18 ft). It prefers pools of warm creeks and rivers, and feeds on insects, worms, mites, microcrustaceans, and algae. This species was chosen based on its similarity to the endangered Cape Fear Shiner, which is of great importance to regulatory agencies in North Carolina.

Source: http://www.cnr.vt.edu/efish/families/swallowtail2.html
Figure 1.8: Swallowtail Shiner

2.0 Materials and Methods

2.1 Collection of Fish

Fish were collected from local streams at least 15 hours in advance of using them for testing purposes. With a team of two to three people, the fish were collected by electrofishing using a model 12-A POW electrofisher from Smith-Root, Inc. Two sites along Crabtree Creek in Raleigh, NC, were used for collection. One site is located beside Crabtree Valley Mall and another near Crabtree Lake. The third site used for collection was Rocky Branch, near the intersection of Western Blvd. and Hunt Dr. in Raleigh, NC. Approximate longitudinal and latitudinal coordinates are as follows:

Crabtree Creek (near Crabtree Valley Mall)	35º 50’ 12” N,	78º 40’ 29.9” W
Crabtree Creek (near Crabtree Lake)	35º 50’ 16” N,	78º 46’ 50.8” W
Rocky Branch	35º 46’ 32” N,	78º 39’ 33.8” W

After the fish were collected they were transported in a 37.85 Liter (10 Gallon) Coleman Advantage cooler. A portable air pump named the “Bubble Box” by Marine Metal Products was used to provide oxygen to the cooler during transfer to the project site. After collecting the fish, the larger species including the Bluehead Chub, Redbreast Sunfish, and Bluegill were stored and allowed to rest overnight in a 0.61 m x 0.61 m (2 ft x 2 ft) Team Numark Bait Cage floating in the secondary pond. The smaller fish, including the Swallowtail Shiner, Margined Madtom, and Johnny Darter were stored in the cooler with the bubbler providing oxygen.

2.2 Project Site

The data collection site was located on the Lake Wheeler Road Field Laboratory operated by North Carolina State University south of Raleigh, NC. The primary pond for the site is shown in Figure 2.1. From the primary pond, water is pumped to a smaller secondary pond used for flume studies. Water is then pumped from the secondary pond using a 0.11 cm^3/s (4 ft^3/s) gravity flow pump into the flume. The pump could be controlled electrically by a Cutler-Hammer general duty safety switch and manually with a screw valve. For the purposes of this experiment both methods were used in order to achieve the necessary flow rates.

Figure 2.1: Lake Wheeler road field laboratory showing primary pond

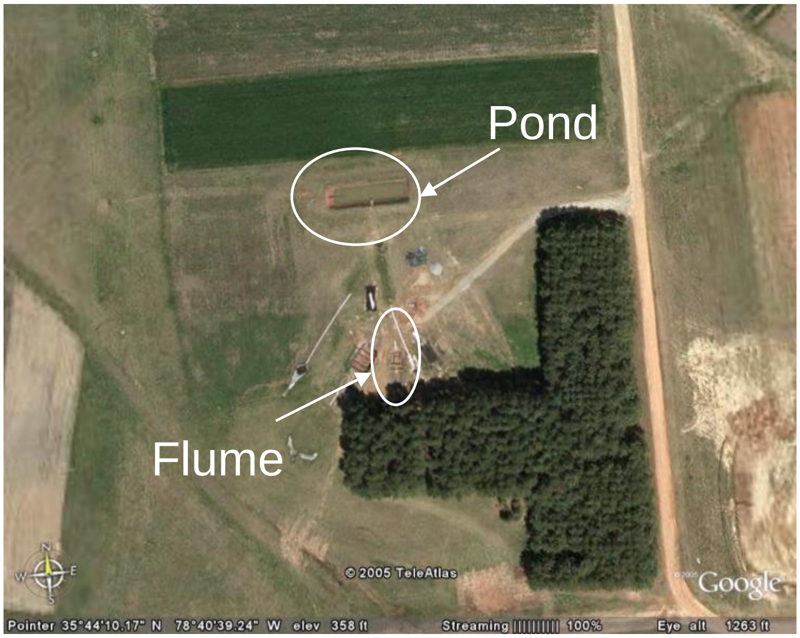


Figure 2.2: Worksite showing secondary pond and flume

2.3 Flume Design

The experiment utilized a flume as a means for testing the fishes' critical velocity. The flume is located in a basin formerly used for sediment studies south of the secondary pond shown in Figure 2.2. One side of the flume rested at the edge of the sediment basin, while the other end of the flume was in the middle of the basin resting on concrete blocks. It was surveyed and set at a zero percent slope. The flume, shown in Figures 2.3 and 2.4, is 4.9m (16 ft) in length and 0.41m (1.35 ft) in width. The flume walls are 0.61m (2 ft) in height. The basic structure of the flume is constructed of lumber with plywood walls and floor. Connected alongside the flume is a walkway to use while the test is being run. A mesh lining covers the end of the flume located in the basin to catch the fish when they have reached their critical velocity and become exhausted. A series of two triangular wire mesh filters were used to normalize the initial turbulent flow coming from the inlet pipe. The walls and floor of the flume were painted white in order to better see the fish. A synthetic fabric connected the inlet pipe to the flume in order to prevent water from flowing out of the back of the flume. Additional photographs and figures can be found in Appendix A.

During the test, water flowed out of the back of the flume and into the basin. As the basin filled a Honda 4.0 GX 120 Hypro gasoline driven, self priming centrifugal pump (model 1572-SPX) was used to pump water from the basin. A small 5.08 cm (2 in.) pipe drained water from the bottom of the pond. Also a section was cut from a wooden gate at the back of the basin, so that when water rises to a higher level it spills out of the back of the basin into a constructed waterway leading towards the woods shown in Figure 2.5.

The flume was calibrated using predicted flowrate calculations for the site and measuring devices to ensure that the flow meter was indicating the proper velocity. A series of test runs were preformed with the flume prior to the experiment in order to become efficient in the experimental process before adding the fish.

Figure 2.3: Side view of flume

Figure 2.4: Front/Top view of flume

Figure 2.5: The pipe leading to the woods carries the drained water, while the channel carries the water exiting through the section cut from the wooden gate.

In this experiment the depth of water in the flume did not remain constant. In order for the depth to remain constant with the increasing flowrates the slope of the flume would have to increase as well. Test runs were performed for each scenario, one with constant depth, and one with constant slope. It was decided to perform the experiment at a constant slope of nearly zero percent. This experiment mimics a culvert placed at grade in a stream. The increasing depth of water with increasing flowrate would then mimic what occurs in nature with storms of increasing intensities. As a result of choosing this experimental setup, water velocity in the flume varies with depth. The velocity readings were taken at 60% of the water depth in the flume. This depth is accepted as the average velocity.

2.3.1Flowmeter and other equipment

The current meter used in the experiment was produced by the Rickly Hydrological Company. The model description below is taken from their website: http://www.rickly.com/sgi/pygmy.htm

"*USGS Pygmy-MH Meter-Model 6225*

The USGS Pygmy-MH meter is a magnetic head current meter with the same basic design as the standard Pygmy meter with the exception of shaft and binding post contact. The Pygmy-MH has a miniature reed switch and magnetic shaft which allows for reduced friction for better low velocity response and produces a cleaner signal for the AquaCalc 5000 and AquaCount. The meter uses the standard Pygmy rating table."

2.4 Experimental Design

Experiments were conducted eight times over a 62 day period between September and November, 2005. No fish was used twice, and none was kept longer than 15 hours before use. Each experiment run included a mix of the six test species. The data set for each species was comprised of individuals tested on different days and, when possible, different streams. A minimum of 20 individuals were tested for each species.

The experiment began by running water through the flume at a rate of 0.2m/s (0.66 ft/s). This is considered the resting velocity for all species. Fish were put into the flume at this flowrate and given a minimum of ten minutes to acclimate to the surroundings. By the end of the ten minutes, the fish are facing the current and swimming against it, towards the flume inlet. If a fish was flat against the mesh at the outlet of the flume by the end of the acclimation period it was considered to be exhausted and not used as part of the experiment.

After ten minutes the velocity was increased by approximately 0.1 m/s (0.33 ft/s). After this ten minute period the velocity was lowered back to the resting velocity for five minutes. After the rest, the velocity was increased by approximately 0.1 m/s (Figure 2.6) from the last ten minute test period, followed again by a five minute rest. The velocity was increased in this manner until it either reached the maximum velocity the pump could provide, or all of the fish were exhausted.

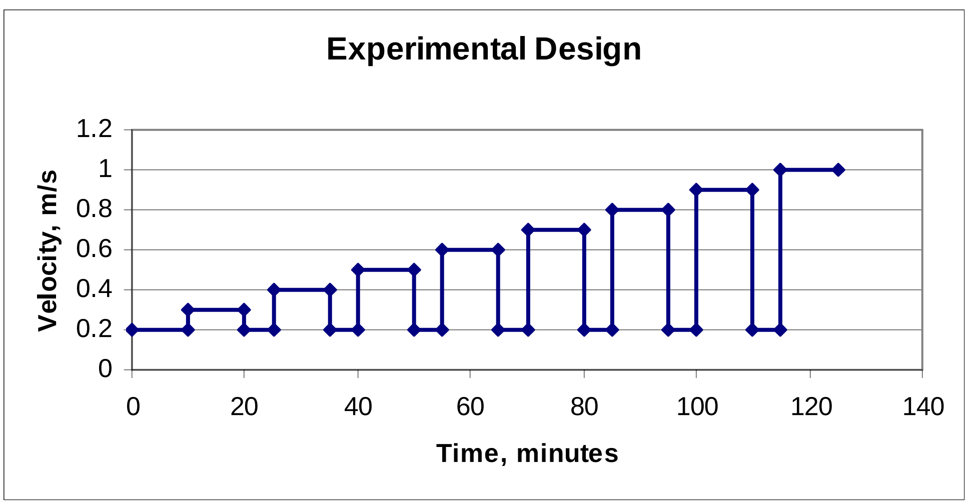


Figure 2.6: Experimental design of velocity changing with time from beginning to end of test

A fish was considered to be exhausted when it was pushed up against the mesh at the outlet of the pipe. If it did not start swimming after a gentle prod with a hand it was removed from the flume. The species, body length, and the velocity at which it became exhausted were recorded for each individual. A ruler connected to a flat board was used as a measuring device, as shown in Figure 2.7. The critical velocity of the fish was considered to be the greatest velocity which it could swim against for a period of ten minutes. Using this definition, the critical velocity assigned to each fish is the velocity for the last ten minute period it successfully completed and not the velocity at which it became exhausted.

Figure 2.7: Measuring the total length of a Bluegill from the tip of the snout to the end of the caudal fin.

3.0 Results

3.1 Hypotheses

1. The null hypothesis is that there is no difference in critical velocities between species tested in this experiment.

2. The secondary hypothesis is that the velocity ranges within each species will be dependent on the length of the individual fish.

3.2 Data Summary

The data for this experiment were analyzed using SAS® 9.1.3 statistical software. There were a total of 202 observations over the six species of fish. The number of observations and the mean critical velocity for each species can be found in Table 3.1. The Bluehead Chub had the highest critical velocity at 85.55 cm/s (2.81 ft/s), and the Bluegill had the lowest critical velocity at 37.05 cm/s (1.22 ft/s). The overall mean for the 202 observations was 53.57 cm/s (1.76 ft/s).

Table 3.1: Summary of mean critical velocities for each species in cm/s. Statistical data for Margined Madtom is not based on a normalized data set and should not be used as basis for design. Means for Johnny Darter and Bluehead Chub do not reflect true means, because the maximum flows tested for each species were 70 cm/s (2.3 ft/s) and 100cm/s (3.3 ft/s) respectively.

Species		Individuals Tested	Mean Critical Velocity cm/s
Overall Mean		**202**	**53.57**
Bluegill		61	37.05
Bluehead	chub	33	85.56
Johnny	darter	21	67.76
Margined	madtom	9	48.67
Redbreast	sunfish	52	43.89
Swallowtail	shiner	26	61.42

3.2.1 Bluehead Chub

The behavior of the Bluehead Chub in the flume was very consistent. The chubs adjusted to the flume environment quickly, and were easy to work with during the test. The individuals tended to swim along the bottom of the flume remaining in one place during the entire experiment. About half of them would stay at the back of the flume a few inches in front of the net, while the rest would hover near the entrance of the flume. The individuals were tested on four different days, and were collected from both Crabtree Creek and Rocky Branch in Raleigh, NC.

There were 33 individual Bluehead Chubs tested in this experiment. The body lengths ranged from 55mm to 155mm (2.17 in. to 6.1 in.). The mean critical velocity found was 85.55 cm/s (2.81 ft/s) with a standard deviation of 23.3 cm/s (0.76ft/s). The minimum critical velocity for an individual was 20cm/s (0.66 ft/s), and the highest was 100 cm/s (3.28 ft/s). During the testing of the Bluehead Chub the maximum velocity that the flume could obtain was 100cm/s. Therefore the critical velocity for the Bluehead Chub may be greater than this. As seen in Figure 3.1, the majority of the data points are at 100 cm/s (3.28ft/s) despite changes in body length, which suggests there is little effect of body length on critical velocity. However, linear the linear regression discussed in Section 3.3 proves otherwise.

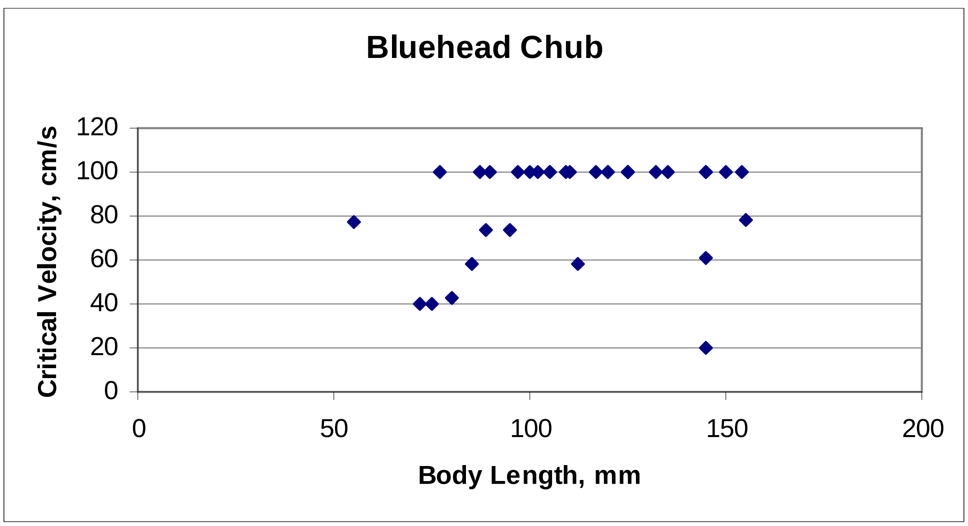


Figure 3.1: Critical velocity related to body length for the Bluehead Chub. Values shown as 100 cm/s represent the maximum velocity tested in the experiment.

3.2.2 Readbreast Sunfish

The Readbreast Sunfish, along with the Bluegill, was one of the easiest species to collect. They were prolific in the region and were found along the stream banks at all of the collection sites. A total of 52 individuals were tested, originating from all of the collection sites. Experiments for the Readbreast Sunfish were run on seven different days. The species as a whole performed fairly well in the experiment. However, there were a number of juveniles that did not recover well from the electrofishing and either died, or were too tired to withstand the resting velocity in the flume. These fish were not used for testing.

Of the 52 individuals tested the body lengths ranged from 31 - 155cm (1.22 - 6.1 in.). The critical velocities ranged from 20 - 100cm/s (0.66 - 3.28 ft/s). The average critical velocity was 43.87 cm/s (1.44 ft/s) with a standard deviation of 17.81 cm/s (0.58 ft/s). The data collected for the Readbreast Sunfish, shown below in Figure 3.2, seems to indicate a mild interaction between body length and critical velocity.

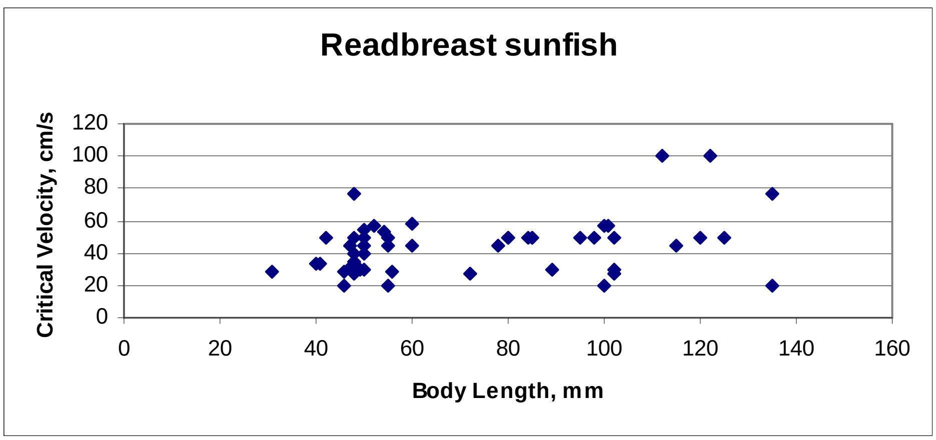


Figure 3.2: Critical velocity related to body length for the Readbreast Sunfish

3.2.3 Johnny Darter

The Johnny Darter was difficult to collect. In addition to their speed, they were much harder to see than the other species, with their brown and black coloring blending into the stream's substrate. The most efficient way to collect them was to electroshock upstream of a riffle and net them as they floated downstream. The darters performed very well in the flume experiment. They were the most active of any species. Unlike most species, they would swim up and down the length of the flume during the experiment. They would also swim vertically in the water column, playing in areas with the greatest flow rate. During the resting periods they would dart all over the flume as individuals or in small groups.

Tests were run on four different days for the Johnny Darter, and all individuals were collected in Crabtree Creek. A total of 21 individuals were tested with body lengths ranging from 40 - 78mm (1.57 – 3.07 in.) and the average critical velocity was 67.76 cm/s (2.22 ft/s) with a standard deviation of 6.61 cm/s (0.22 ft/s). The minimum critical velocity was 43 cm/s (1.41 ft/s) and the maximum was 70 cm/s (2.30 ft/s). Maximum flows that could be achieved in the flume were not the same during each test due variations in head created by the water level in the secondary pond. On the days that the Johnny Darter was tested the maximum velocity the flume could obtain was 70 cm/s (2.30 ft/s), so the critical velocity of this species may be greater than that which was tested. The relationship between critical velocity and body length for the Johnny Darter is shown in Figure 3.3 below.

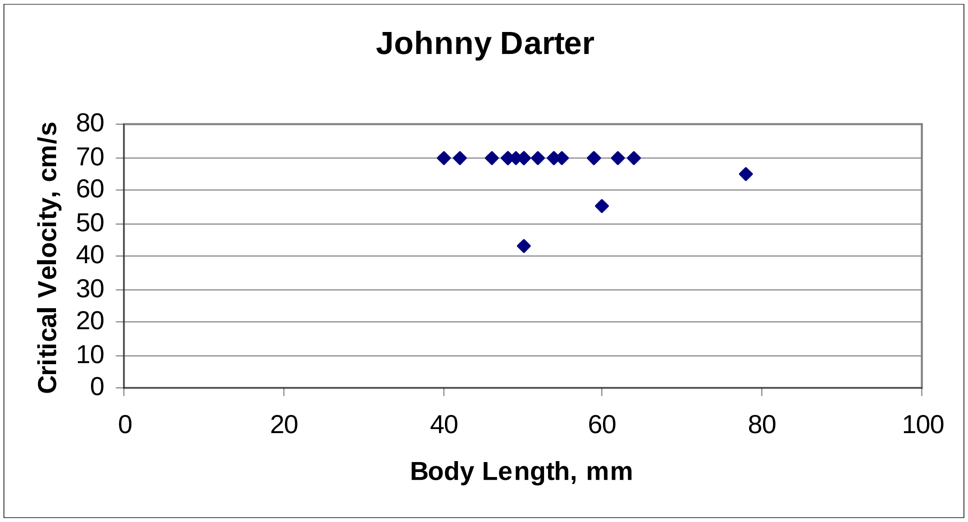


Figure 3.3: Critical velocity related to body length for the Johnny Darter, where 70cm/s represents the maximum velocity used for testing in the experiment.

3.2.4 Bluegill

The Bluegill performed similarly to the Readbreast Sunfish in the experiment. They were also very easy to obtain and test and were found in all streams used for collection. The same problems occurred with some of the juveniles as with the Readbreast Sunfish. A total of 61 individuals were tested over six different days. The Bluegill had the largest range of body lengths within a species, with a minimum of 25 mm (1 in.) and a maximum of 210mm (8.27 in.). The average critical velocity was 37.05 cm/s (1.22 ft/s) with a standard deviation of 16.71 cm/s (0.55 cm/s). The critical velocities ranged from 20 - 77 cm/s (0.66 - 2.53 ft/s). As seen in Figure 3.4, the relationship between body length and critical velocity is much stronger with the Bluegill than with the species previously discussed. The linear regression for this species is discussed in Section 3.3.

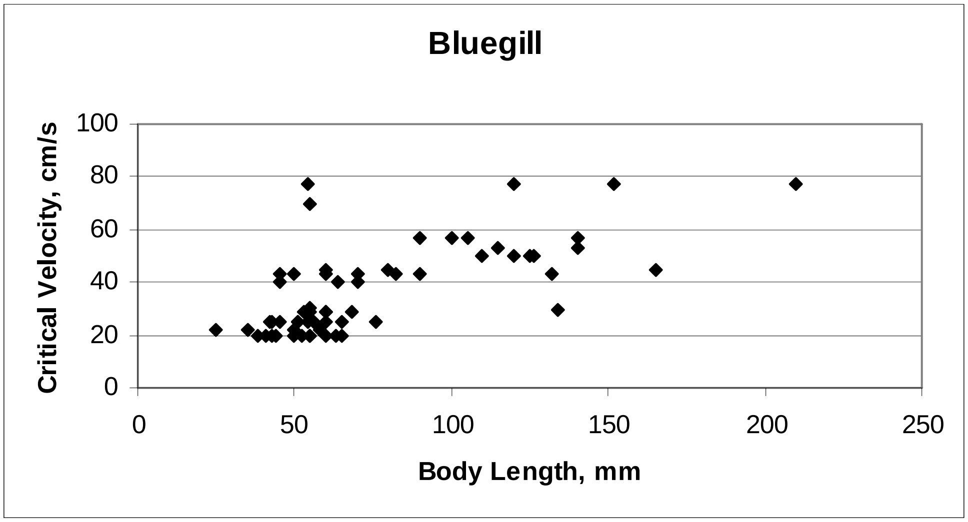


Figure 3.4: Critical velocity related to body length for the Bluegill.

3.2.5 Swallowtail Shiner

The Swallowtail Shiner was fairly easy to collect because the species swam in schools. Multiple individuals from a school could be collected in one shock. The Swallowtail had the most mortalities associated with electrofishing. Often half of the individuals collected would not survive to be tested the next day. When placed in the flumes, the Swallowtails would group together forming small schools within the flume. They tended to swim in the bottom half of the vertical water column. Individuals tended to swim halfway down the flume, in between the wire grid at the entrance to the flume and the mesh at the exit.

There were a total of 26 individuals tested over three days. All individuals were collected from Crabtree Creek in Raleigh, NC. The body lengths ranged from 40 – 72 mm (1.57 – 2.83 in.). The average critical velocity was 61.42 cm/s (2.02 ft/s) with a standard deviation of 14.8 cm/s (0.49 ft/s). The critical velocities ranged from 25 –

70cm/s (0.82 – 2.3 ft/s). As shown in Figure 3.5 below, the majority of individuals became exhausted at 70cm/s (2.3 ft/s). In this test the species was not limited by the maximum flow produced by the flume. All fish did in fact reach their critical velocities and become exhausted

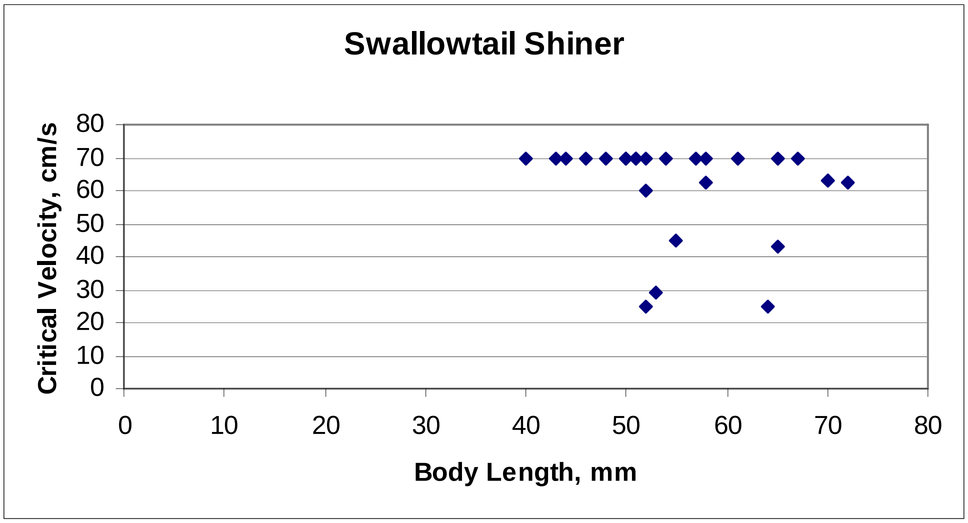


Figure 3.5: Critical velocity related to body length for the Swallowtail Shiner.

3.2.6 Margined Madtom

The Margined Madtom was the hardest species to collect. They burrowed themselves in the muck and leaves along the banks of the stream. They were hard to spot when shocked because they did not float to the surface. The Margined Madtom behaved poorly in the flume experiment. The individuals would either swim between a larger fish and the bottom of the flume, or they would swim through the wire mesh barriers to a pool that had formed underneath the pipe. They could not be forced to stay in the area of constant flow within the flume. Nearly 20 individuals were tested, but critical velocities were only found for nine of them. As a result the data set is not a normalized sample of the population. Some individuals lasted the entire experiment, but it is unknown whether they hid in the pool beneath the pipe or actually swam against the flow the entire time. The Margined Madtom is a nocturnal fish, which may explain the individual's behavior in the experiment. Testing this species at night may produce entirely different results in behavior and swimming ability.

The body lengths of the nine individuals ranged from 60-90mm (2.36 – 3.54 in.). The average velocity was 48.67 cm/s (1.6 ft/s) with a standard deviation of 19.38 cm/s (0.64 ft/s). The critical velocities ranged from 15-70 cm/s (0.49 – 2.30 ft/s). The relationship between critical velocity and body length is shown in Figure 3.6 below.

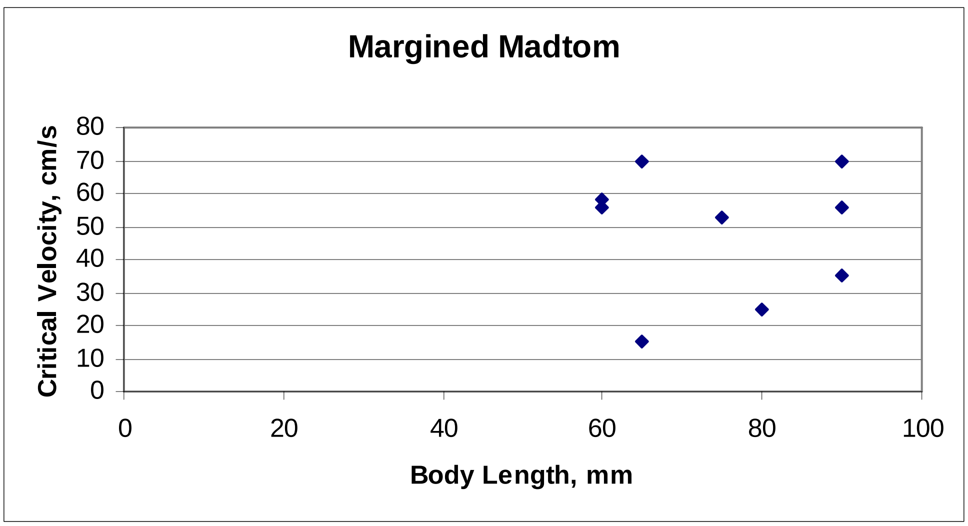


Figure 3.6: Critical velocity related to body length for the Margined Madtom

It is important to note the lack of confidence in this data. It should not be used as a basis for design of culverts, or as definitive information on the swimming ability of this species. Further tests on this species are necessary.

3.2.7 Box Plot Comparison

The box plot shown in Figure 3.7 compares the critical velocities of each species. The Bluegill has the highest average velocity, but has a broad range between the first and third quartiles. The Johnny Darter has the second highest average velocity, and has no range in values between the first and third quartiles. The Swallowtail Shiner was the most consistent performer after the Johnny Darter. The median velocities were higher than the average critical velocities for all species except the Bluegill.

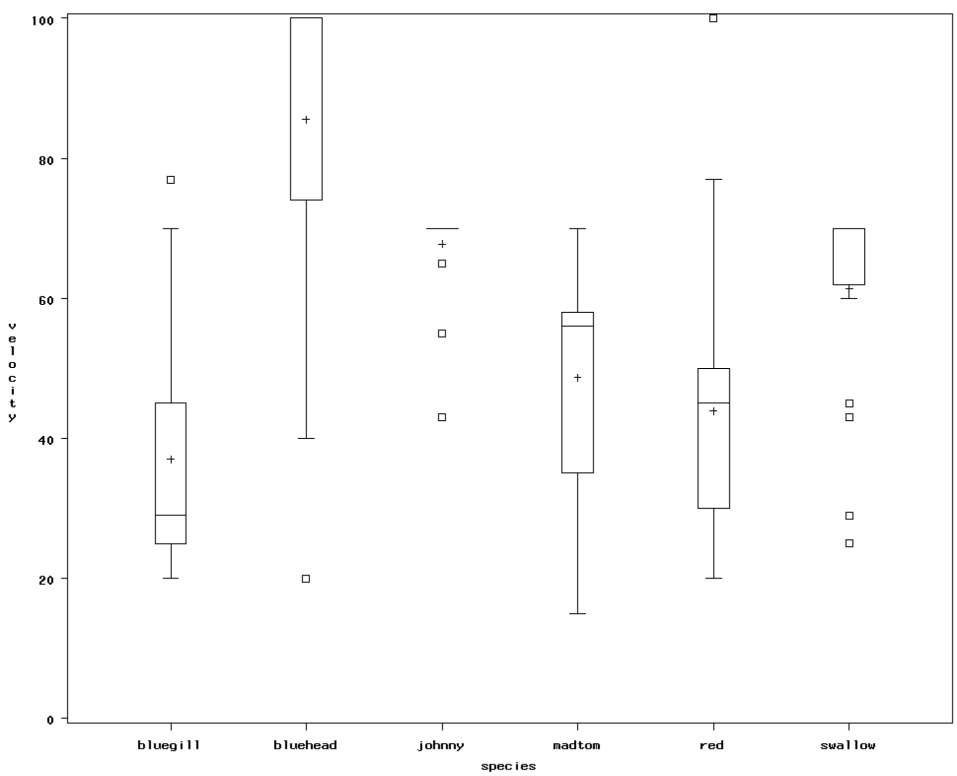


Figure 3.7: Box plot showing differences in critical velocities for each species. The velocity is in cm/s. Note that maximum velocities used for testing Johnny Darter and Bluhead Chub were not the same. Maximum flows tested for each species were 70 cm/s (2.3 ft/s) and 100cm/s (3.3 ft/s) respectively.

3.3 Testing Hypotheses

3.3.1 Primary Hypothesis

The data in this experiment was assumed to have a normal distribution for the purpose of statistical analysis.A General Linear Model (GLM) was used to test the primary and secondary hypotheses discussed in Section 3.1. The test for the primary hypothesis was run setting the critical velocity as a function of species, body length, and the interaction between species and body length.

$$\text{Critical Velocity} = C_1 \text{ (Species)} + C_2 \text{ (Body Length)} + C_3 \text{ (Species * Body Length)} \quad (3.1)$$

With the high probability of errors associated with the data for the Margined Madtom, the GLM model was run without inputting the data for that species to insure the accuracy of the test. In this study "significance" is defined as $p = 0.05$. As shown in the summary table (Table 3.2), there is a significant relationship between species and critical velocity as well as body length and critical velocity. The test for the interaction of species and body length was not significant.

Table 3.2: Results of the GLM for the relationship given in Equation 3.1.

Source	**DF**	**Sum of Squares**	**Mean Square**	**F Value**	**Pr > F**
Model	9	71809.698	7978.8553	31.77	<.0001
Error	183	45958.82	251.1411		
Corrected Total	192	117768.52			

R-Square	**Coeff Var**	**Root MSE**	**Velocity Mean**
0.609753	29.45449	15.84743	53.80311

Source	**DF**	**Type I SS**	**Mean Square**	**F value**	**Pr > F**
species	4	61109.270	15277.318	60.83	<.0001
length	1	9548.591	9548.591	38.02	<.0001
length*species	4	1151.836	287.959	1.15	0.3361

3.3.2 Secondary Hypothesis

A second GLM was used to test the significance of body length on critical velocity within each species. This model showed the significance of body length on critical velocity after species was already accounted for. Using this GLM each species has an intercept and a slope associated with it which contributes to the model's final equation.

Critical Velocity (Bluegill) = (0.3BG + 14.48) (3.2)

Critical Velocity (Bluehead Chub) = (0.21BC + 61.61) (3.3)

Critical Velocity (Johnny Darter) = (-0.1JD + 72.93) (3.4)

Critical Velocity (Redbreast Sunfish) = (0.21RS + 28.96) (3.5)

Critical Velocity (Swallowtail Shiner) = (-0.33SS + 79.87) (3.6)

Where: Critical Velocity = cm/s
BG = Bluegill Body Length, mm
BC = Bluehead Chub Body Length, mm
JD = Johnny Darter Body Length, mm
MM = Margined Madtom Body Length, mm
RS = Readbreast Sunfish Body Length, mm
SS = Swallowtail Shiner Body Length, mm

The slope is the relationship between body length and critical velocity, and the intercept reflects the average value of critical velocity. The test results for the individual species are shown below in Table 3.3.

Table 3.3: Significance of slope and intercept for each species, based on a P=0.05 significance level.

Species	**Estimate of Intercept cm/s**	**Standard Error**	**P-value**	**Significant**
Bluegill	14.479	4.63	0.002	Yes
Bluehead chub	61.611	12.215	<0.0001	Yes
Johnny darter	72.929	22.95	0.0017	Yes
Redbreast sunfish	28.957	6.06	<0.0001	Yes
Swallowtail shiner	79.866	20.522	0.0001	Yes
Species	**Estimate of Slope cm/s/mm**	**Standard Error**	**P-value**	**Significant**
Bluegill	0.2998	0.055	<0.0001	Yes
Bluehead chub	0.2145	0.107	0.0456	Yes
Johnny darter	-0.0971	0.426	0.8200	No
Redbreast sunfish	0.2054	0.078	0.0088	Yes
Swallowtail shiner	-0.3311	0.364	0.3643	No

There is a significant relationship between critical velocity and body length for the Bluegill, Bluehead Chub, and the Readbreast Sunfish. Each of these species have a positive estimate for the slope, with a value greater than 0.2 (cm/s Velocity/ mm Body Length). The other two species (Johnny Darter and Swallowtail Shiner) do not have a significant relationship between body length and critical velocity.

After observing the differences in slope estimates for each species, a series of contrasts were run to determine if any of these differences were significant. The species tested against each other in the contrasts are shown in Table 3.4 along with the significance of the contrast. None of the contrasts performed were proven to be significant, meaning there is no significant difference in the relationship between the body length and critical velocity for the six species tested.

Table 3.4: Contrasts performed on relationship between Body Length and Critical Velocity for each species, based on a P=0.05 significance level.

Species Contrast	**P-value**	**Significant**
Swallowtail Shiner vs Bluehead Chub	0.1469	No
Swallowtail Shiner vs Johnny Darter	0.6727	No
Swallowtail Shiner vs Bluegill	0.0843	No
Swallowtail Shiner vs Redbreast Sunfish	0.146	No
Bluegill vs Bluehead Chub	0.4716	No
Bluegill vs Redbreast Sunfish	0.3166	No
Bluegill vs. Johnny darter	0.3505	No
Bluehead Chub vs Redbreast Sunfish	0.945	No
Bluehead Chub vs Johnny Darter	0.4733	No
Redbreast Sunfish vs Johnny Darter	0.4801	No

3.3.3 Finalized GLM

The finalized GLM was developed after taking into account the results of the primary and secondary hypothesis tests. The final model includes the variables species, body length and critical velocity. Since the primary hypothesis proved that there is a significant relationship between species and critical velocity, the model accounts for the individual effects of each species. However, since the secondary hypothesis showed that there is no significant difference in the relationship of body length and critical velocity for each species, body length is used as an overall variable. The data for the Margined Madtom is not used in the final model due to the high error associated with the collection of that data. The estimate of the intercept for each species is shown in Table 3.5. Figure 3.8 graphically illustrates the final GLM equations for each species as they are given below. The ANOVA table for this GLM is shown in Table 3.6.

$$\text{Critical Velocity (Bluegill)} = 0.247BL + 18.28 \quad (3.7)$$

$$\text{Critical Velocity (Bluehead Chub)} = 0.247BL + 57.72 \quad (3.8)$$

$$\text{Critical Velocity (Johnny Darter)} = 0.247BL + 54.49 \quad (3.9)$$

$$\text{Critical Velocity (Redbreast Sunfish)} = 0.247BL + 25.77 \quad (3.10)$$

$$\text{Critical Velocity (Swallowtail Shiner)} = 0.247BL + 47.54 \quad (3.11)$$

Where BL = Body length of an individual, mm

Table 3.5: Estimate of intercept for each species associated with finalized GLM model

Species	**Estimate of Intercept, cm/s**
Bluegill	18.28
Bluehead Chub	57.72
Johnny Darter	54.49
Readbreast Sunfish	25.77
Swallowtail Shiner	47.54

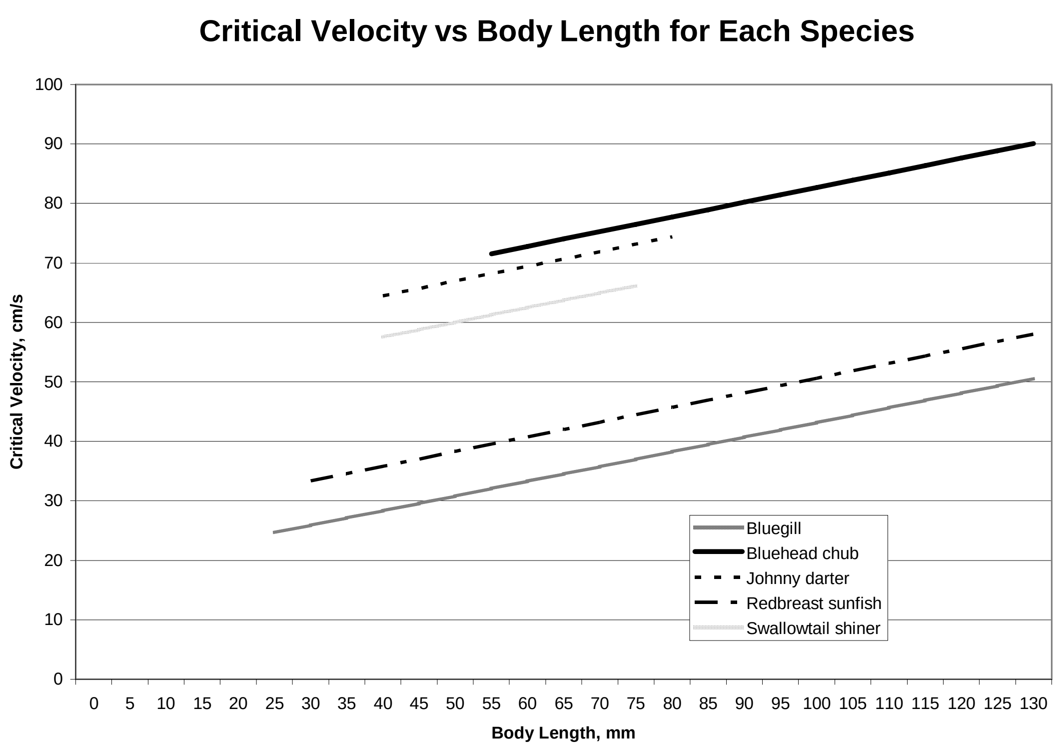


Figure 3.8: Graph of the relationship between body length and critical velocity for each species using equations 3.7 – 3.11, developed from the finalized GLM.

Table 3.6: ANOVA table for the finalized GLM.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	6	629349.3438	104891.5573	416.35	<.0001
Error	187	47110.6562	251.9286		
Uncorrected Total	193	676460			

R-Square	Coeff Var	Root MSE	Velocity Mean
0.599972	29.50064	15.87226	53.80311

Source	DF	Type I SS	Mean Square	F value	PR > F
species	5	619800.7524	123960.1505	492.04	<.0001
length	1	9548.5914	9548.5914	37.9	<.0001

4.0 Discussion

4.1 Performance of the flume

The flume performed well in the experiment. The triangular wire mesh filters were efficient in dissipating the turbulence at the inlet and allowed for a more rectilinear flow pattern. The mesh at the exit proved to be a great way of catching the fish as they became exhausted and allowed for easy collection. Painting the bottom white made the fish easy to see, which aided in the analysis of their behavior. The flume was stable and handled the weight of the water passing through the flume. The walkways running along both sides of the flume were able to hold multiple people during the test. This feature enabled the flume to be used as a teaching tool, allowing several students to see the experiment run.

There were, however, variability and errors in this experiment due to the setup of the pumps and the flume. The velocity of the water within the flume depended both on the head created by the water depth in the secondary pond and the rate at which the pump transferred water from the secondary pond downhill to the flume. Due to this variability, the test could not be recreated exactly each time. Between each velocity stage in the test the flowrate through the pump would be increased, and the velocity would be measured through the flume. Often two or three iterations of this process were needed in order to obtain the correct velocity in the flume. Due to the variability in the depth of water in the secondary pond, the maximum velocity that could be achieved in the flume was not the same each day it was run. Thus explaining why the Bluehead Chub was tested at a maximum velocity of 100cm/s (3.28 ft/s) but the Johnny Darter was tested at a maximum velocity of 70cm/s (2.3 ft/s). Performing this test in a more controlled environment, perhaps with a more simplistic design, would have removed some of the factors of variability associated with this experiment.

4.2 Additional comments on fish behavior

All of the species adapted to the flume environment very quickly. Few were unable to adapt by the end of the ten minute acclimation period. Individuals of the same species would often form a group and swim with one another for the entire test. The Johnny Darter and Margined Madtom were the only species where this behavior was not observed. Many of the species swam against the lower flows at the floor and sides of the flume. They could be expected to behave in the same manner in a culvert, using the edge effects within the pipes or boxes in order to conserve energy and traverse the entire culvert. Figure 4.1 shows the fish positioned in an arc, with the biggest fish swimming against the greatest velocities at the center of the flume. This behavior was noted for both species of sunfish and the Bluehead Chub.

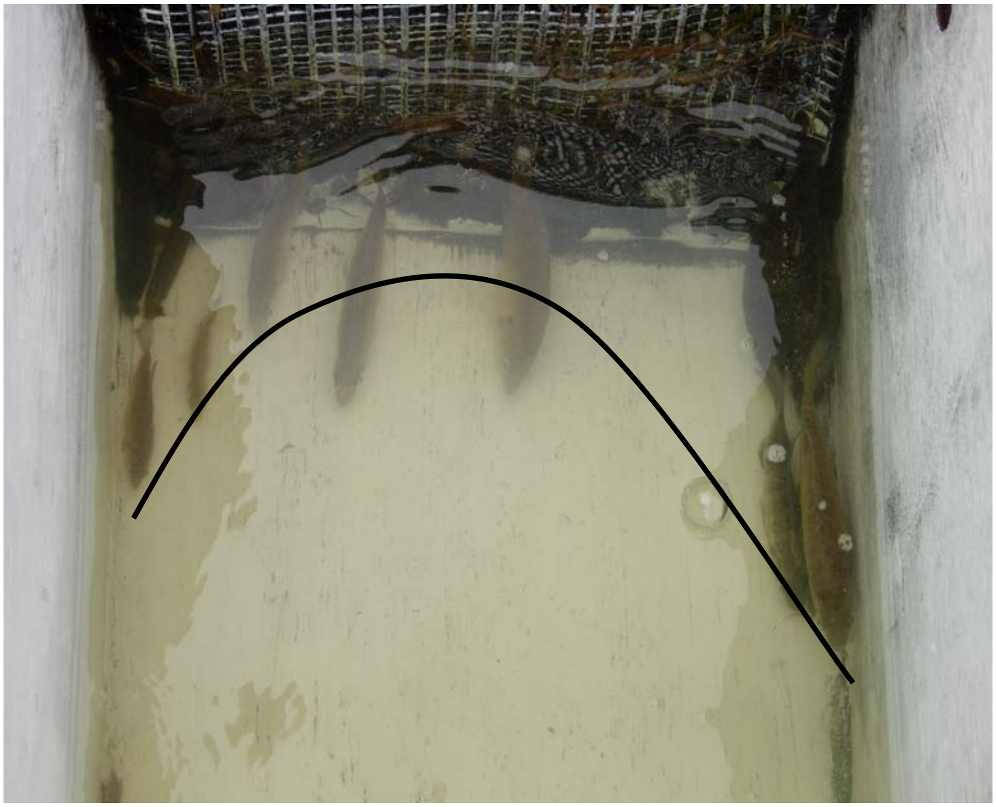


Figure 4.1: Bluegill and Redbreast Sunfish swimming in arc pattern during October 14th test

4.3 Comparison of findings to other experiments

A variety of both passive and active experiments have been performed to determine the critical velocities of fish. Species of trout and salmon are very important for recreation, and so more research has been done on their swimming capabilities. Table 1.2 shows that for trout, salmon, adult chinook, coho, sockeye and steelhead, the critical velocities range from 60.96cm/s (2 ft/s) to 182.88cm/s (6ft/s) depending on the length of the culvert (Bates 2003). The Commonwealth of Virginia sites the critical velocity of trout as 120cm/s (1.2 ft/s). In another experiment on the critical velocities of trout, performed by Belford and Gould in 1989, the velocities were in the range of 67- 96 cm/s (2.2 – 3.15 ft/s).

There are other experiments which have explored the swimming capabilities of fish outside of the trout family. In the mark-recapture experiment performed by Warren and Pardew in 1996, the average critical velocity for the 26 species tested ranged from 30-40 cm/s (1-1.3 ft/s). Jones, Kicenuik, and Bamford performed an experiment in 1974 on Burbot, Broad whitefish, Mountain whitefish, Arctic char, and Arctic cisco. They found the critical velocities to be in the range of 42.5-100.2 cm/s (1.39-3.29 ft/s).

The mean critical velocity when considering individuals from every species tested in this experiment is 53.57cm/s (1.75 ft/s), and the means for species range from 37.05 – 85.54 cm/s (1.215-2.8 ft/s). This average velocity is less than the velocities recommended for trout and salmon waters from Washington State's manual (Bates 2003) for fish passage through road culverts (Figure 2). The velocity does, however, meet the guidelines set by the Virginia for trout waters. The results of the six species tested in this experiment were most akin to the fish tested by Jones, Kicenuik, and Bamford.

Results of this experiment indicate that if culverts are designed to facilitate trout and salmon they may be acting as barriers to other native fish. Species of sunfish, specifically, had the lowest critical velocities in the experiment, and may not be able to traverse culverts designed for trout.

5.0 Excel Model for Culvert Design

5.1 Flow regimes

In the design of road culverts there are six possible flow regimes to consider. Types 1, 2, and 3 are for culverts flowing partially full, and Types 4, 5, and 6 are for culverts flowing full. In the first three types the head waters (h1) do not come in contact with the soffit of the culvert. The six flow types with their defining characteristic are listed below.

Type 1: Critical Depth at inlet
Type 2: Critical Depth at outlet
Type 3: Tranquil flow throughout
Type 4: Submerged outlet
Type 5: Rapid flow at inlet
Type 6: Full flow free outfall

This model focuses on designing culverts that flow partially full. The model was designed to produce the "worst case scenario", that being the maximum possible velocity of flow through a culvert. The maximum velocity calculated by the model is then compared to the critical velocities of any of the six species. If the maximum velocity is greater than the critical velocity, variables of the culvert can be altered to provide a design suitable for the swimming capabilities of the fish.

The Type 1 flow regime was chosen as the flow type that would give the greatest velocities in the culvert. In flow Type 1 water enters the flume at critical depth, and remains below critical depth throughout the culvert. This means that the flow through the culvert is supercritical. A diagram of the six flow types is shown in Figure 5.1. Culvert flow diagrams are separated into four sections. Section 1 represents the flow in the channel before it enters into the culvert. Section 2 is the flow at the entrance of the culvert. Section 3 is at the exit of the culvert, and Section 4 is the flow once it has exited the culvert.

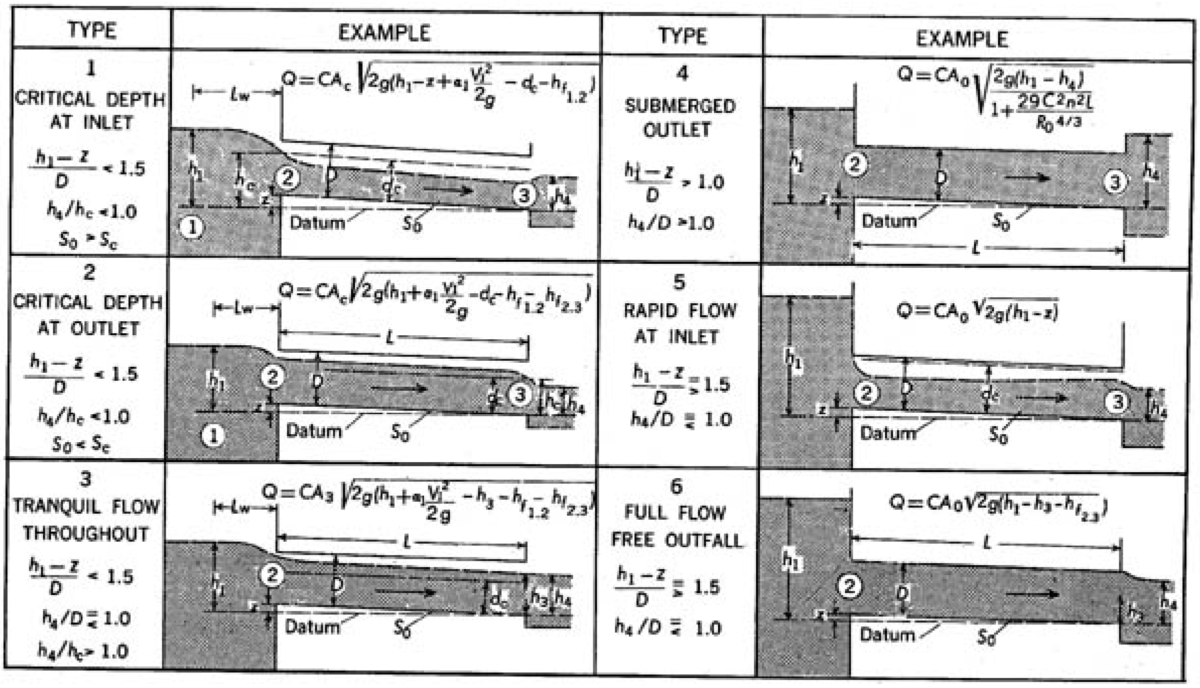


Figure 5.1: Diagrams of the six flow types. Source: USGS can be found in original context at http://wwwrcamnl.wr.usgs.gov/sws/fieldmethods/Indirects/rantz.htm

5.2 Modeling flow Type 1

Each flow type has a different flow equation. Equation 5.1 (Lindenberg 1999) shown below gives the flowrate of the water through the culvert for flow Type 1.

$$Q = Cd * Ac * \sqrt{(2g(h1 - z + (\alpha V_1^2)/(2g) - dc - h_{f\,1,\,2}))} \qquad (5.1)$$

Where Q = flowrate m^3/s

Cd = Coefficient of Discharge, dimensionless

Ac = Cross sectional area at critical depth, m^2

g = Acceleration of gravity, $9.81 m/s^2$

h1 = Head at section 1, m

z = Elevation of bottom of culvert at outlet, m

α = Coriolis Coefficient (typically set to 1.0)

V_1 = Velocity at section 1 m/s

$H_{f1,\,2}$ = friction loss between sections 1 and 2, m

The loss of head due to friction between sections 1 and 2 is described in Equation 5.2 (Lindenberg 1999).

$$h_{f\,1,2} = (L * Q^2)/ (K_1 * K_2) \tag{5.2}$$

Where L = length of the culvert, m
Q = flowrate at normal depth, m^3/s
K_1 = Conveyance at section 1
K_2 = Conveyance at section 2

For culverts flowing partially full conveyance is described by Equation 5.3 (Lindenberg 1999).

$$K = (1/n) * R^{2/3} * A \tag{5.3}$$

Where n = Mannings n
R = Hydraulic radius, m
A = Area of flow, m^2

In modeling Type 1 flows it is important to calculate the critical depth of flow through the culvert, because this is the depth at the entrance (section 2). Glenn Schwab (1993) describes critical depth as the depth where energy head is at a minimum. The critical depth is calculated as follows (Schwab 1993):

$$Dc = (2/3)He \tag{5.4}$$

$$He = y + q^2/(2a^2g) \tag{5.5}$$

Where He = Specific energy, m
y = Depth of flow (at h1), m
q = Flow rate, m^3/s
Dc = Critical Depth, m
G= acceleration of gravity, 9.81 m/s^2
A = Cross-sectional area of flow, m^2

5.3 Process of the Excel Model

Microsoft Excel® was used to create the calculation model. The model can calculate flow through three geometries of culverts: circular, sunken circular, and box. These three geometries were chosen because they are the most frequently used and often the least expensive to install. A separate spreadsheet is used for each culvert shape. For each calculation there is a list of input variables which can be manipulated by the designer.

The variables listed in Table 5.1 are input variables for the model which the designer must provide and can manipulate in order to produce the desired flowrates. Appendix C contains the additional equations used in the model based on the geometry of the culvert.

Table 5.1: Variables that are required to be input by the designer in the Culvert design model. The variables are defined in equations 5.1-5.5.

Input Variables		
Circular	**Sunken Circular**	**Box**
Cd	Cd	Cd
h1	h1	h1
Z	Z	Z
V1	V1	V1
Culvert Slope	Culvert Slope	Culvert Slope
Culvert Length	Culvert Length	Culvert Length
diameter	diameter	Width
Manning’s n pipe	Manning’s n pipe	Height
	Manning’s n bottom	Manning’s n box
	Sunken Depth	Manning’s n bottom

After the designer inputs the variables, the model will output the flowrate and the maximum velocity in the culvert. In flow Type 1 the depth of water remains under the critical depth for the entire length of the culvert, so the maximum velocity is estimated to occur at three quarters of the critical depth.

Once the velocity is calculated, it can be input into the fourth sheet of the model, labeled “Input Velocity”. The velocity calculated can be input next to as many of the species of the designers choosing. The model then compares the value for velocity to a series of confidence intervals of the mean critical velocity that were developed from the statistical output of the finalized GLM (Section 3.3.3). Each confidence interval contains a percentage of the critical velocities for of the individuals tested in the experiment. If it is a 25% confidence interval, than the critical velocities for 25% of the individuals tested falls within that given range. When the velocity is input next to the species, the model outputs the lowest confidence interval that the velocity is within. Therefore, if the model says it is in the 25% confidence interval it is also a part of the 35, 40, 50, 60, 75, 85, and 95% confidence intervals. If the velocity is too great and lies outside of the 95% confidence interval, then the model will output “Fish Cannot Pass”. In this case the designer should return to the culvert design sheet and change parameters until a velocity is calculated which enables the fish species of choice to pass through.

5.4 Sensitivity Analysis

For the sensitivity analysis the input variables were set at a combination which produces a maximum velocity below 100 cm/s (3.28 ft/s). For the testing of an individual variable, all other variables remained at the set base values, while the tested variable changed. The maximum velocities output by the model, along with the change in values for a single variable were then graphed. The graphs give a visual idea of how the model reacts to a change in each variable. The graphs developed in the sensitivity analysis can all be found in Appendix C.

5.4.1 Circular Culverts

The calculations used in the model for circular culverts can be found in Appendix C. The graphs showing the results of the sensitivity analysis for circular culverts are located in Section C.4. The base values input for the sensitivity analysis are given in Table 5.2. This combination of variables outputs a maximum velocity of 91.72cm/s (3.01 ft/s).

Table 5.2: Values input into the model for the sensitivity test of a circular culvert

Input Variables	**Values**
Cd	0.6
h1, m	0.2
Z, m	0
V1, m	0.1
Culvert Slope, m/m	0.001
Culvert Length, m	100
Diameter, m	3
Manning's n pipe	0.012

The sensitivity analysis shows that the maximum velocity within the culvert decreases as the length of the culvert increases. This is expected due to the increase in the friction head loss, and energy dissipation across the length. The maximum velocity increases with increased culvert diameters; however, the curve shown in Figure C.5

begins to level out at a culvert diameter of three meters. The model shows positive relationships for both h1 and V1 with maximum velocity within the culvert.

During the sensitivity test it was found that the model could not test culvert diameters less than 0.5 m (1.6 ft). This is reasonable considering culverts placed in small streams must not restrict the flow of the natural channel. Also, the minimum height for h1 is 0.3 m (0.98 ft). This is reasonable because Flow Type 1 requires flow head at the inlet greater than the critical depth.

5.4.2 Sunken Circular Culverts

Graphs representing the sensitivity analysis for sunken circular culverts are located in Appendix C, Section C.5. The base input variables for the sensitivity analysis of sunken circular culverts are shown in Table 5.3. These values output a maximum velocity of 58.25 cm/s (1.91 ft/s). The value of 0.03 used for “Manning’s n bottom” assumes natural bed material is used on the culvert bottom.

Table 5.3: Values input into the model for the sensitivity test of a sunken circular culvert

Input Variable	**Value**
Cd	0.6
h1, m	0.5
z, m	0
V1, m/s	0.5
Culvert Slope, m/m	0.001
Culvert Length, m	60
Diameter, m	2.5
Manning’s n pipe	0.012
Manning’s n bottom	0.03
Sunken Depth, m	0.2

The maximum velocity in the culvert decreases as the length of the culvert increases, similar to the circular culvert. The relationship between culvert diameter, h1, and maximum velocity also had relationships similar to the circular culvert. However, the curve for the sunken circular culvert did not begin to level out until the diameter reached five meters instead of three meters. This is probably due to the lower carrying capacity of a sunken culvert. There is an interesting relationship between sunken depth and maximum velocity, and the model proved to be very sensitive to this variable. The critical velocity increased with sunken depth up to a value of 0.25 m (0.82 ft) for sunken depth and 60 cm/s (1.97 ft/s). After that point the critical velocity began to decrease as sunken depth continued to increase.

The sensitivity analysis showed that the model was limited to testing culverts less than 60 m (196.9 ft). This is a restriction in modeling Flow Type 1. If the length is greater than 60 m (196.9 ft) Flow Type 1 is no longer an appropriate model to use. Also the value for h1 had to be at least 0.3m for the same reasons as stated in the previous section.

5.4.3 Box Culverts

The calculations used for the geometry of box culverts can be found in Appendix C. Graphs depicting the sensitivity of the model to the input variables are located in Section C.6. Table 5.4 gives the base input values used in the sensitivity test for box culverts. The maximum velocity associated with these input values is 55.94 cm/s (1.84 ft/s). The value of 0.03 was again used for "Manning's n bottom" to represent a natural channel bottom.

Table 5.4 Base input values used in the sensitivity test for box culverts.

Input Variables	Values
Cd	0.6
h1, m	0.5
z, m	0
V1, m/s	1
Culvert Slope, m/m	0.001
Culvert Length, m	17
Width, m	3
height of box, m	2
mannings in box	0.012
mannings n bottom	0.03

Using these base input values the sensitivity analysis showed that the maximum velocity in the flume increased with the width of the flume, similar to the sunken circular culvert. The increase in width allows water to spread out more and maintain a water depth far under the critical depth. A width less than 2.5 m (8.2 ft) created flows too slow to be calculated. Small widths allowed water to deepen and become higher than the critical depth. Both h1, and V1 had relationships with critical velocity much like the sunken circular culvert. The length of the culvert had the same effect on maximum velocity as the other two culvert geometries, decreasing with increasing length. The similarities in flow patterns and restrictions between the sunken circular culvert and the box culvert indicates the increase in the value of Manning's "n" across the bottom of the culvert can have a significant effect on the conveyance of water through the culvert.

5.4.4 Conclusions based on sensitivity analysis

The sensitivity analysis, specifically on the box culvert and sunken circular culvert, showed that modeling flow Type 1 did not work for long culverts. There were also limitations on the headwaters entering the culvert. The headwater, h1, had to be at least 0.30 m (0.98 ft) for all culvert geometries in order for the model to work. The limitations of the model indicate that flow Type 1 may not be the best equation to use for fish passage calculations. In order to produce flow Types 1-6 there must be a storm event. This storm event produces the velocities, V1, and headwaters, h1, necessary to produce this flow. When designing road culverts for fish passage one is designing for the flow that will occur during 90 % of the fish migration season. It can be argued that storm events producing flow Types 1-6 are not a part of this 90 %.

After discovering the limitations of the model, it had to be altered in order to properly calculate flows which would occur during 90% of the fish migration season. To do this a section of the model was created which uses Manning's Formula (Equation 1.1). While the model can still be used to calculate a "worst case scenario" using flow Type 1, it can now also be used to calculate flows occurring during 90% of the fish migration season.

5.5 Suggested Uses for the model

This model can be used to do preliminary design work on culverts. Adjusting different variables will allow the designer to see the ranges of values they can use without impeding fish passage. This model should be used along with other available hydrologic models, and not as the only tool for culvert design. Other models must be used in order to calculate water profiles upstream and downstream of the culvert.

It is important to consider what flow type a culvert is being designed for. After a basic design is drafted, additional checks should be done to insure the flow is Type 1. This model should not be used in culverts that will flow full for significant periods of time during fish migration season. Being able to compare the design velocities to the critical velocities of fish provides a tangible guideline in designing culverts for AOP guidelines. The "Input Velocities" sheet can also be used to test velocities calculated using other models.

6.0 Conclusions and Recommendations

6.1 Utilizing the Data

The equations from the final GLM (Equations 4-8) relate the critical velocities to the body length of each species. These equations can be helpful in predicting critical velocities for different life stages in a species by inputting smaller body lengths for juveniles and larger body lengths for adults. The equations can also be used in the hydrologic design of culverts based on a target species, as discussed in Section 1.4.3. The Excel model discussed in Section 5 is based on the hydrologic design of culverts, and it can be used as suggested in Section 5.5 to aid in the design process.

6.2 Design recommendations

Based on the data found in this experiment it is recommended that the maximum velocities during periods of fish migration be kept under 55 cm/s (1.8 ft/s) during 90% of the fish migration season, depending on the species of concern. This represents the average critical velocity of all the species in the experiment combined. In areas of Eastern North Carolina where the endangered Cape Fear shiner is of particular concern, the data for the Swallowtail shiner (mean critical velocity of 61.42 cm/s) can be used as a guideline in the design process.

Culvert should be installed as instructed by the North Carolina State BMP manual suggests. As stated in the manual, the bottom side of the culvert should be sunken to a depth of at least 1ft (0.3048m), or 20% of the diameter of the culvert.

This study is the first step in developing a regional screen for the state of North Carolina. While this study includes six species, of five morphologies, many other species should be tested in order to make a complete regional screen for North Carolina. Species with morphologies different from those in this study should be tested to find their physical limitations. It is recommended that all endangered species, or species similar to those which are endangered, be tested. This will aid in the protection of these species, by ensuring culverts built in watersheds where they are prevalent will not impede their migration. Adding species will provide a more completed screen. Information on these species can then be collected to create a model similar to FishXing, or the information could be added to this model.

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Appendices

Appendix A

Additional Photos and Figures of the Experiment

Figure A.1: Electrofishing in Brier Creek with crew from the NC DWQ.

Figure A.2: Angela Gardner and Dan Clinton running test on October 14, 2005.

Figure A.3: View of secondary pond. Fish were held in a floating bait cage off the pier overnight.

Figure A.4: Looking towards inlet of the flume.

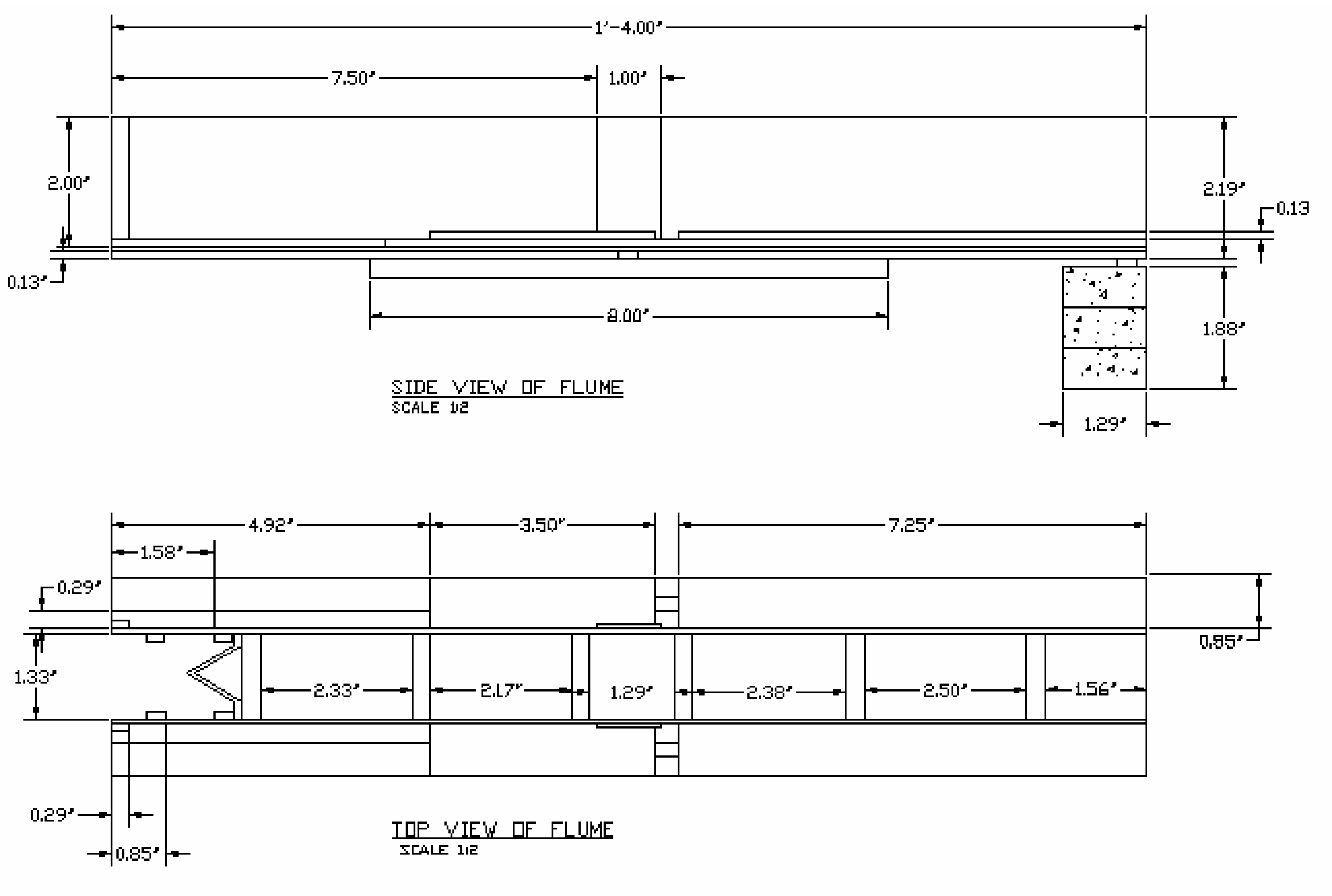


Figure A.5: Side and top view AutoCAD drawings of flume

Appendix B

Federal and State Regulations

Public Notice
Final Regional Conditions for Nationwide Permits

Effective May 12th 2002

II. List of Final Corps Regional Modifications and Conditions for All Nationwide Permits

5) For all NWPs that involve the construction of culverts, measures will be included in the construction that will promote the safe passage of fish and other aquatic organisms. All culverts in the 20 CAMA coastal counties must be buried to a depth of one foot below the bed of the stream or wetland. For all culvert construction activities, the
Attachment 1. Final Regional Conditions
dimension, pattern, and profile of the stream, (above and below a pipe or culvert), should not be modified by widening the stream channel or by reducing the depth of the stream. Culvert inverts will be buried at least one foot below the bed of the stream for culverts greater than 48 inches in diameter. For culverts 48 inches in diameter or smaller, culverts must be buried below the bed of the stream to a depth equal to or greater than 20 percent of the diameter of the culvert. Bottomless arch culverts will satisfy this condition. A waiver from the depth specifications in this Regional Condition may be requested in writing. The waiver will only be issued if it can be demonstrated that the impacts of complying with this Regional Condition would result in more adverse impacts to the aquatic environment.

P 4

NATIONWIDE PERMIT 14
DEPARTMENT OF THE ARMY
CORPS OF ENGINEERS
FINAL NOTICE OF ISSUANCE AND MODIFICATION OF NATIONWIDE PERMITS
FEDERAL REGISTER
AUTHORIZED MARCH 18, 2002

General Conditions

4. Aquatic Life Movements. No activity may substantially disrupt the necessary life-cycle movements of those species of aquatic life indigenous to the waterbody, including those species that normally migrate through the area, unless the activity's primary purpose is to impound water. Culverts placed in streams must be installed to maintain low flow conditions.
P 3

11. Endangered Species.
a. No activity is authorized under any NWP which is likely to jeopardize the continued existence of a threatened or endangered species or a species proposed for such designation, as identified under the Federal Endangered Species Act (ESA), or which will destroy or adversely modify the critical habitat of such species. Non-federal permittees shall notify the District Engineer if any listed species or designated critical habitat might be affected or is in the vicinity of the project, or is located in the designated critical habitat and shall not begin work on the activity until notified by the District Engineer that the requirements of the ESA have been satisfied and that the activity is authorized. For activities that may affect Federally-listed endangered or threatened species or designated critical habitat, the notification must include the name(s) of the endangered or threatened species that may be affected by the proposed work or that utilize the designated critical habitat that may be affected by the proposed work. As a result of formal or informal consultation with the FWS or NMFS the District Engineer may add species-specific regional endangered species conditions to the NWPs.

P 11

NORTH CAROLINA DIVISION OF WATER QUALITY
GENERAL CERTIFICATION CONDITIONS
GC3375

9. Placement of culverts and other structures in waters, streams, and wetlands must be placed below the elevation of the streambed to allow low flow passage of water and aquatic life unless it can be shown to DWQ that providing passage would be impractical. Design and placement of culverts including open bottom or bottomless arch culverts and other structures including temporary erosion control measures shall not be conducted in a manner that may result in aggradation, degradation or significant changes in hydrology of wetlands or stream beds or banks, adjacent to or upstream and down stream of the above structures. The applicant is required to provide evidence that the equilibrium shall be maintained if requested to do so in writing by DWQ. Additionally, when roadways, causeways or other fill projects are constructed across FEMA-designated floodways or wetlands, openings such as culverts or bridges must be provided to maintain the natural hydrology of the system as well as prevent constriction of the floodway that may result in aggradation, degradation or significant changes in hydrology of streams or wetlands;
p 24

14. If an environmental document is required, this Certification is not valid until a Finding of No Significant Impact (FONSI) or Record of Decision (ROD) is issued by the State Clearinghouse;
P 25

http://www.saw.usace.army.mil/wetlands/general&nationwide_permits.html#Nationwide Permits

NC DENR – DIVISION OF WATER QUALITY
"REDBOOK"
SURFACE WATAERS AND WETLANDS STANDARDS
NC ADMINISTRATIVE CODE 15A NCAC 02B .0100, .0200 & .0300
AMENDED EFFECTIVE AUGUST 1, 2004

North Carolina Administrative code effective August 1 2004

15A NCAC 02B .0231 WETLAND STANDARDS
(a) General. The water quality standards for all wetlands are designed to protect, preserve, restore and enhance the quality and
uses of wetlands and other waters of the state influenced by wetlands. The following are wetland uses:
(1) Storm and flood water storage and retention and the moderation of extreme water level fluctuations;
(2) Hydrologic functions including groundwater discharge that contributes to maintain dry weather streamflow and, at other locations or times, groundwater recharge that replenishes the groundwater system;
(3) Filtration or storage of sediments, nutrients, toxic substances, or other pollutants that would otherwise adversely impact the quality of other waters of the state;
(4) Shoreline protection against erosion through the dissipation of wave energy and water velocity and stabilization of sediments;
(5) Habitat for the propagation of resident wetland-dependent aquatic organisms including, but not limited to fish, crustaceans, mollusks, insects, annelids, planktonic organisms and the plants and animals upon which these aquatic organisms feed and depend upon for their needs in all life stages; and
(6) Habitat for the propagation of resident wetland-dependent wildlife species, including mammals, birds, reptiles and amphibians for breeding, nesting, cover, travel corridors and food.
(b) The following standards shall be used to assure the maintenance or enhancement of the existing uses of wetlands identified in Paragraph (a) of this Rule:
(1) Liquids, fill or other solids or dissolved gases may not be present in amounts which may cause adverse impacts on existing wetland uses;
(2) Floating or submerged debris, oil, deleterious substances, or other material may not be present in amounts which may cause adverse impacts on existing wetland uses;
(3) Materials producing color, odor, taste or unsightliness may not be present in amounts which may cause adverse impacts on existing wetland uses;

p 50

(b) The following standards shall be used to assure the maintenance or enhancement of the existing uses of wetlands identified
in Paragraph (a) of this Rule:
(1) Liquids, fill or other solids or dissolved gases may not be present in amounts which may cause adverse impacts on existing wetland uses;
(2) Floating or submerged debris, oil, deleterious substances, or other material may not be present in amounts
which may cause adverse impacts on existing wetland uses;
(3) Materials producing color, odor, taste or unsightliness may not be present in amounts which may cause adverse impacts on existing wetland uses;
NORTH CAROLINA ADMINISTRATIVE CODE *Eff. August 1, 2004* Page 51
(4) Concentrations or combinations of substances which are toxic or harmful to human, animal or plant life may
not be present in amounts which individually or cumulatively may cause adverse impacts on existing wetland uses;

(5) Hydrological conditions necessary to support the biological and physical characteristics naturally present in
wetlands shall be protected to prevent adverse impacts on:
(A) Water currents, erosion or sedimentation patterns;
(B) Natural water temperature variations;
(C) The chemical, nutrient and dissolved oxygen regime of the wetland;
(D) The movement of aquatic fauna;
(E) The pH of the wetland; and
(F) Water levels or elevations.
(6) The populations of wetland flora and fauna shall be maintained to protect biological integrity as defined at
15A NCAC 2B .0202.
History Note: Authority G.S. 143-214.1; 143-215.3(a)(1);
RRC Objection Eff. July 18, 1996 due to lack of statutory authority and ambiguity;
Eff. October 1, 1996.

P 53, 54

15A NCAC 02B .0110 CONSIDERATIONS FOR FEDERALLY-LISTED THREATENED OR ENDANGERED
AQUATIC SPECIES
Certain waters provide habitat for federally-listed aquatic animal species that are listed as threatened or endangered by the U.S.Fish and Wildlife Service or National Marine Fisheries Service under the provisions of the Endangered Species Act, 16 U.S.C. 1531-1544 and subsequent modifications. Maintenance and recovery of the water quality conditions required to sustain and recover federally-listed threatened and endangered aquatic animal species contributes to the support and maintenance of a balanced and indigenous community of aquatic organisms and thereby protects the biological integrity of the waters. The Division shall develop site-specific management strategies under the provisions of 15A NCAC 2B .0225 or 15A NCAC 2B.0227 for those waters. These plans shall be developed within the basinwide planning schedule with all plans completed at the end of each watershed's first complete five year cycle following adoption of this Rule. Nothing in this Rule shall prevent the Division from taking other actions within its authority to maintain and restore the quality of these waters.
History Note: Authority G. S. 143-214.1; 143-215.3(a)(1); 143-215.8A;
Eff. August 1, 2000.

P 12

Appendix C

Additional Information on Culvert Excel Design Model

C.1: Equations for circular culvert

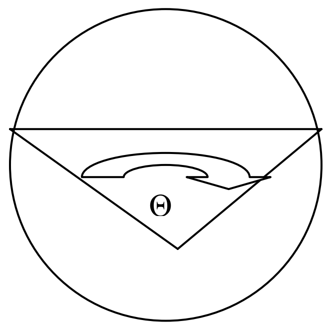


Figure C.1: Diagram of circular culvert showing theta as the angle between the water surface and the center of the culvert.

Θ H_2O

$\Theta = 2\pi - 2\cos^{-1}((R - \text{depth})/R)$ (?.1)

Where Θ = angle of water, radians
Depth = depth of water, m

Area of flow

$a = (1/8)(\Theta - \sin\Theta)D^2$ (?.2)

Where a = area of flow, m^2
D = diameter of culvert, m
Θ = angle of water, radians

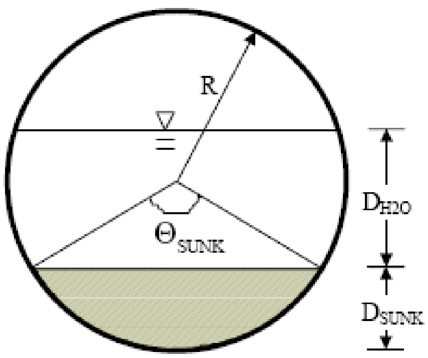
Critical depth

$dc = (2/3)(h1 + (V_1 h1)^2/(2ga^2))$ (?.3)

where dc= critical depth, m
h1 = depth of water at section 1, m
V_1= velocity of water at section 1, m/s
a = cross sectional area of flow (equation ?.2), m^2
g = acceleration of gravity, m/s^2

C.2: Equations for sunken circular culvert

The following figure and equations are taken from the help menu for CMP culverts in FishXing.



$$\Theta_{SUNK} = 2\cos^{-1}\left(\frac{R - D_{SUNK}}{R}\right) \qquad (?.4)$$

$$A_{SUNK} = \frac{R^2}{2}\left[\Theta_{SUNK} - \sin(\Theta_{SUNK})\right] \qquad (?.5)$$

O7
$$P_{BOTTOM} = 2R\sin\left(\frac{\Theta_{SUNK}}{2}\right) \qquad (?.6)$$

$$\Theta_{H2O} = 2\cos^{-1}\left[\frac{R - \left(D_{SUNK} + D_{H_20}\right)}{R}\right] \qquad (?.7)$$

$$P_{SIDES} = R\Theta_{H2O} - P_{SUNK} \qquad (?.8)$$

$$W_{TOP} = 2R\sin\left(\frac{\Theta_{H_2O}}{2}\right) \qquad (?.9)$$

$$A_{H2O} = \left[\frac{R^2\left(\Theta_{H_2O} - \sin\left(\Theta_{H_2O}\right)\right)}{2}\right] - A_{SUNK} \qquad (?.10)$$

Where:

DSUNK = Sunken depth, m

ASUNK = Sunken area, m^2

PSUNK = Outside perimeter of sunken area, m

PBOTTOM = Perimeter of water on the bottom (0 for At Grade culvert), m

PSIDES = Perimeter of pipe from sunken depth to the water level, m and

WTOP = Top width of the water surface, m.
Critical Depth

$dc = (2/3)(h1+ (q^2/(2gA_{H2O}^2))$

Where dc = critical depth, m
h1 = head at section 1, m
q = flowrate at h1, m^3/s
g = acceleration of gravity, m/s^2
A_{H2O} = area of water, m^2

C.3: Equations for box culvert

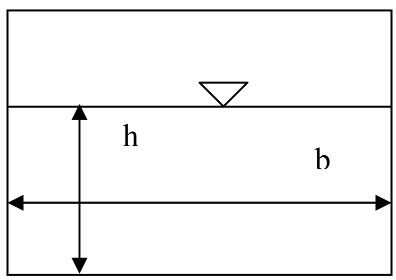


Figure C.2: Diagram of a box culvert showing width and height of water.

a = b*h

Where b = width of culvert, m
h = height of flow, m

$dc = (2/3)(h1 + (q^2/(2gb^2h^2)))$

Where dc = critical depth, m
h1 = head at section 1, m
q = flowrate at h1, m/s^2
b = width of culvert, m
h = height of flow, m

C.4: Graphs for sensitivity analysis of circular culverts

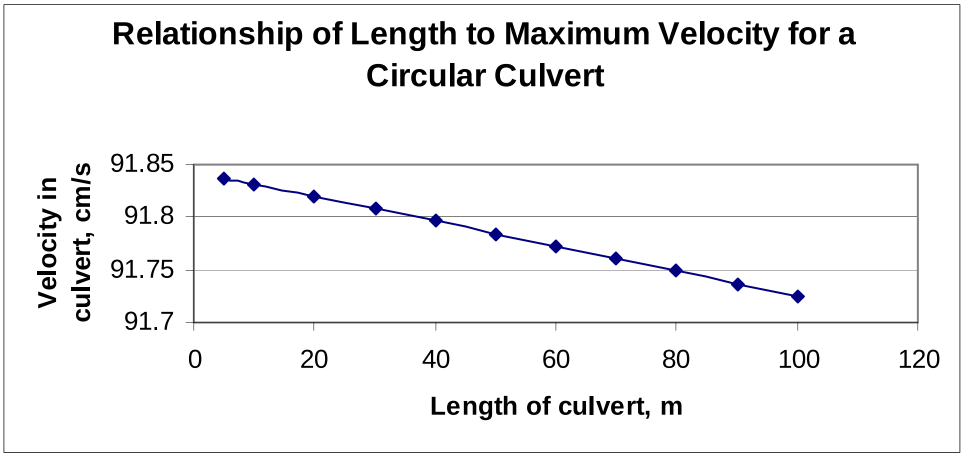


Figure C.3: Velocity response to the change in the input variable Length for a circular culvert.

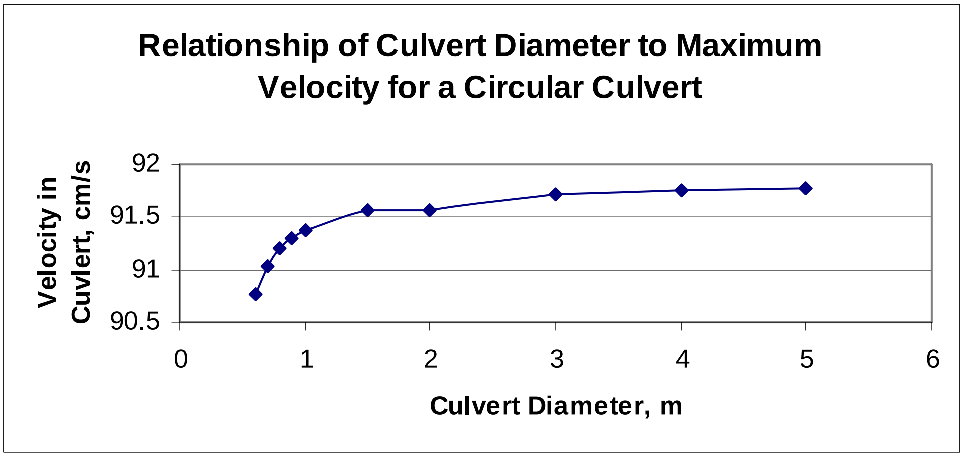


Figure C.4: Velocity response to the change in the input variable Culvert Diameter for a circular culvert.

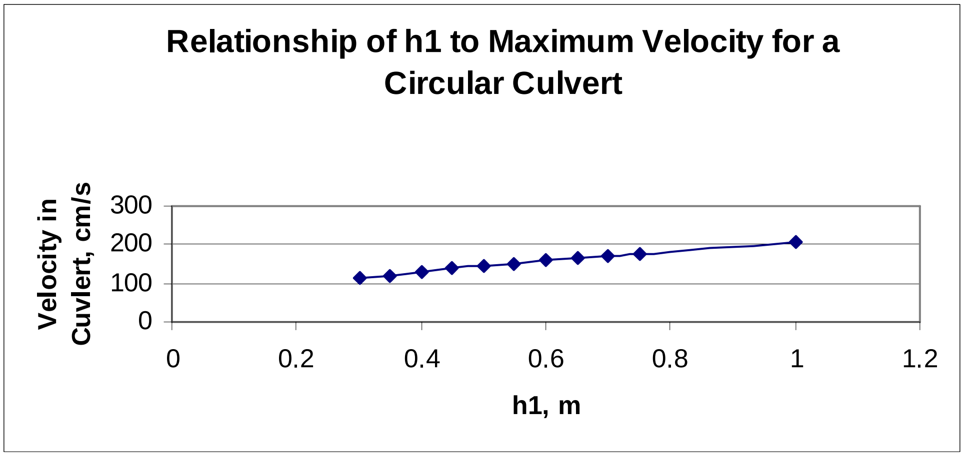


Figure C.5: Velocity response to the change in the input variable h1, head at section 1, for a circular culvert.

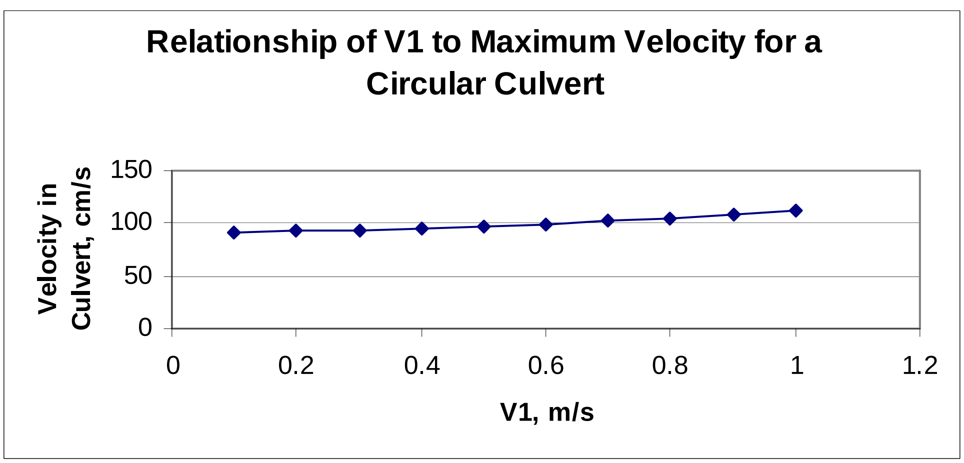


Figure C.6: Velocity response to the change in the input variable V1, velocity at section 1, for a circular culvert.

C.5: Graphs of sensitivity analysis for sunken circular culverts

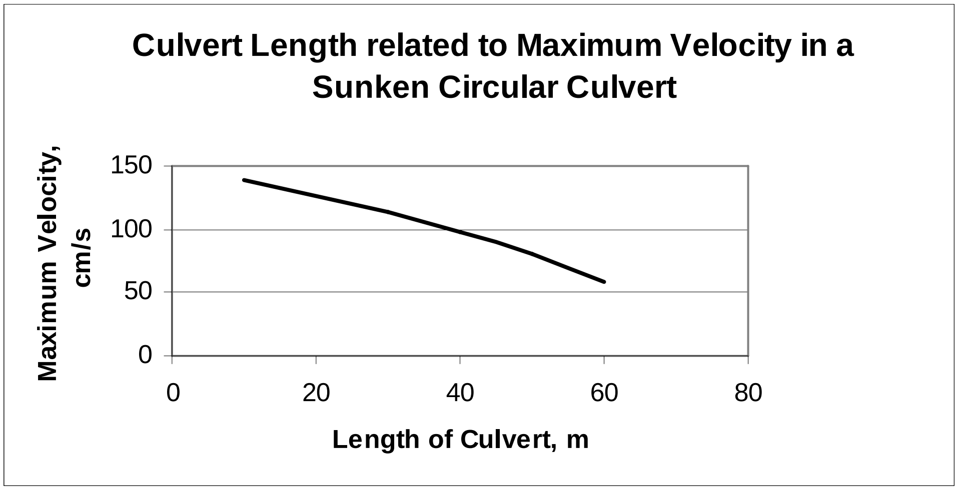


Figure C.7: Velocity response to the change in the input variable Length for a sunken circular culvert

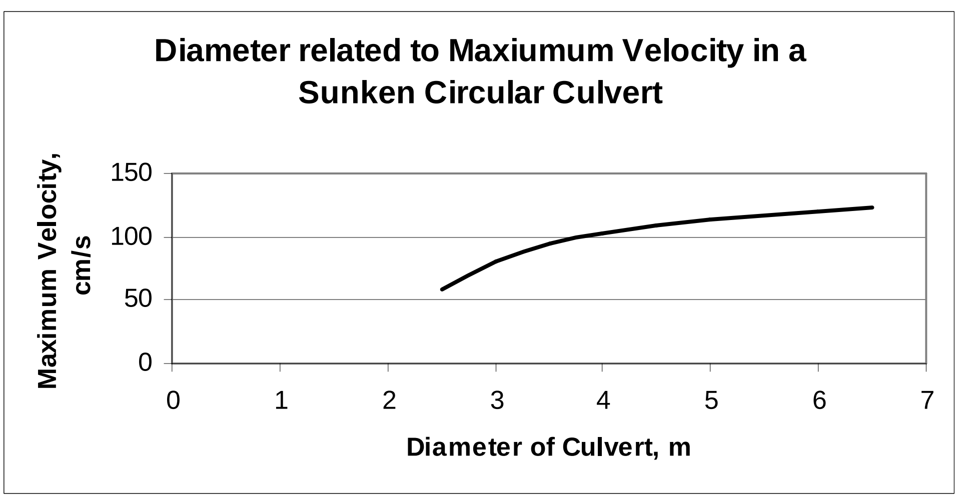


Figure C.8: Velocity response to the change in the input variable Diameter for a sunken circular culvert.

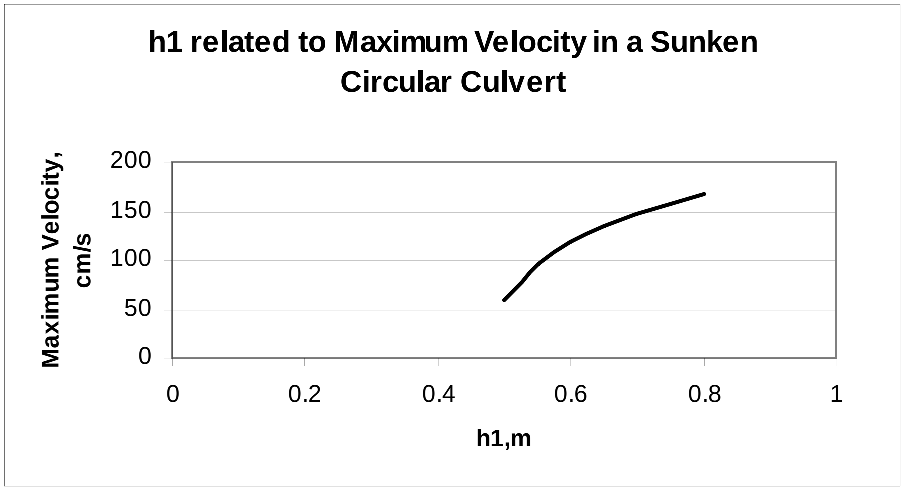


Figure C.9: Velocity response to h1 in a sunken circular culvert.

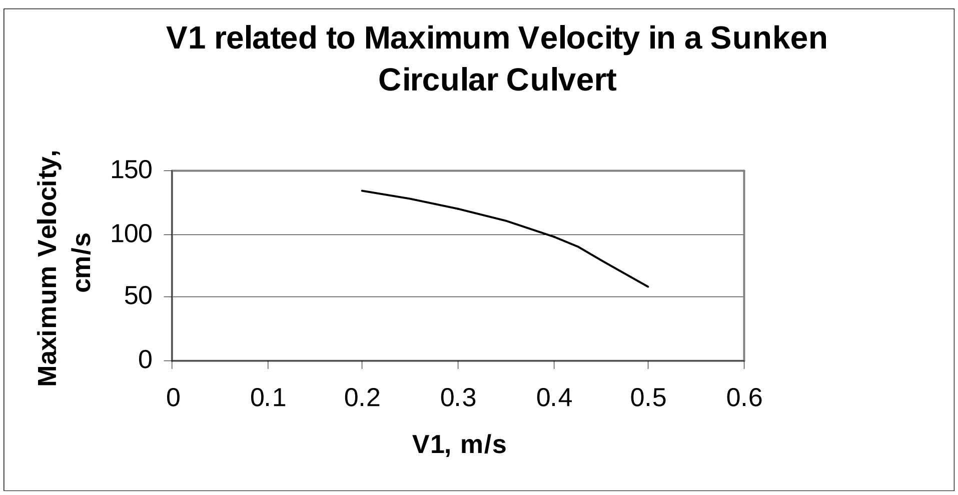


Figure C.10: Velocity response to V1 in a sunken circular culvert.

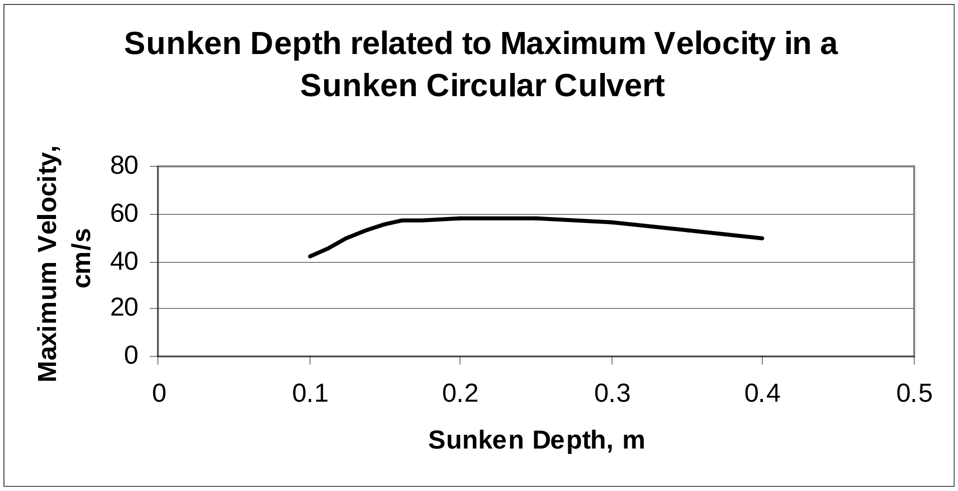
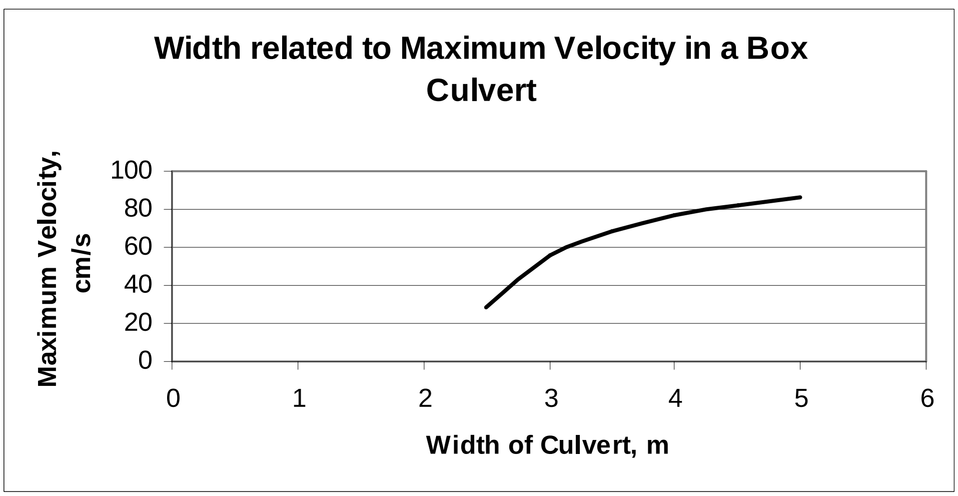


Figure C11: Velocity response to sunken depth in a sunken circular culvert.

C. 6: Graphs from the sensitivity analysis of box culverts



FigureC.12: Velocity response to width of a box culvert.

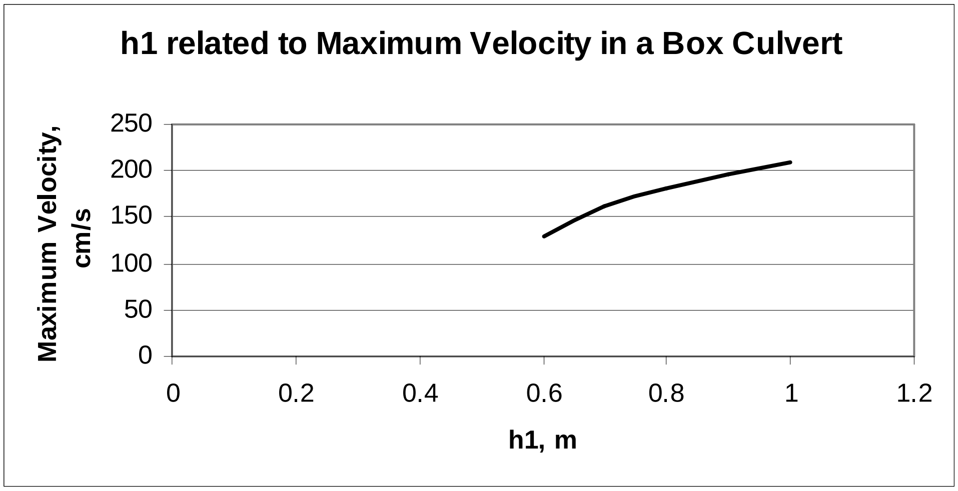


Figure C.13: Velocity response to h1 in a box culvert.

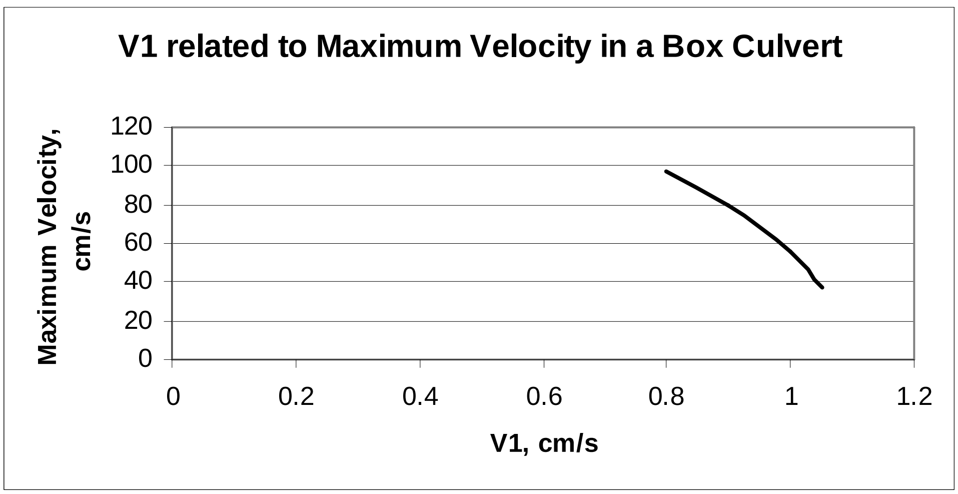


Figure C.14: Velocity response to V1 in a box culvert.

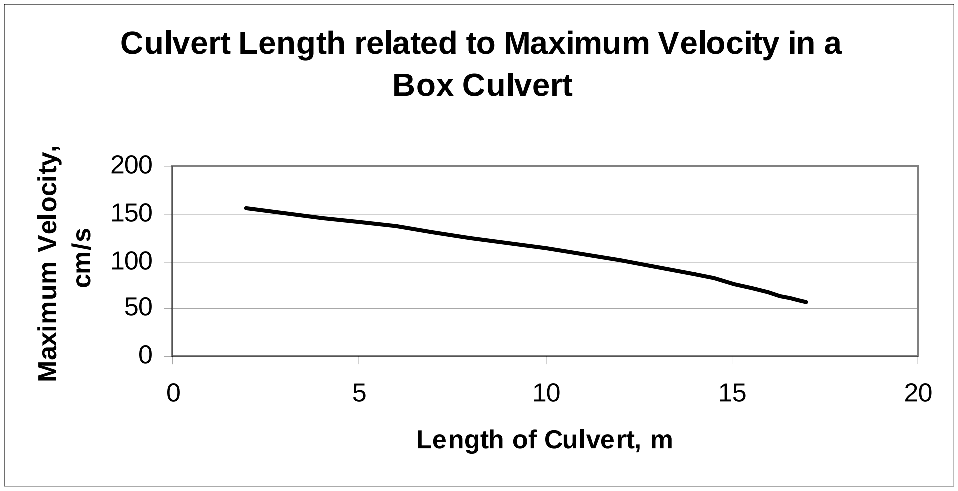
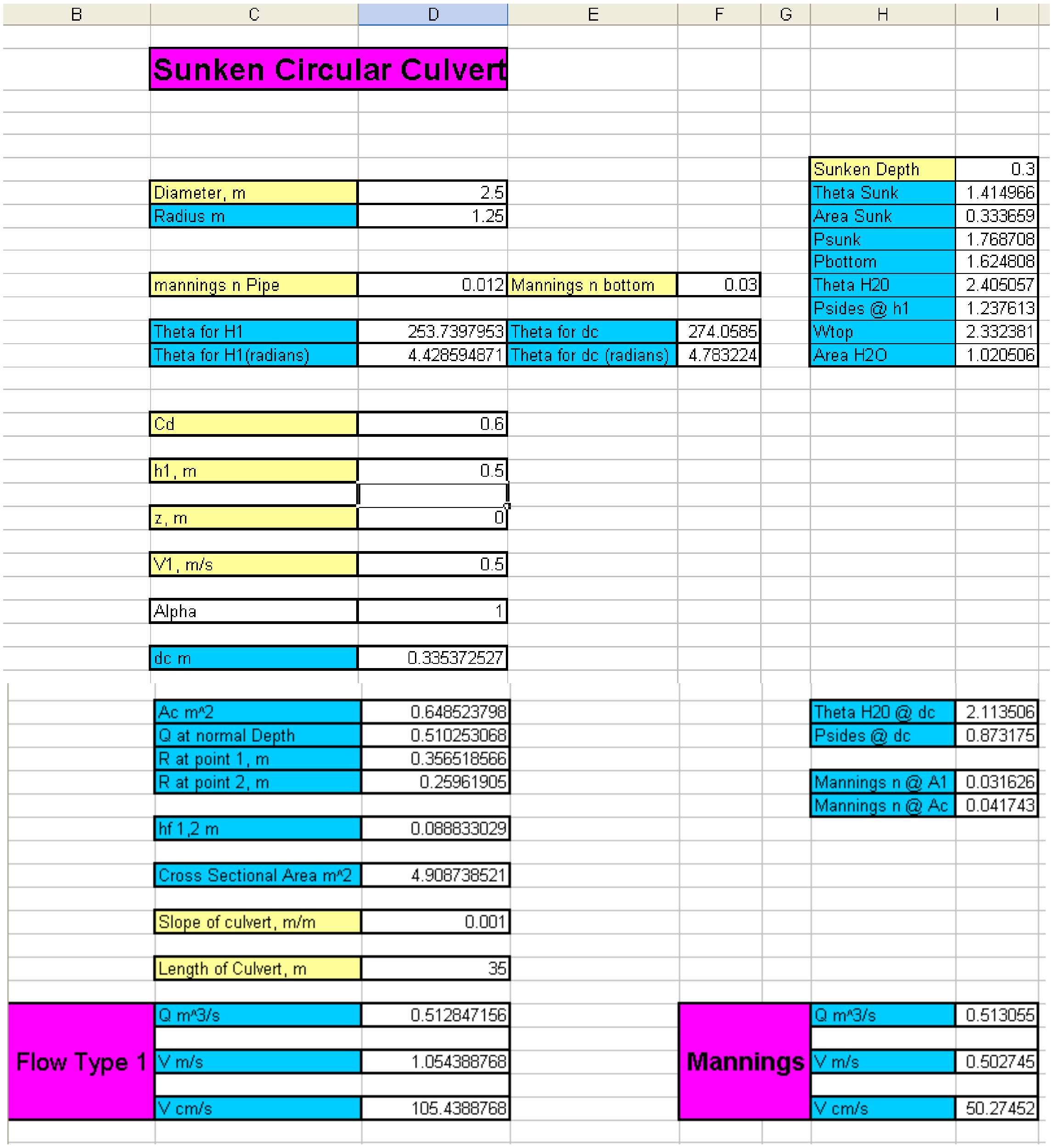


Figure C.15: Velocity response to culvert length in a box culvert

C.7 Model Interface

A	B	C	D	E	F	G	H	I
		Circular Culvert				input value		
		Diameter, m	2.5					
		Radius m	1.25			calculated value		
		mannings n Pipe	0.012					
		Theta for H1	253.7397953	Theta for dc	274.3306			
		Theta for H1(radians)	4.428594871	Theta for dc (radians)	4.787971			
		Cd	0.6					
		h1, m	0.5					
		z, m	0					
		V1, m/s	0.2					
		Alpha	1					
		dc m	0.333352506					
		Ac m^2	4.519622258					
		R at point 1, m	0.760483154	A at point 1, m^2	4.20984			
		R at point 2, m	0.755162769	A at point 2, m^2	4.519622			
		hf 1,2 m	0.000776544	Q for hf 1,2	0.841968			
		Cross Sectional Area m^2 of culvert	4.908738521					
		Slope of culvert, m/m	0.001					
		Length of Culvert, m	100					
Flow Type 1		Q m^3/s	4.921990444		**Mannings**		Q m^3/s	9.242952398
		V m/s	1.452035934				V m/s	2.195559205
		V cm/s	145.2035934				V cm/s	219.5559205

Figure C.16: Model interface for circular culvert



Sunken Circular Culvert

Diameter, m	2.5		
Radius m	1.25		
mannings n Pipe	0.012	Mannings n bottom	0.03
Theta for H1	253.7397953	Theta for dc	274.0585
Theta for H1(radians)	4.428594871	Theta for dc (radians)	4.783224
Cd	0.6		
h1, m	0.5		
z, m	0		
V1, m/s	0.5		
Alpha	1		
dc m	0.335372527		
Ac m^2	0.648523798		
Q at normal Depth	0.510253068		
R at point 1, m	0.356518566		
R at point 2, m	0.25961905		
hf 1,2 m	0.088833029		
Cross Sectional Area m^2	4.908738521		
Slope of culvert, m/m	0.001		
Length of Culvert, m	35		

Sunken Depth	0.3
Theta Sunk	1.414966
Area Sunk	0.333659
Psunk	1.768708
Pbottom	1.624808
Theta H20	2.405057
Psides @ h1	1.237613
Wtop	2.332381
Area H2O	1.020506
Theta H20 @ dc	2.113506
Psides @ dc	0.873175
Mannings n @ A1	0.031626
Mannings n @ Ac	0.041743

Flow Type 1	Q m^3/s	0.512847156	Mannings	Q m^3/s	0.513055
	V m/s	1.054388768		V m/s	0.502745
	V cm/s	105.4388768		V cm/s	50.27452

Figure C.17: Model interface for Sunken Circular Culvert

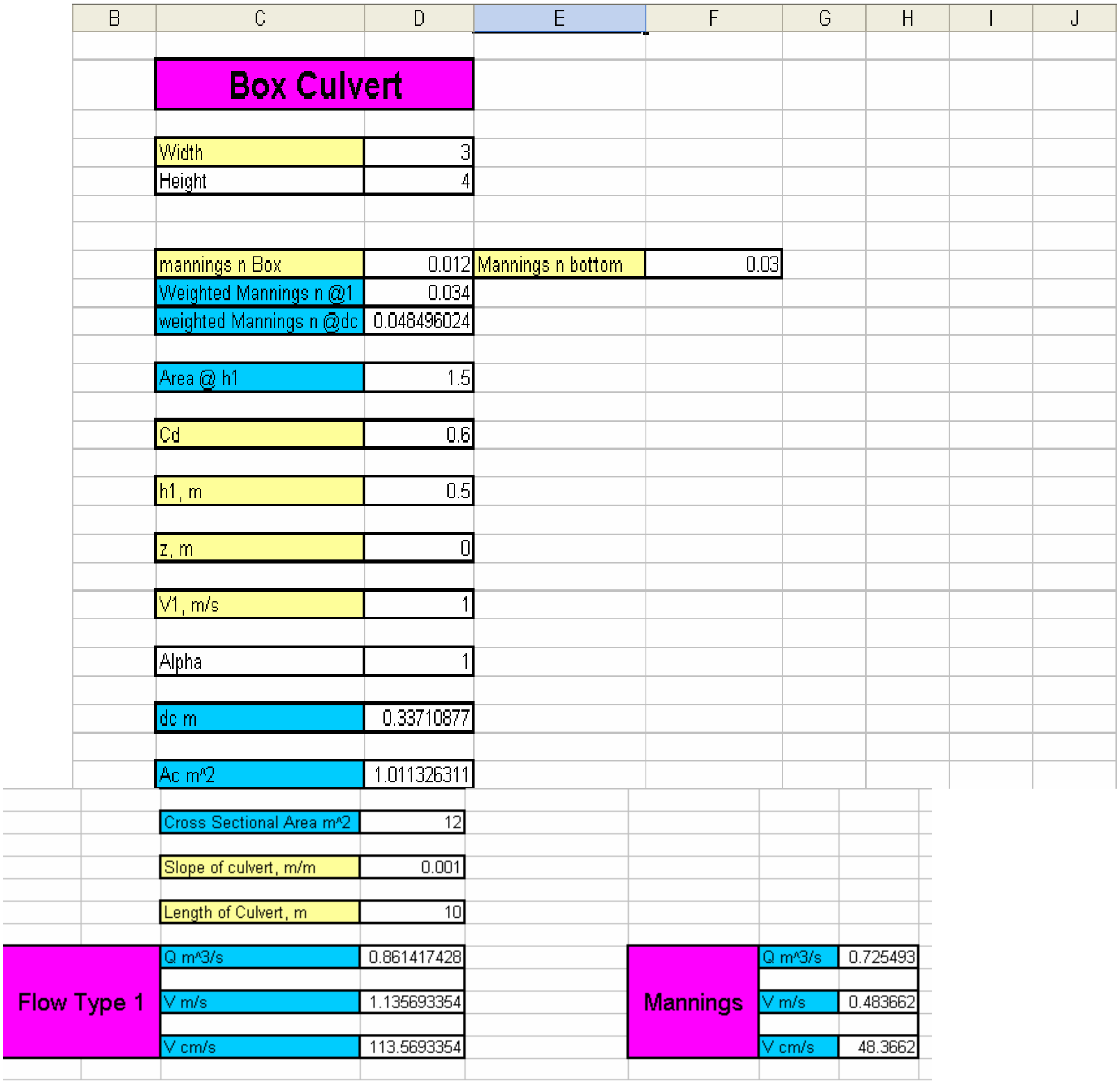


Figure C.18: Model Interface for Box Culvert

Species	LS mean	25% CL		35% CL		40% CL		50% CL		60% CL		75% CL		85% CL		95% CL	
Bluegill	37.15315	36.50	37.81	36.22	38.09	36.07	38.23	35.76	38.54	35.42	38.89	34.78	39.52	34.18	40.12	33.10	41.21
Bluehead chub	76.67097	75.66	77.68	75.24	78.10	75.01	78.33	74.54	78.80	74.01	79.33	73.03	80.31	72.11	81.23	70.45	82.89
Johnny darter	73.3068	72.15	74.46	71.66	74.95	71.41	75.21	70.86	75.75	70.25	76.36	69.13	77.48	68.08	78.54	66.17	80.44
Margined madtom	48.83544	47.13	50.54	46.40	51.27	46.03	51.64	45.22	52.45	44.32	53.35	42.66	55.01	41.11	56.57	38.29	59.38
Redbreast sunfish	44.63751	43.93	45.35	43.62	45.65	43.47	45.81	43.13	46.14	42.76	46.52	42.07	47.21	41.42	47.86	40.24	49.03
Swallowtail darter	66.36167	65.32	67.40	64.88	67.84	64.65	68.07	64.17	68.56	63.62	69.10	62.61	70.11	61.66	71.06	59.95	72.77

	Velocity	Confidence interval on the mean critical velocity for each species
Bluegill		25% or less
Bluehead chub		25% or less
Johnny darter		25% or less
Margined madtom		25% or less
Redbreast sunfish		25% or less
Swallowtail darter		25% or less

If the velocity is greater than the upper limit of the 95% confidence interval the model will stat that the fish cannot pass through the cuvlert

Figure C.19: Model interface for the “Input Velocity” sheet.