ASSESSING FISH PASSAGE SUCCESS IN CULVERT STRUCTURES WITH THE DEVELOPMENT OF A TWO-DIMENSIONAL ALGORITHM CONSIDERING PHYSICAL CAPABILITIES OF JUVENILE SALMONIDS

By

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Abstract

Fish passage through culvert structures requires suitable behavioral and physical conditions for fish. Current practice consists of "stream simulation" design where the stream is replicated throughout the crossing structure; however, space and/or budget constraints do not always allow this practice and require the designer to model hydraulics against fish swimming abilities to assess for barriers. Current models are one-dimensional and can be overly conservative.

This thesis analyzed stream properties within a culvert structure on Buddy Creek near Talkeetna, Alaska, and utilized this data to develop a two-dimensional algorithm with hydraulic output from River2D, to determine if the depth and velocity throughout the structure were conducive to passage of juvenile salmon. Modeled velocity and water depth from River2D were used and compared to published fish species' characteristics to determine if fish passage through the structure, in two-dimensions, would be successful. Additionally, the commonly used one-dimensional model, FishXing, was run to assess passage and to compare against the algorithm. Passage results from FishXing and the algorithm were compared against actual juvenile salmonid passage data at known flows provided by the Alaska Department of Fish and Game.

Both one-dimensional and two-dimensional models produced similar results. Based on the outcome, the two-dimensional model does not appear to add much more accuracy, and FishXing appears to fairly accurately take into account occupied velocity of the juvenile fish when using proper velocity reduction factors. Although, FishXing and the two-dimensional algorithm are still fairly conservative and appear to be limited by the studied fish swimming abilities, especially for Chinook and coho salmon.

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List of Abbreviations

ADOT&PF	Alaska Department of Transportation & Public Facilities
ADV	Acoustic Doppler Velocimeter
AOP	Aquatic Organism Passage
ADF&G	Alaska Department of Fish & Game
BF	Bankfull
CFR	Code of Federal Regulations
CFS	Cubic Feet per Second
FHWA	Federal Highway Administration
FPS	Feet per Second
GVF	Gradually Varied Flow
HEC-RAS	Hydrologic Engineering Center's River Analysis System
HGL	Hydraulic Grade Line
MOA	Memorandum of Agreement
PHABISM	Physical Habitat Simulation
PIT	Passive Integrated Transponder
UAA	University of Alaska Anchorage
UAF	University of Alaska Fairbanks
USFS	United States Forest Service
USFWS	United States Fish & Wildlife Service
USGS	United States Geological Survey

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1 Introduction

1.1 Background and Current Practice of Aquatic Organism Passage

Stream simulation design, as described in the U.S. Forest Service's guide (Forest Service Stream-Simulation Working Group, 2008) is becoming common practice in the design and construction of many new stream crossings across the state of Alaska as well as the rest of the United States. Stream simulation entails careful survey of existing conditions outside of the influence of any existing crossing structure in order to recreate this natural environment. Recreating the natural habitat allows for continued passage of aquatic life. Older designs have often only considered hydraulic capacity of the structure and have therefore disturbed the natural environment and have, in many cases, created a barrier in the stream and disrupted natural geomorphic and hydraulic characteristics.

Fish and aquatic life barriers in streams have been an ongoing issue for years. "Habitat fragmentation is an important factor contributing to population declines of many fish, and crossing structures that are barriers are a large part of the problem" (Forest Service Stream-Simulation Working Group, 2008). For years, infrastructure has been built with little concern for fish passage. Bridges, culverts, dams, and other structures were constructed, designed only for hydraulic capacity and ultimately blocking the stream for some aquatic organisms. Fortunately, this practice is being abandoned and permitting agencies are requiring consideration of fish passage at any new crossing site where fish are present. Fish streams, particularly anadromous streams (where fish migrate between freshwater spawning grounds and the ocean) often require special permit stipulations. There is also a current movement of rehabilitating streams and removing barriers through the existing infrastructure to help reestablish native populations.

It is now law to provide adequate passage for fish. Clean Water Act Section 404(f) states "The design, construction and maintenance of the road crossing shall not disrupt the migration or movement of those species of aquatic life inhabiting the water body [33 CFR 323.4 (a)(6)(vii)]. In Alaska, the Alaska Fishway Act (Alaska Statute 16.05.841) states:

> If the commissioner considers it necessary, every dam or other obstruction built by any person across a stream frequented by salmon or other fish shall be provided by that person with a durable and efficient fishway and a device for efficient passage of downstream migrants. The fishway or device or both shall be maintained in a practical and efficient manner in the place; form and capacity the commissioner approves. For which plans and specifications shall be approved by the department upon application to it. The fishway or device shall be kept open, unobstructed, and supplied with a sufficient quantity of water to admit freely the passage of fish through it.

If stream simulation is not feasible (for instance if there are space constraints for a structure spanning the width of the stream) design can be done in consideration of hydraulic characteristics and potential for fish passage. In this case, fish passage modeling is often conducted.

Current design practice for fish passage modeling with consideration of velocity is done with a one-dimensional program called FishXing (pronounced “fish crossing”). This program was developed by an interdisciplinary group of engineers, hydrologists, geologists, biologists, and programmers with various agencies and private companies across the Pacific Northwest. It allows for modeling of a known fish species of a certain size within a known structure to assess passage adequacy. The program assumes continuity of flow (steady flow), uses normal depth, assumes a velocity of zero at the inlet of the culvert, and ignores any backwater effects as it only utilizes Manning’s equation for depth and velocities. The program assesses the modeled culvert through identification of limitations within the structure of a specific fish species at a specific life stage or size. Fish data within the FishXing program is based on various biological studies on species capabilities, including: maximum jump height with required pool depth, maximum velocity for prolonged and burst swimming, and minimum depths. In addition to FishXing, other programs and one-dimensional hydraulic models (such as the U.S. Army Corps of Engineers’ program HEC-RAS or Federal Highway Administration’s HY-8) are often used in conjunction for additional hydraulic analysis to design a crossing structure (e.g., preventing roadway overtopping at higher flows).

Fish and other aquatic organisms traverse through streams finding zones where hydraulic characteristics are within their capabilities. This includes appropriate water depth and velocities that allow the fish to find the conditions that warrant passage based on their swimming prolonged and burst speeds. Within a cross-section of a stream, pools, or roughness features may exist to create a resting zone or areas of lower velocities to allow continued passage in a stream or crossing structure. One-dimensional hydraulic and fish passage models (such as FishXing) create an average cross-sectional velocity, and assess fish passage along the longitudinal plane. The user can select velocity reduction factors in FishXing to reduce the average velocity within the cross-section for comparison against fish swimming abilities; however, studies and direction for selection of these factors are limited. The model does not fully account for the variation in velocities in the transverse direction, and therefore, has been speculated to be overly conservative (Mahlem et al., 2013, Burford et al., 2009, Bourne et al., 2011). Being over conservative adds a factor of safety for fish passage; however, as Mahlem et al., (2013) stated, "The installation and replacement of stream crossings is an expensive endeavor and using inaccurate barrier assessment methods to prioritize culvert restoration could unnecessarily burden limited financial resources when no action is needed to promote fish passage". No model currently exists to determine if a fish can pass a culvert utilizing transient velocity zones in both the longitudinal and transverse direction (two dimensions) within a stream reach or crossing structure.

1.2 Objective

The main objective of this thesis was to create a two-dimensional fish passage algorithm able to assess hydraulic variations within the structure associated with streambed or varied roughness along the pipe that compares two-dimensional hydraulics (velocity and depths) through a culvert structure to known, published, juvenile salmonid swimming capabilities (as used in FishXing), specifically coho (*Oncorhynchus kisutch*), Chinook (*Oncorhynchus tshawytscha),* and rainbow trout (*Oncorhynchus mykiss*), between the tagged sizes of roughly 55 and 120 millimeters (mm). The purpose was to closely study the more realistic two-dimensional pathways of fish through a structure, or the "occupied velocity" to allow for better understanding of fish movement, and to allow for a simple and more accurate method for analyzing passage through structures.

The secondary objective of this thesis was to compare passage results from FishXing, the developed two-dimensional algorithm, and actual passage results surveyed by the Alaska Department of Fish and Game (ADF&G) between 2013 and 2016.

2 Literature Review

Studies and other literature related to fish passage, fish swimming capabilities, and hydraulic modeling were reviewed throughout this study. This literature review specifically discusses the history of fish passage design and modeling as it pertains to fish swimming abilities.

Fish passage design generally falls under three types of design: 1) stream simulation, 2) geomorphic design, and 3) hydraulic design. Stream simulation is typically the preferred option as it attempts to design the structure to mimic the actual stream. Geomorphic design is similar to the latter, simulating the stream within the structure based on the stream's geomorphology. Hydraulic design, however, typically only considers passing flow through the structure, and not passage of aquatic organisms. The following discusses swimming abilities that were considered for this study, and models and design procedures used in either geomorphic or hydraulic simulation.

2.1 Fish Swimming Abilities

Various studies have been conducted, primarily between the mid-1970s and into the early 1990s, on fish swimming abilities, and areas where fish prefer to swim.

The document "Fundamentals of Culvert Design for Passage of Weak Swimming Fish" (Behlke et al., 1991), was a founding document in Alaska for design of fish passages considering fish swimming capabilities, specific to "weak swimming" fish—the design fish is considered an Arctic grayling; however, equivalent length factors allow a conversion of other fish species to the design fish. Juvenile salmonids are an exception as the size difference between a juvenile salmonid and an Arctic grayling is large enough that the equivalent length results in excessive calculation of gradient forces (Alaska Department of Fish and Game & Alaska Department of Transportation and Public Facilities, 2001).

The design document (U.S. Federal Highway's document number: FHWA-AK-RD-90-10) developed by the University of Alaska Fairbanks (UAF) and the Alaska Department of Transportation and Public Facilities (ADOT&PF), describes hydraulic formulas using profile drag (velocity), non-Archimedean buoyant forces (gradient), and virtual mass forces, to determine if the fish has enough swimming power and energy to pass through the culvert.

In addition to the above, the document provides discussion on the hydraulic variances within the longitudinal profile of the culvert and the variances in fish swimming abilities as the fish swims along the profile. Fish use either red muscle, white muscle, or a combination of the two to traverse a stream or fish passage structure. The use of these muscles correlates with different propulsive modes.

The following defines propulsive modes of “cruising speed”, “sustained (or prolonged) speed” and “burst (or darting) speed” according to ADF&G and ADOT&PF (2001):

> Cruising speed is the speed a fish can maintain for an extended period of travel without fatigue. Metabolic activity in this mode is strictly aerobic and utilizes only red muscle tissues.
>
> Sustained (prolonged) speed is the speed that a fish can maintain for a prolonged period, but which ultimately results in fatigue. Metabolic activity in this mode is mixed anaerobic and aerobic and utilizes some white muscle tissue and possibly red muscle tissues.
>
> Burst (darting) speed is the speed a fish can maintain for a very short period, generally 5-7 seconds, without gross variation in performance. Burst speed is employed for feeding, escape, and negotiating difficult hydraulic situations, and represents maximum swimming speed. Metabolic activity in this mode is strictly anaerobic and utilizes all of the white muscle tissues.

Accommodating the different muscle groups is imperative in fish passage design. Through their studies of Arctic grayling, Belhke et al. (1993), indicated that fish seek locations within a structure where swimming is the easiest, staying close to areas with higher roughness (such as the surface, bottom, or near culvert corrugations), and that they appear to understand their white and red muscle swimming abilities by swimming quickly through areas requiring white muscle, and conserving their energy by taking their time when using red muscle. Engineers are mostly interested in accommodating the white muscle (burst speed) through difficult, high-velocity, or turbulent areas. However, if the fish exhaust their white muscles at the culvert outlet, it is likely they will not be capable of traversing the entire structure if other areas of high velocity or need for burst speed present themselves, unless there is a resting location within the structure.

The following figure (from Behlke, 1991), displays the free body diagram that shows the analyzed forces that act on the fish as it swims through a structure.

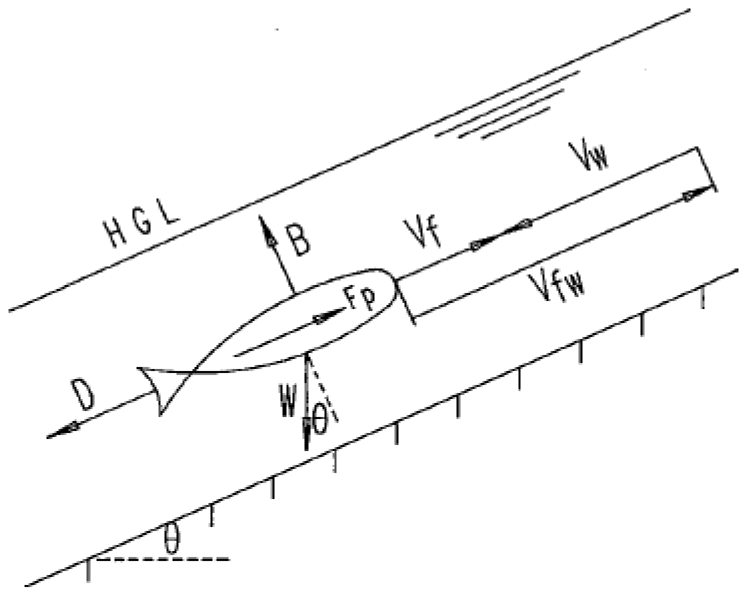

Figure 1. Forces acting on fish passing through culvert (Behlke, 1991) HGL=hydraulic grade line, B=buoyancy force, D=drag, F_p=net propulsive force, W=mass of fish, V_f=velocity of fish, V_w=velocity of water, V_{fw}=velocity of fish with respect to water, and θ=angle of the channel with respect to the horizontal

Other factors that Behlke et al. (1993), who summarizes the 1991 design document in the report titled, "Economic Culvert Design Using Fish Swimming Energy and Power Capabilities" considered were non-Archimedean buoyancy effects and acceleration of the fish and/or surrounding water within the passage structure; although, they found that most fish did not accelerate while swimming through a structure. Additionally, where the surface slopes (Hydraulic grade line [HGL] is not parallel to the channel) an additional drag force acts on the upstream-swimming fish. Belkhe (1991) mentioned that these analyses did not take into account yawing of the fish, centripetal forces, turbulent forces, or the potential drag decrease due to the mucus on the fish.

Equation 1 describes the power (P) necessary for the design fish to overcome specific hydraulic conditions:

$$P = (F_D + F_G + F_{vm})V_{fw} \tag{1}$$

F_D (shown in Figure 1 as D) is the drag force, F_G is the resultant between the buoyancy force (B) and weight of the fish (W), F_{vm} is the virtual mass force shown in Equation 2, below (where g is the acceleration due to gravity (32.2 ft/s^2), a_{fw} is the acceleration of the fish with respect to the surrounding water), and V_{fw} is the velocity of the fish with respect to water.

$$F_{vm} = 1.2\left({}^{W}/_{g}\right)a_{fw} \tag{2}$$

These studies, mentioned above, are used to provide guidance in designing culverts specifically for what they refer to as “Class I swimmers” or “weak swimming fish”, such as the Arctic grayling and juvenile salmonids. These fish likely cannot pass structures with supercritical flow, and therefore require mild slopes and outlet depths greater than critical depth (an M-1 or M-2 gradually varied flow water surface profile in the culvert barrel). They also found the importance of large culvert corrugations that create a larger boundary zone of low water velocities (occupied velocity—where the fish would actually swim or rest) affected by the roughness of the culvert sides. Many current design procedures for fish passage culverts require embedment of the culvert which adds additional roughness inside the barrel due to substrate.

Another key document for fish passage design and fish swimming information is the U.S. Army Corps of Engineers, North Pacific Division, Fish Passage Development and Evaluation Program, “Fisheries Handbook on Engineering Requirements and Biological Criteria” (Bell, 1991), particularly *Chapter 6: Swimming Speeds of Adult and Juvenile Fish*. Bell compiled data from lab and field tests presenting ranges of cruising, sustained, and burst speeds for 12 juvenile and 22 adult fish species. With this data, Bell presented a ratio of sustained speed to dart speed based on species and length of fish, and temperature. It was noted that not just length of fish and temperature affect swimming abilities, but also other environmental factors such as oxygen availability in the water, presence of light (a fish is more likely to attempt an obstacle when it is light rather than dark), and presence of pollutants. Bell presented sustained speed as approximately half that of the maximum (darting) speed and cruising speed as approximately a sixth of the maximum speed. Temperature affected the speed (cruising, specifically, in this study), where a underyearling coho would have peak ability for cruising speed at approximately 68° Fahrenheit (20° Celsius). Ability would decrease at approximately the same rate with temperature increase or decrease. Bell noted that 7.5 seconds is an appropriate time to use for time to exhaustion in darting speed for juvenile salmonids.

Hunter and Mayor (1986) also led research on fish swimming abilities, and produced a set of regression equations based on previously performed swim speed tests. This is shown in Equation 3 as the "Swim Speed Equation" and is used extensively in the one-dimensional FishXing program.

$$V = aL^b t^{-c} \quad [3]$$

V is the swim speed of the fish relative to the water (m/s), L is the total length of the fish in meters, t is time to exhaustion in seconds, and a, b, and c are regression constants. Equations 4-6 are sustained velocity (V_s) equations (in m/s) for coho at the noted sizes and temperatures.

Coho (40-178 mm) at temperatures 8-12° Celsius:

$$V_s = 3.02L^{0.52} t^{-0.1} \quad [4]$$

Coho (40-133 mm) at temperatures 13-15° Celsius:

$$V_s = 5.67L^{0.7} t^{-0.1} \quad [5]$$

Coho (40-120 mm) at temperatures 18-20° Celsius:

$$V_s = 5.87L^{0.7} t^{-0.1} \quad [6]$$

Only eight fish were included in the study that produced the above regression equations. For juvenile Chinook salmon, Kerr (1953) completed a study that included 282 fish. The test was a fixed velocity test where juvenile Chinook, with a length range of 31.8 to 48 mm, were exposed to a velocity with a range of 15.24 cm/s to 61.96 cm/s. The median resulting sustained velocity was 30.48 cm/s. Time to exhaustion was 600 seconds. Water temperature during the study was not reported.

Unfortunately, very little data exists on burst speeds in juvenile salmonids. Bell (1991) has provided ratios, but only that should be applied to adult fish. Robert Gubernick with the U.S. Forest Service (USFS), lead fish passage engineer for the Tongass National Forest, a contributing author of the USFS Stream Simulation Guide, and co-developer of FishXing, has provided guidance for the Tongass National Forest on inputs for modeling fish passage more accurately (n.d.). Gubernick suggested a sustained speed of 1.3 feet per second (fps) for a 55 mm coho, and a burst speed of 2.6 fps. Gubernick recommended a time to exhaustion of 15 minutes for prolonged swimming, and 7.5 seconds for burst swimming (in agreement with Bell).

The California Salmonid Stream Habitat Restoration Manual (Flosi et al., 2010) also includes recommendations for juvenile salmonid swim speeds. A sustained speed of 1.5 fps and a burst speed of 3 fps are listed for juvenile salmonids with exhaustion times of 30 minutes and 5 seconds, respectively. Minimum water depth recommended in the manual was 0.3 feet, whereas minimum water depth, recommended by Gubernick, was 0.1 feet. Lastly, the NOAA Fisheries Northwest Region provides guidance, and utilizes a maximum prolonged velocity of 1 fps for all juvenile salmonids without any variations for temperature (NMFS, 2008).

Overall, it was determined, based on initial analysis and correspondence with ADF&G that Chinook swimming data was greatly lacking and research only existed for smaller fish. They were tested in this thesis; however, it was generally assumed that Chinook possess similar swimming abilities as juvenile coho (O'Doherty, 2017).

In addition to coho and Chinook, some rainbow trout were also assessed. Jones et al. (1974) provided a sustained speed of 2.6 fps for coastal rainbow trout (subspecies *O. m. irideus*) at a temperature of 22.6°C and an exhaustion time of 20 minutes. Hunter and Mayor's regression equation for water temperatures ranging from 7 to 19°C was given for burst speed with a time to exhaustion of 1 to 12.5 seconds. This equation is shown as Equation 7 (in meters per second). No length data was provided for these studies, and burst data was based on the fasted fish tested. Time to exhaustion varied, so Furniss et al. (2006) recommended use of 5 seconds in the FishXing program.

$$V_b = 12.03L^{0.62}t^{-0.51} \qquad [7]$$

2.2 Fish Passage Design/Modeling History

Modeling techniques for fish passage design in Alaska could be described in tiers as is generally laid out in the Memorandum of Agreement (MOA) between ADF&G and ADOT&PF (2001). Tier 1 is a geomorphic-based design, titled "Stream Simulation Design"; however, it does not meet all of the criteria for USFS stream simulation design. Tier 2 is hydraulic design, in which the designer uses models to simulate hydraulics in the structure to assure fish can pass successfully—in the case of the 2001 MOA, the one-dimensional model FISHPASS is used. FishXing could also fall under this hydraulic design tier and is often used by USFS. Tier 3 is a hydraulic engineering design which purely models the crossing for hydraulic criteria and does not consider fish passage. Tier 3 design generally does not allow for successful passage of fish and is therefore not discussed further in this document.

2.2.1 FISHPASS

FISHPASS is a one-dimensional computer model that was developed by UAF and ADF&G (Behlke et al., 1991). The model is not based on acceptable cross-section velocities inside the culvert, but is based on the method described above evaluating the hydraulic forces within the structure against the fish's available power and energy capabilities (ADF&G and ADOT&PF, 2001). Firor (2000), one of the developers of FishXing, describes this as the "Power and Energy Method" in her Master's thesis comparing FISHPASS to FishXing. FISHPASS uses limitations on burst energy, burst power, and prolonged energy as barriers for a fish traversing a culvert.

Since FISHPASS does not use direct velocity as a passage criterion, it was not used in this study. Additionally, FISHPASS force equations take weight into account instead of length. Weight plays a bigger role in larger fish, and the length conversion for smaller, juvenile fish (studied here) may overestimate the juvenile fish's abilities (ADF&G and ADOT&PF, 2001).

2.2.2 FishXing

FishXing is a one-dimensional fish passage modeling program that calculates average cross-sectional velocity. This model was developed after FISHPASS, in the late 1990s by Pacific Northwest Research Station, Forest Service Engineering Technology and Development Program, the Federal Highway Administration, the Stream Systems Technology Center, Rocky Mountain Research Station, and the U.S. Fish and Wildlife Service. This program provides one-dimensional analysis through a culvert, uses normal depth for fish passage estimates, and allows input for outlet conditions, embedment options, culvert selection (including corrugation size for metal pipes and any end treatment), and input for fish species and size. The model does not take into account backwater effects as it uses Manning's Equation (Equation 8), and velocity is assumed to start at 0 fps at the culvert inlet.

$$V = \frac{1.49}{n} R^{\frac{2}{3}} S^{\frac{1}{2}} \quad [8]$$

The Manning's equation solves for velocity (fps) based on a roughness value "n", and channel characteristics such as the hydraulic radius (R) and the slope of the channel (S).

The model also utilizes the gradually varied flow (GVF) equation, as shown in Equation 9. This provides solutions throughout the length of the culvert, allowing the user to view velocity results near the inlet, throughout the barrel, and at the outlet of the culvert, and to determine location of failure and barrier type to the fish.

$$\frac{dy}{dx} = \frac{S_0 - S_f}{(1 - Fr^2)} \quad [9]$$

The GVF equation shows the change in vertical (dy) with respect to the change in horizontal (dx) is equal to the difference between the bottom slope (S_0) and the friction slope (S_f), divided by 1 less the Froude number (Fr), Equation 10, squared. The friction slope is approximated using the Manning's equation (back solving for S in Equation 8). D, in Equation 10, is depth of the water.

$$Fr = \frac{V}{\sqrt{gD}} \quad [10]$$

Also available for input into FishXing, are fish species and their specific capabilities as discussed in the previous section. Fish species available for selection in the model include a wide range of species and their sustained (prolonged) speeds and burst (darting) speeds for varying sizes and water temperatures based on actual studies.

FishXing provides a quick and user-friendly tool for assessment of culverts, but the user may need to alter inputs to create a more realistic result as they would for any computer model. One such input is using velocity reduction factors to more accurately model the occupied velocity within the structure. Since FishXing uses an average cross-sectional velocity, the use of velocity reduction factors creates a more realistic simulation since fish tend to take advantage of slower velocities around the structures boundaries, such as culvert walls or bottom. Typically these are applied only to smaller fish that benefit from the roughness of the corrugations of the culvert. The occupied velocity, shown in Figure 2, typically varies between 10 to 50% of the average water velocity (Powers, 1997).

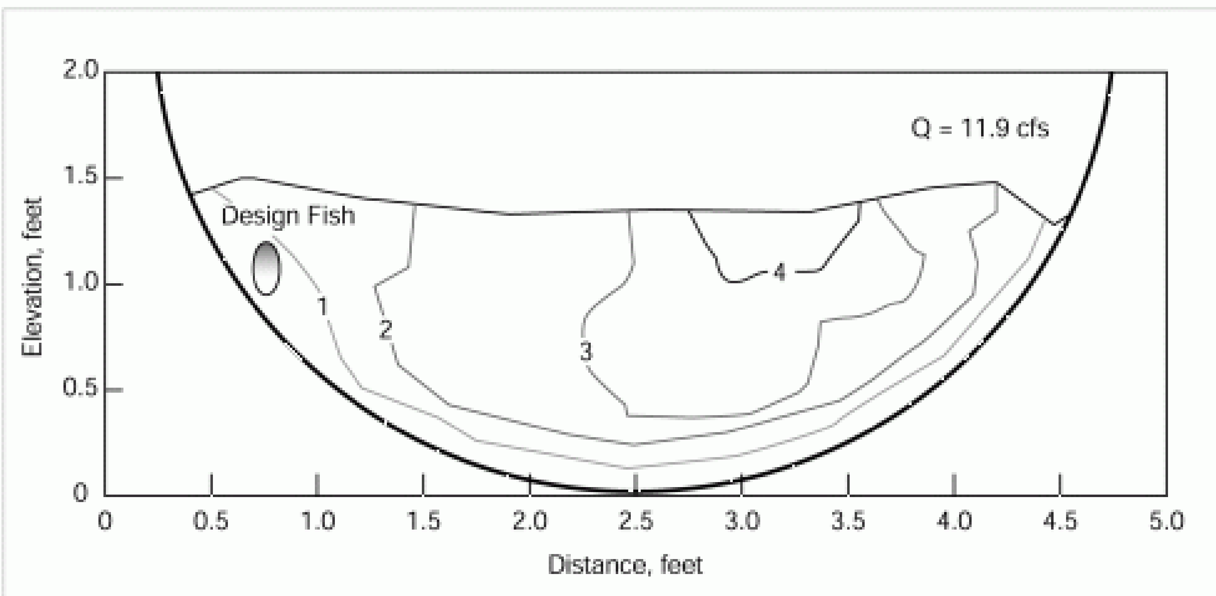

Figure 2. Occupied velocity (Furniss et al., 2006)

A Master’s thesis paper, titled “Velocity Reduction Factors in Near Boundary Flow and the Effect on Fish Passage through Culverts” (Jensen, 2014) was reviewed for this project. Based on research, Jensen developed recommended velocity reduction factor equations to account for the occupied velocity within the culvert. Without velocity reduction factors, the model purely calculates the barrier based on average velocity within the culvert. As mentioned previously, Behlke, et al. (1993) found that weak swimming fish tend to find areas of lower velocity within the structure (i.e., occupied velocity). The velocity reduction factors allow for decreased velocity within the occupied portions of the culvert in the boundary zones, such as along the corrugations. Jensen developed an equation using Prandtl's Law (Log-law) considering relative depth and relative roughness within the culvert. The final recommendation, given by Jensen, was to use velocity reduction factors along with engineering judgement for non-embedded culverts.

In addition to the recommended velocity reduction factors by Jensen, Gubernick provided methodology for the Tongass Fish Passage Program for assessment of structures for barrierity or classification as a "red pipe". Gubernick provided velocity reduction factors for the inlet, barrel, and the outlet based on percent of bedload in the culvert. Velocity reduction factors, recommended by Gubernick, are presented in the following table.

Table 1. FishXing velocity reduction factors recommended by Gubernick

Percent Bedload Cover or Corrugation Size	Velocity Reduction for Inlet	Velocity Reduction for Barrel	Velocity Reduction for Outlet
>80% to <100%	0.8	0.4	0.8
>20% to <79.9%	0.8	0.6	0.8
0% to 19.9%	0.8	0.8	0.8
Corrugations = 6"x2"	0.8	0.4	0.8

Additionally, Belhke et al. (1991) stated that juvenile salmonids occupy 40% to 80% of the average cross-sectional velocity. This lead Furniss et al. (2006) to recommend 0.8 for the inlet and outlet, and 0.6 for the barrel for Fishxing input.

Use of velocity reduction factors are key in FishXing; however, multiple studies have been conducted showing that, even when using the above suggested velocity reduction factors, FishXing can still be very conservative. Mahlem et al. (2013) stated specifically for their study, "...FishXing predictions of suitable fish passage discharges were conservative, with tagged fish successfully navigating partial barriers at least 2 to 3 times the upper limits of stream flow that were predicted to allow successful passage." This conservatism is primarily blamed on incomplete knowledge of fish physiology and behavior. Other authors, such as Bourne et al. (2011) and Burford et al. (2009) have determined the same.

2.2.3 Stream Simulation

Stream simulation design is the preferred method by all agencies, as the crossing is designed and constructed to emulate a chosen reference reach within the stream (known to pass the design anadromous or resident fish) that does not constrict the water body, or create high velocity zones or other barriers to aquatic organisms. In many cases, this form of design provides quick permitting acceptance and requires very little, to no, fish passage hydraulic analysis.

The design procedure requires survey of a “reference reach” to replicate within the proposed crossing structure. Stream simulation typically includes an open-bottom arch, bridge, or an embedded culvert structure that spans bankfull (BF) width of the stream, and may be a wider span to include some stream bank on either side. By basically reconstructing an existing stream reach, the crossing should be neither harder nor easier to pass by aquatic organisms, than what is naturally occurring in the stream.

An in-depth design manual titled, “STREAM SIMULATION: An Ecological Approach to Providing Passage for Aquatic Organisms at Road-Stream Crossings” was developed by the Forest Service Stream-Simulation Working Group, and published in May 2008. This manual provides guidance on all steps needed to successfully design and construct a stream simulation project. The manual was created due to increase in popularity and acceptance of the stream simulation approach in Alaska and the Pacific Northwest.

Although stream simulation is the ideal design for streams containing anadromous or resident fish, some areas, due to space constraints, or a limited budget, do not allow a structure to span the bankfull width or addition of stream banks. The alternative is hydraulic design and fish passage modeling, such as the aforementioned one-dimensional models.

3 Materials and Methodology

In summary, the methodology for this thesis included the following:

1) Collected necessary preliminary data (i.e., survey of cross-sections and longitudinal profile)
2) Modeled existing culvert battery and replacement arch hydraulics in FishXing
3) Modeled replacement arch in two-dimensional hydraulic model, River2D
4) Used output from River2D and physical swimming abilities of fish (also used in FishXing) to create a two-dimensional fish passage algorithm
5) Calibrated hydraulic models with measured point velocities and depths at known discharges
6) Tested 2D fish algorithm against actual fish passage counts at known discharges
7) Compared the accuracy of the results from the algorithm and FishXing to the actual passage rates

3.1 Study Area/Site Characteristics

A specific site was chosen for this study due to existing stream data, frequent stage/discharge measurements, passive integrated transponder (PIT) tagging studies on a specific species and life stage of various juvenile fish, and overall interest and support from fish passage teams with ADF&G and U.S. Fish and Wildlife Service (USFWS).

The study site is an approximate two-hour drive north of Anchorage near Talkeetna, Alaska. The site originally consisted of a degraded culvert battery crossing of Buddy Creek at Sawyer's Shady Street, and has now been upgraded to a crossing consisting of a large stream simulation-designed arch culvert structure. Buddy Creek is the largest tributary to Montana Creek, which is considered by the State of Alaska as highly important for the spawning, rearing, or migration of anadromous fish (National Fish Habitat Partnership, 2014).

The overall project area is shown in Figure 3, a snapshot from ADF&G's fish passage database from 2014. Note that this is prior to the culvert battery being replaced. Culverts in the database are rated based on the Level 1 assessment of passage for a 55 mm coho

(Eisenman & O'Doherty, 2014). Ratings are green: conditions are likely to be *adequate* for passage for a 55 mm coho; gray: conditions *may be adequate* for passage for a 55 mm coho; and red: conditions are likely to be *inadequate* for passage for a 55 mm coho.

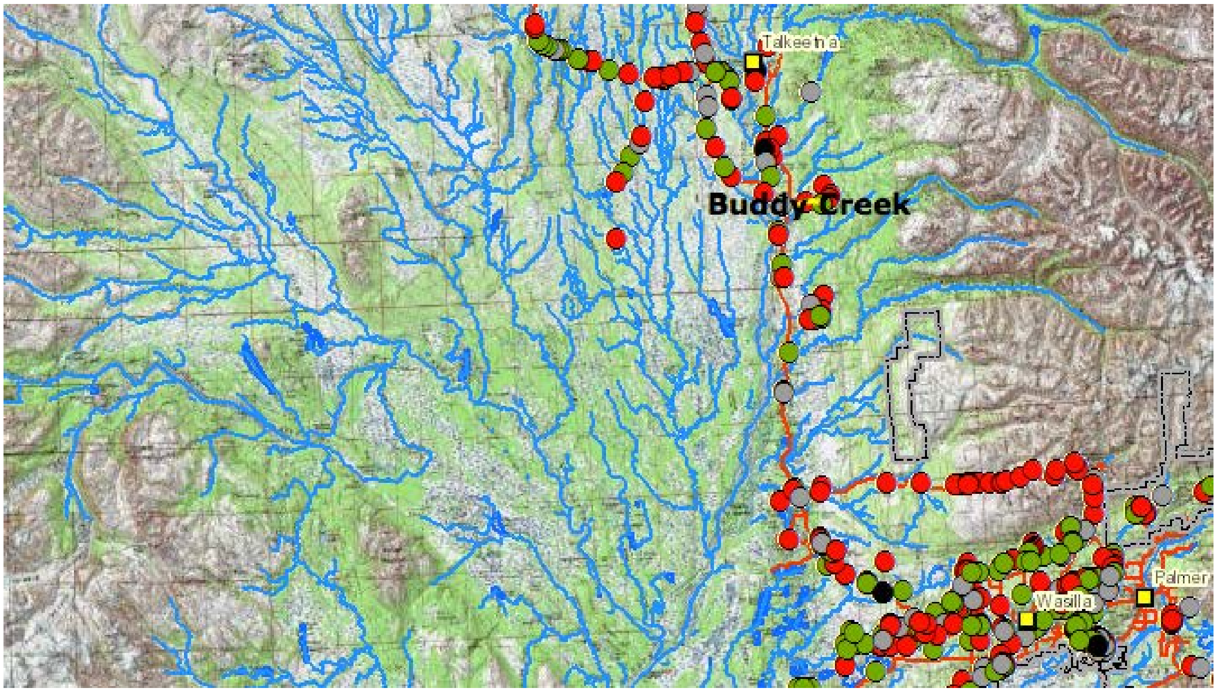

Figure 3. Overview of fish passages between Palmer and Talkeetna, Alaska (ADF&G Fish Passage Inventory Database, 2014)

The initial surveyed conditions at Sawyer's Shady Street included an array of three 48-inch diameter corrugated metal pipe culverts in poor condition (see Figure 4). Very little road cover resulted in the road overtopping during events where flows reached as little as 80 cubic feet per second (cfs). See Figure 5 taken by DOWL-HKM during a site visit. This crossing was assessed by ADF&G as red, or likely to be inadequate for the passage of a 55 mm juvenile coho, and was replaced by a single, larger arch culvert structure during the summer of 2015. This new structure was designed by DOWL-HKM (DOWL).

Figure 4. Buddy Creek culvert crossing – inlet, October 2014

Figure 5. Buddy Creek overtopping the road - looking downstream (DOWL, 2013)

DOWL, along with their design, produced a hydrology and hydraulics (H&H) report analyzing: hydrologic return interval flows through USGS regression equations, substrate material via a pebble count, and a hydraulic analysis utilizing U.S. Federal Highway's one-dimensional HY-8 program. Return interval discharges are presented in Table 2 along with a design fish passage flow, designated "Fish", the flow at which fish typically migrate through the stream. These return estimates were purely based on 2003 U.S. Geological Survey (USGS) regression equations (Curran et al., 2003), and when compared to the gage data, they appear to be under conservative. A hydrograph for Buddy Creek during

ADF&G's study period, prepared by ADF&G, is shown in Figure 6. The new structure, installed in 2015, is shown in Figure 7.

Table 2. Buddy Creek discharges (DOWL, 2014)

Return Interval *[year]*	**Discharge (Q)** *[cubic feet per second]*
Fish	29
2	73
5	116
10	149
25	194
50	230
100	268

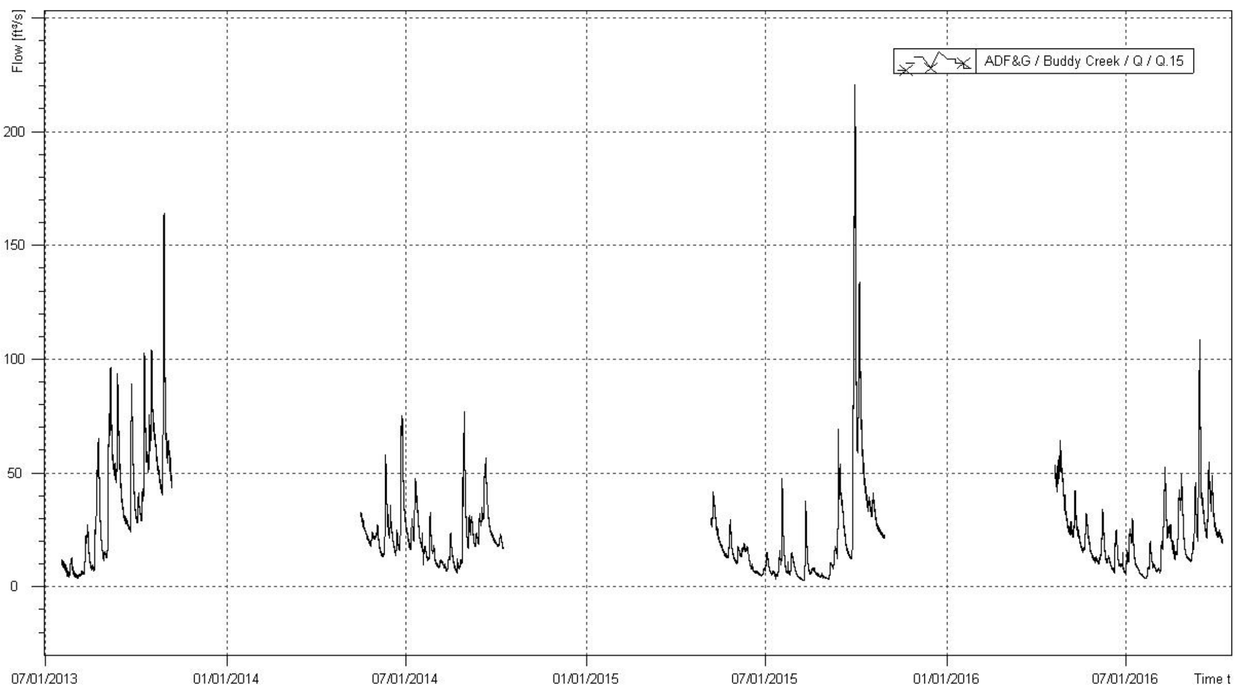

Figure 6. Buddy Creek hydrograph 2013-2016 (ADF&G, 2017)

Figure 7. Newly installed arch on Buddy Creek, July 2015

Bankfull flow in southcentral Alaska is typically around the 2-year flow; however, as mentioned above, after review of gage data it was determined that the presented 2-year flow is much lower than actual. An analysis was completed comparing Montana Creek and Buddy Creek flow data from their respective gages and found a well-fitted linear relationship. The linear relationship between Montana Creek and Buddy Creek allowed for the calculation of a 2-year flow for Buddy Creek. Additionally, ADF&G provided photographs from site visits at known flows that helped estimate bankfull conditions. After the above analysis, it was determined that bankfull flow at the crossing on Buddy Creek is approximately 125 cfs. The stage versus discharge plot for 2015 at the gage site is displayed in Figure 8, showing peak flow at approximately 220 cfs. Note that the gage site was at a pool, and the stream is fairly entrenched.

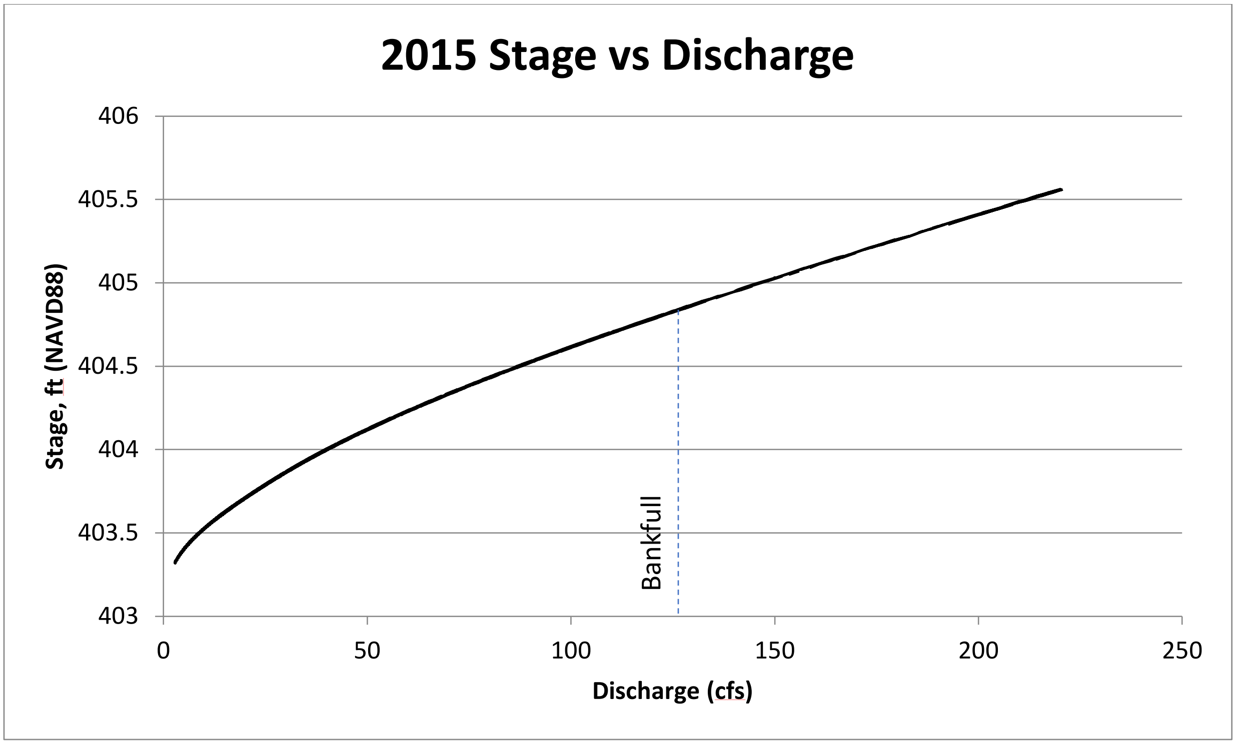

Figure 8. Buddy Creek stage vs. discharge

Concurrently with design work, ADF&G was conducting a study on fish passage rates at Buddy Creek. This included tagging juvenile coho and Chinook salmon, and rainbow trout between 65 and 120 mm in length, and measuring passage rates at known discharges. They installed a stream gage approximately 600 feet (along the creek) downstream of the Sawyer's Shady Street crossing of Buddy Creek to represent flows at the site, and took measurements during each site visit during the summers of 2013-2016. ADF&G had PIT tag antennas, with casings made of PVC pipe, installed upstream and downstream of the culverts (shown in Figure 9) that allowed them to track the known tagged fish (size and species) passing through the crossing at a gaged discharge. ADF&G continued this study through October 2016 with the new structure, as shown above. Additionally USFWS had been conducting a PIT tagging study in the Montana Creek watershed on coho and Chinook of similar size (down to 55 mm). Some of these USFWS-tagged fish passed through the structure and were used in this study.

Figure 9. Buddy Creek PIT tag antennas shown with taped measured cross-sections in October 2014, looking downstream

It should be noted that the PIT tag antennas had no way of differentiating which culvert within the old culvert array was used by the tagged fish. For the purposes of this study, it was assumed that the fish swam through the most attractive culvert (i.e., deeper water and lower velocities).

3.2 Data Collection

The methods used for data collection and modeling were per typical practice and as recommended per the models' developers. Data (such as cross-sections, survey, discharge and stage, point velocities, and fish passage data at the existing culvert array) were collected in fall of 2014 (or earlier) by DOWL, ADF&G, and/or USFWS. A cross-section, surveyed in 2014, at a riffle just downstream of the gage is shown in Figure 10.

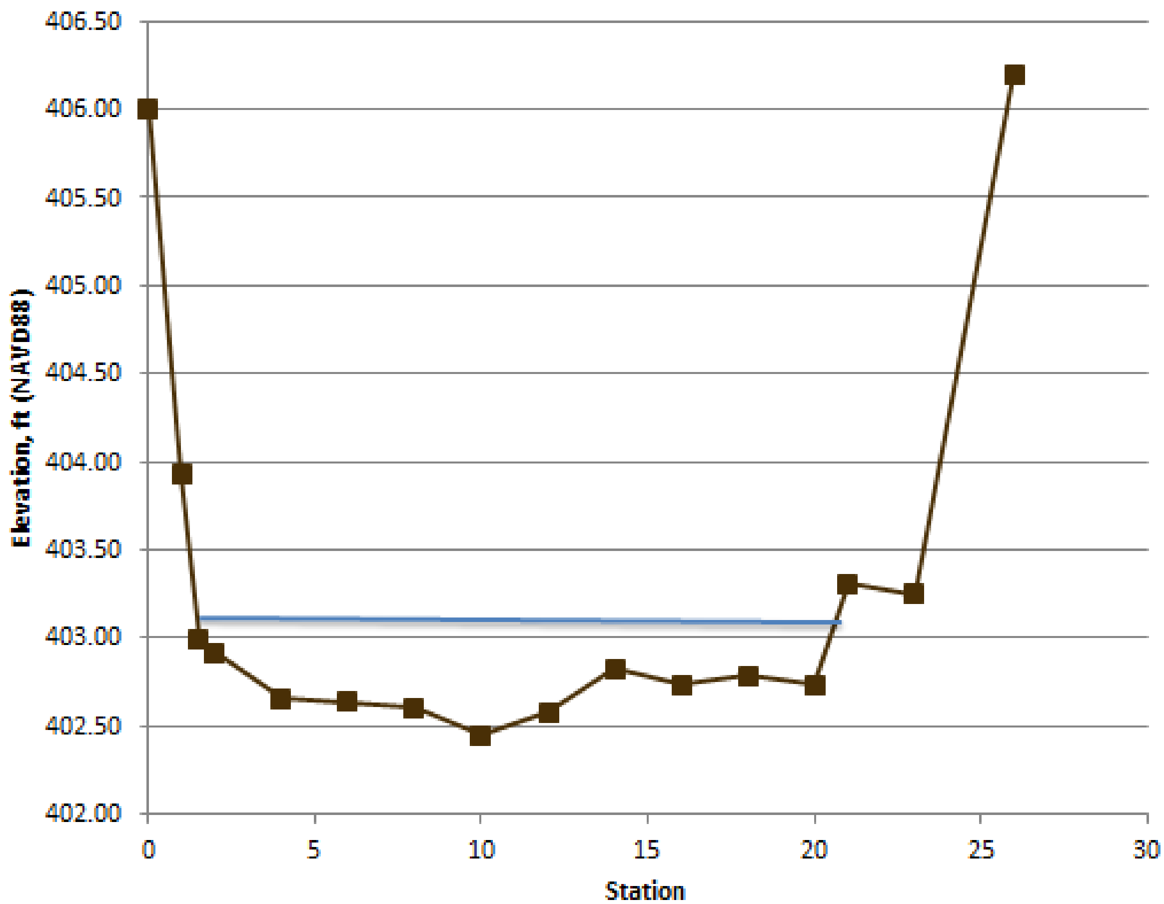

Figure 10. Measured cross-section downstream of culvert array

This data, along with DOWL's design drawings for the culvert replacement, were used to model the array and arch crossing structure in FishXing. The arch culvert was modeled in FishXing and River2D using both the design drawings and surveyed data from 2015, approximately one month after the new structure was installed, and surveyed data from 2016, depending on the modeled discharge and date of fish passage occurrence.

Surveyed cross-sections were collected using a Leica NA700 Series Automatic Level, and discharge and velocity measurements were collected using either a Marsh-McBirney Flo-Mate™ portable velocity flow meter or a FlowTracker handheld Acoustic Doppler Velocimeter (ADV), shown in Figure 11.

Figure 11. ADF&G-owned ADV used for measurements

3.3 Hydraulic Modeling Procedures

3.3.1 FishXing

FishXing, as previously discussed, is a commonly used one-dimensional program used to model fish passage through culvert structures. The model utilizes studied fish capabilities and models culvert hydraulics across a range of stream discharge inputs. The model can calculate water profiles for different types of culverts and uses gradually varied flow equations. The hydraulic output (flows, velocities, and leap conditions) is then compared against the swimming abilities of the fish species of interest (Furniss et al., 2006). Velocity reduction factors can be used for culverts to account for the occupied velocity within the structure that is typically adjacent to the sides and/or corrugations of a corrugated metal pipe.

Hydraulic inputs into FishXing include length of pipe and culvert properties (such as diameter, bottom slope, etc.), Manning's roughness value for the culvert and substrate material (if embedded), embedment depth, and tailwater elevation. For fish properties, a species and length of fish are selected and studied capabilities for prolonged and burst speeds are available for selection based on temperatures and sizes that best model the design fish. Additionally, minimum depth and jump speed are often populated by selection of literature physiological information.

Version 3 of the software was used for this study.

3.3.2 River2D

River2D is a two-dimensional finite element hydrodynamic model for transient conditions that was developed specifically for fish habitat evaluations to provide local details of velocity and depth distribution, unlike one-dimensional models. It utilizes different components for input of bed forms and topography, ice, and other data along a grid system. River2D uses this input data to solve for water depths and water velocities through discretization. River2D also includes a module for assessment of fish habitat that is based on the USGS Physical Habitat Simulation (PHABSIM) software that simulates the relationship between streamflow and physical habitat (depth, velocity, channel index) for various life stages of a species of fish (Milhous & Waddle, 2012). This allows analysis of a "weighted usable area" for the stream segment.

River2D requires input of a BED file that includes x, y, and z components associated with a roughness value (Manning's "n"). This BED file is then imported into a MESH module for triangulation and any required adjustments. Within the MESH module the user also inputs boundary conditions (topographic boundary, inflow, and downstream water surface elevation) before exporting to a River2D input file for analysis.

Buddy Creek was modeled in River2D with the arch culvert to pull velocity and depth data across the mesh for input into a developed two-dimensional fish passage algorithm. Figure 12 displays the mesh within the culvert.

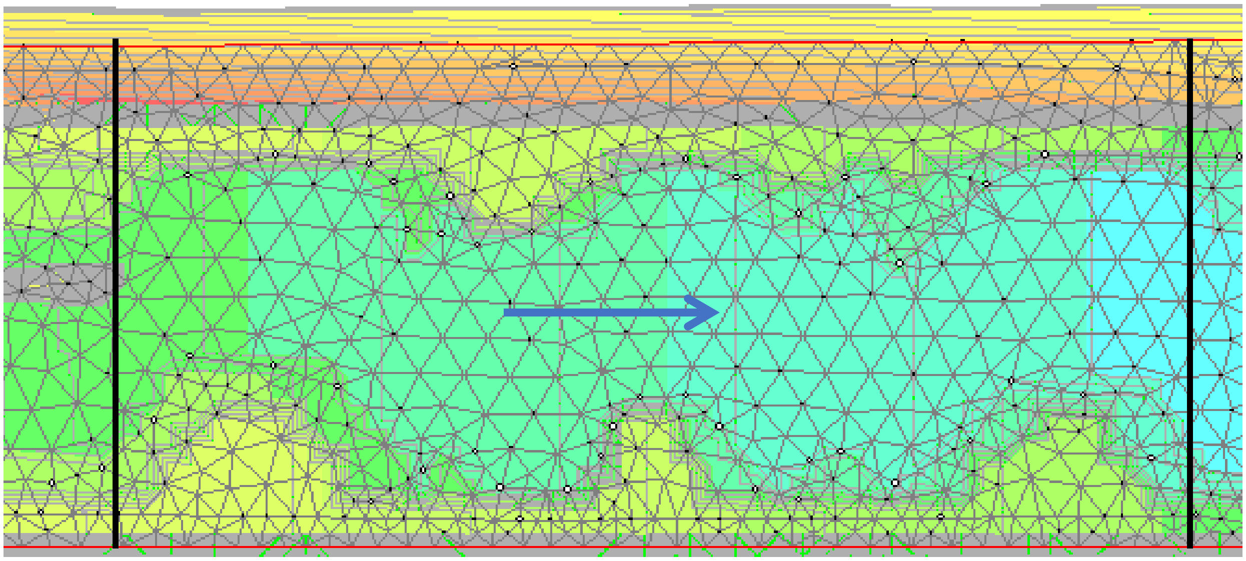

Figure 12. River2D culvert mesh

3.4 Algorithm Generation

The output from River2D, specifically velocities and depths, in conjunction with published juvenile salmonid characteristics (as used in FishXing) was used to develop and test an algorithm to determine fish passage throughout a structure in two dimensions. Physical characteristics used in the algorithm, for juvenile coho and Chinook salmon, and rainbow trout can be found in Table 3. This data was selected from the FishXing database, or other studies, based on species, age/size, and temperature of the water closest to Buddy Creek, and the fish in ADF&G's passage study. This algorithm includes a list of outputs from the River2D model, such as point velocities, and water depths throughout the structure on a 3-inch grid, that are entered into Microsoft Excel. Utilizing the fish characteristics, and following a procedure (displayed in Figure 13), a series of if-then statements was constructed to determine if the fish could move from one point to the other in two dimensions to successfully pass through the structure. Data inputs included fish species, fish size, culvert size, and velocity and depth from River2D across a grid. Culvert size was used to create a grid pattern in the x-y plane. Velocity and depths along the grid were compared to fish abilities at each grid location to determine successful passage.

Table 3. Fish swimming capabilities used in algorithm

Species Modeled	Swim Type	V *(m/s)*	t *(s)*	Length of Fish (L) *(mm)*	Water Temp *(°C)*	Reference
Coho & Chinook	Prolonged	$5.87L^{.7}t^{-.1}$	1800	40-133	18-20	Hunter & Mayor, 1986
	Burst	0.8	7.5	55	No data	Gubernick, n.d.
Rainbow Trout	Prolonged	0.8	1200	-	22.6	Jones et al., 1974
	Burst	$12.30L^{.62}t^{-.51}$	5	-	7-19	Hunter & Mayor, 1986

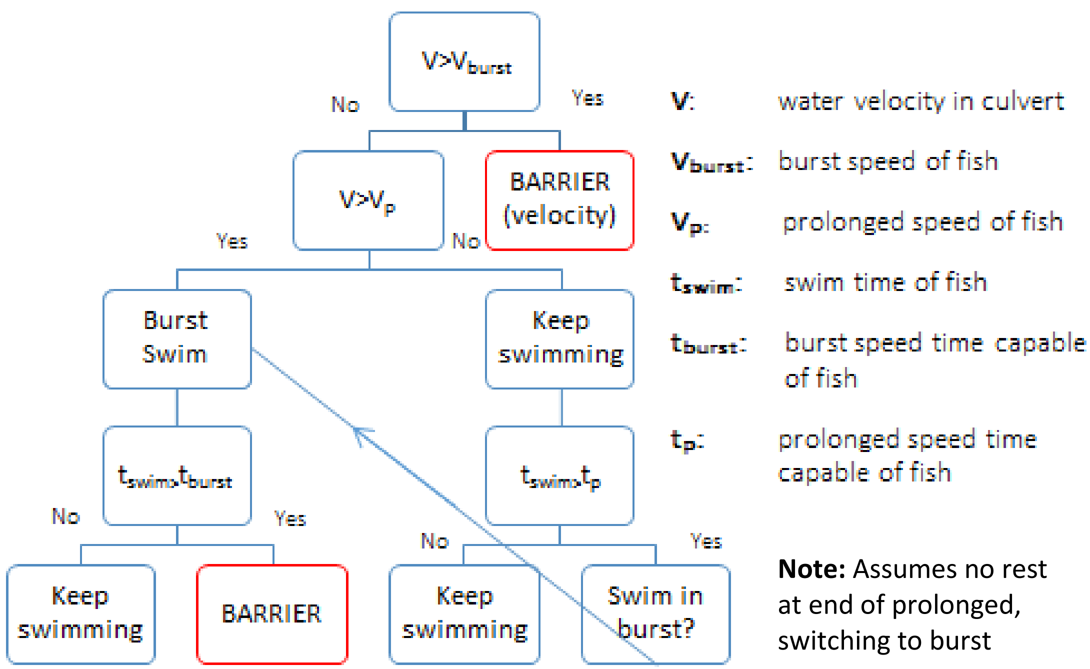

Figure 13. Algorithm flow chart

Initial runs with Chinook proved 0% accuracy with both FishXing and the algorithm, potentially because available, studied data were for much smaller fish. Per conversations with Gillian O'Doherty (ADF&G), it is fairly accurate to assume that the coho salmon swimming abilities are the same for other juvenile salmon (such as Chinook). Therefore, coho abilities, as presented in the above table were used in the algorithm for both Chinook and coho. Additionally, water temperature varied throughout the summer/fall, ranging from 2° to slightly over 20°C. The range of 18° to 20° C was the most similar of the available studied ranges to actual conditions during passage events, so 20°C was used.

The developed algorithm runs the series of checks against stream velocity and depths along the grid. If a series of connections of successful grid-section passages occur throughout the entire culvert, the fish successfully passes. Figure 14 displays a sample section of velocity input (blue cells are water and green is dry land).

Velocity	fps																					
y/x	0	0.25	0.5	0.75	1	1.25	1.5	1.75	2	2.25	2.5	2.75	3	3.25	3.5	3.75	4	4.25	4.5	4.75	5	
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
0.25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
0.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
1.25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
1.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
1.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
2.25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
2.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
2.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
3.25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
3.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
3.75	0.153215223	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
4	0.183070866	0.143372703	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
4.25	0.208661417	0.169291339	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
4.5	0.234580052	0.195209974	0.155839895	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
4.75	0.260498688	0.221128609	0.181430446	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
5	0.286417323	0.24671916	0.224409449	0.203740157	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
5.25	0.43996063	0.419291339	0.398293963	0.377624672	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
5.5	0.614173228	0.593175853	0.572506562	0.551509186	0.530839895	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
5.75	0.788057743	0.767060367	0.746391076	0.725393701	0.704724409	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
6	1.036089239	0.947178478	0.920275591	0.899606299	0.878608924	0.817257218	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
6.25	1.288713911	1.19980315	1.111220472	1.073490814	1.052493438	0.922572178	0.74343832	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
6.5	1.541338583	1.452755906	1.363845144	1.274934383	1.207020997	1.027887139	0.848753281	0.669619423	0	0	0	0	0	0	0	0	0	0	0	0	0	
6.75	1.794291339	1.705380577	1.616469816	1.523293963	1.410761155	1.212598425	1.014435696	0.816272966	0.618110236	0	0	0	0	0	0	0	0	0	0	0	0	
7	2.04691601	1.956036745	1.858267717	1.760170604	1.662401575	1.464238845	1.266076115	1.067913386	0.869750656	0.671587927	0	0	0	0	0	0	0	0	0	0	0	
7.25	2.291010499	2.192913386	2.095144357	1.997047244	1.898950131	1.715879265	1.517716535	1.319553806	1.121391076	0.923228346	0	0	0	0	0	0	0	0	0	0	0	
7.5	2.527887139	2.429790026	2.332020997	2.233923885	2.135826772	1.967519685	1.769356955	1.571194226	1.373031496	1.174868766	0.99835958	0.82480315	0	0	0	0	0	0	0	0	0	
7.75	2.76476378	2.666666667	2.568569554	2.470800525	2.372703412	2.219160105	2.020997375	1.822834646	1.624671916	1.445538058	1.271653543	1.098097113	0.924212598	0	0	0	0	0	0	0	0	
8	2.705380577	2.839566929	2.805446194	2.707677165	2.609580052	2.470800525	2.272637795	2.074475066	1.892716535	1.718832021	1.545275591	1.371391076	1.197506562	1.049212598	0.939304462	0	0	0	0	0	0	
8.25	2.6167979	2.750984252	2.885170604	2.944553806	2.846456693	2.722769029	2.524606299	2.339895013	2.166010499	1.992125984	1.818569554	1.644685039	1.471128609	1.307414698	1.197834646	1.087926509	0	0	0	0	0	
8.5	2.528215223	2.662401575	2.796587927	2.930774278	3.06496063	2.974409449	2.786745407	2.613188976	2.439304462	2.265748031	2.091863517	1.918307087	1.744422572	1.570538058	1.456036745	1.346128609	1.228018373	0	0	0	0	
8.75	2.43996063	2.574146982	2.708333333	2.842519685	2.971128609	3.107939633	3.047244094	2.875	2.702755906	2.530511811	2.358267717	2.186023622	2.013779528	1.841535433	1.707677165	1.589238845	1.470800525	1.352362205	1.233923885	0	0	
9	2.351377953	2.471456693	2.573818898	2.676181102	2.778543307	3.004593176	3.279855643	3.107611549	2.935367454	2.76312336	2.590879265	2.418635171	2.246391076	2.076771654	1.953740157	1.832020997	1.713582677	1.595144357	1.476706037	1.358267717	0	1
9.25	2.176509186	2.278871391	2.381233596	2.483595801	2.592191601	2.901246719	3.210301837	3.340223097	3.167979003	2.995734908	2.823490814	2.651246719	2.479002625	2.325459318	2.202755906	2.079724409	1.957020997	1.837926509	1.719488189	1.601049869	1.482283465	1.
9.5	1.983923885	2.086286089	2.18832021	2.290682415	2.48851706	2.797572178	3.106627297	3.415682415	3.400590551	3.228346457	3.056102362	2.883858268	2.711614173	2.574475066	2.45144357	2.328740157	2.206036745	2.083005249	1.962270341	1.843832021	1.725065617	1.
9.75	1.791010499	1.893372703	1.995734908	2.098097113	2.385170604	2.694225722	3.00328084	3.312335958	3.621391076	3.460958005	3.288713911	3.116469816	2.946194226	2.82316273	2.700459318	2.577755906	2.454724409	2.332020997	2.208989501	2.086286089	1.967519685	1
10	1.598425197	1.700787402	1.803149606	1.972769029	2.281824147	2.590879265	2.899934383	3.208989501	3.518044619	3.69324147	3.520997375	3.348753281	3.19488189	3.072178478	2.949475066	2.82644357	2.703740157	2.580708661	2.458005249	2.327427822	2.245406824	2
10.25	1.405839895	1.5082021	1.610564304	1.869422572	2.17847769	2.487204724	2.796259843	3.105314961	3.414370079	3.723425197	3.753608924	3.581364829	3.443897638	3.321194226	3.19816273	3.075459318	2.94816273	2.815616798	2.683070866	2.550853018	2.489829396	2.
10.5	1.214895013	1.315616798	1.456692913	1.765748031	2.07480315	2.383858268	2.692913386	3.001968504	3.311023622	3.62007874	3.929133858	3.815616798	3.692913386	3.568897638	3.436351706	3.303805774	3.171259843	3.039041995	2.906496063	2.773950131	2.734251969	2
10.75	1.030511811	1.126312336	1.333989501	1.641076115	1.94816273	2.255577428	2.562664042	2.87007874	3.177165354	3.484251969	3.791666667	4.057086614	3.924540682	3.791994751	3.659776903	3.527230971	3.394685039	3.262139108	3.12992126	3.009186352	2.978674541	
11	0	0.980643045	1.06988189	1.335629921	1.642716535	1.950131234	2.257217848	2.564304462	2.87171916	3.178805774	3.504593176	3.817913386	3.956364829	4.015419948	3.882874016	3.750656168	3.618110236	3.485564304	3.353018373	3.253608924	3.223097113	3
11.25	0	0	0.918635171	1.030183727	1.337270341	1.644685039	1.951771654	2.258858268	2.566272966	2.888451444	3.242454068	3.576771654	3.715551181	3.854330709	3.993110236	3.973753281	3.841535433	3.708989501	3.57644357	3.497703412	3.467519685	3.
11.5	0	0	0	0.856299213	1.031824147	1.339238845	1.646325459	1.953412073	2.272637795	2.626312336	2.980314961	3.334317585	3.474737533	3.61351706	3.752296588	3.890748031	4.029527559	3.932414698	3.799868766	3.742125984	3.711942257	3
11.75	0	0	0	0	0.793963255	1.033464567	1.340879265	1.656496063	2.010498688	2.364173228	2.718175853	3.072178478	3.233923885	3.372703412	3.51148294	3.649934383	3.788713911	3.927493438	4.022965879	3.945866142	3.836614173	3.
12	0	0	0	0	0.642716535	0.731627297	1.040682415	1.394356955	1.74835958	2.102362205	2.456036745	2.81003937	2.993110236	3.131889764	3.270669291	3.409120735	3.547900262	3.68667979	3.847769029	3.880905512	3.771653543	3
12.25	0	0	0	0	0	0.644028871	0.790682415	1.132217848	1.486220472	1.840223097	2.193897638	2.547900262	2.752296588	2.891076115	3.029527559	3.168307087	3.307742782	3.470472441	3.633530184	3.796259843	3.706692913	3.

Figure 14. Sample algorithm velocity input for 5 cfs

Figure 15 then shows the pass/fail results (blue cells are pass and red is fail). Notice the cells that are passing are along the boundary zones in the “occupied velocity” area where fish typically swim and/or rest while traversing through a structure.

combines depth & velocity requirements:

y/x	0	0.25	0.5	0.75	1	1.25	1.5	1.75	2	2.25	2.5	2.75	3	3.25	3.5	3.75	4	4.25	4.5	4.75	5
2.5	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL
2.75	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL
3	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL
3.25	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL
3.5	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL
3.75	PASS	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL
4	PASS	PASS	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL
4.25	PASS	PASS	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL
4.5	PASS	PASS	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL
4.75	PASS	PASS	PASS	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL
5	PASS	PASS	PASS	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL
5.25	PASS	PASS	PASS	PASS	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL
5.5	PASS	PASS	PASS	PASS	PASS	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL
5.75	PASS	PASS	PASS	PASS	PASS	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL
6	PASS	PASS	PASS	PASS	PASS	PASS	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL
6.25	PASS	PASS	PASS	PASS	PASS	PASS	PASS	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL
6.5	PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL
6.75	PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL
7	PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL
7.25	FAIL	FAIL	FAIL	PASS	PASS	PASS	PASS	PASS	PASS	PASS	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL
7.5	FAIL	FAIL	FAIL	FAIL	FAIL	PASS	PASS	PASS	PASS	PASS	PASS	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL
7.75	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	PASS	PASS	PASS	PASS	PASS	PASS	PASS	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL
8	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	PASS	PASS	PASS	PASS	PASS	PASS	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL
8.25	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	PASS	PASS	PASS	PASS	PASS	PASS	PASS	FAIL	FAIL	FAIL	FAIL	FAIL
8.5	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	PASS	PASS	PASS	PASS	PASS	PASS	FAIL	FAIL	FAIL	FAIL
8.75	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	PASS	PASS	PASS	PASS	PASS	PASS	FAIL	FAIL	FAIL
9	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	PASS	PASS	PASS	PASS	PASS	PASS	FAIL
9.25	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	PASS	PASS	PASS	PASS	PASS
9.5	PASS	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	PASS	PASS	PASS
9.75	PASS	PASS	PASS	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	PASS
10	PASS	PASS	PASS	PASS	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL
10.25	PASS	PASS	PASS	PASS	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL
10.5	PASS	PASS	PASS	PASS	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL
10.75	PASS	PASS	PASS	PASS	PASS	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL
11	FAIL	PASS	PASS	PASS	PASS	PASS	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL
11.25	FAIL	FAIL	PASS	PASS	PASS	PASS	PASS	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL
11.5	FAIL	FAIL	FAIL	PASS	PASS	PASS	PASS	PASS	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL
11.75	FAIL	FAIL	FAIL	FAIL	PASS	PASS	PASS	PASS	PASS	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL
12	FAIL	FAIL	FAIL	FAIL	FAIL	PASS	PASS	PASS	PASS	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL
12.25	FAIL	FAIL	FAIL	FAIL	FAIL	PASS	PASS	PASS	PASS	PASS	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL
12.5	FAIL	FAIL	FAIL	FAIL	FAIL	PASS	PASS	PASS	PASS	PASS	PASS	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL	FAIL

Figure 15. Sample algorithm results for 120 mm coho at 5 cfs

3.5 Model Validation

In order to determine if the developed FishXing and River2D models were providing accurate results, model validation was necessary.

3.5.1 FishXing

Two different models were used to compare discharges and stages within Buddy Creek: the culvert array and the arch culvert. Stages were measured at known discharges during the summer over a period of four years, and these were compared to the models' outputs.

3.5.1.1 Culvert Array

Three days of discharge, water depth, and velocity measurements were used as comparison against the FishXing culvert array model output. The depth comparison is displayed in Table 4. Measured velocities were taken at 0.6 of the depth in the water column (in order to collect a mean water velocity) with an ADV at varying locations within the culverts. Comparison velocity and depth locations (between measured and modeled) were chosen based on best available data (e.g., some culvert inlets were damaged/warped, or outlet data was unavailable due to high turbulence).

Table 4. Culvert array FishXing depth validation

Culvert	Q *(cfs)*	Measured Depth *(ft)*	Modeled Depth *(ft)*	Percent Difference
1	48.6	2.0	2.1	5%
	29.6	1.3	1.2	8%
2	48.6	1.7	1.7	2%
	29.6	1.3	1.3	0%
3	48.6	0.9	0.9	0%
	29.6	0.7	0.7	1%

For modeling purposes for the culvert array, the measured discharge had to be distributed appropriately throughout the three culverts. With known depths within each culvert at known discharges, flow distribution was calculated based on percentage of water, and applied to each culvert for each modeled discharge. The flow distribution for the three aforementioned discharges is displayed in Table 5. For passage testing, it was generally assumed that Culvert 1 received 40%-50% of the total flow, Culvert 2 also received 40%-50% of the total flow (slightly less than Culvert 1), and Culvert 3 received up to 20% of the total flow when discharge was above 10 cfs.

Table 5. Estimated flow distribution in measured culverts

Q_{total} *(cfs)*	Percent Bankfull	Culvert 1 *(cfs)*	Culvert 2 *(cfs)*	Culvert 3 *(cfs)*
6.7	5%	3.3	3.5	0
48.6	39%	19.2	19.2	10.2
29.6	24%	12.9	11.1	5.6

On average, modeled depth was within 3% of measured. Modeled velocity, however, had a percent difference of 58% between measured and modeled. This is understandable with a one-dimensional program because the comparison is between modeled cross-sectional velocities and measured point velocities. Depths were measured and modeled at the middle of the culvert.

The modeled culvert array assumed perfectly circular culverts; however, the three installed culverts at Buddy Creek were in extremely poor condition, with likely lower capacity due to damage and a much rougher surface than anticipated. An example water surface profile graphic output for the first culvert in the array is shown in Figure 16.

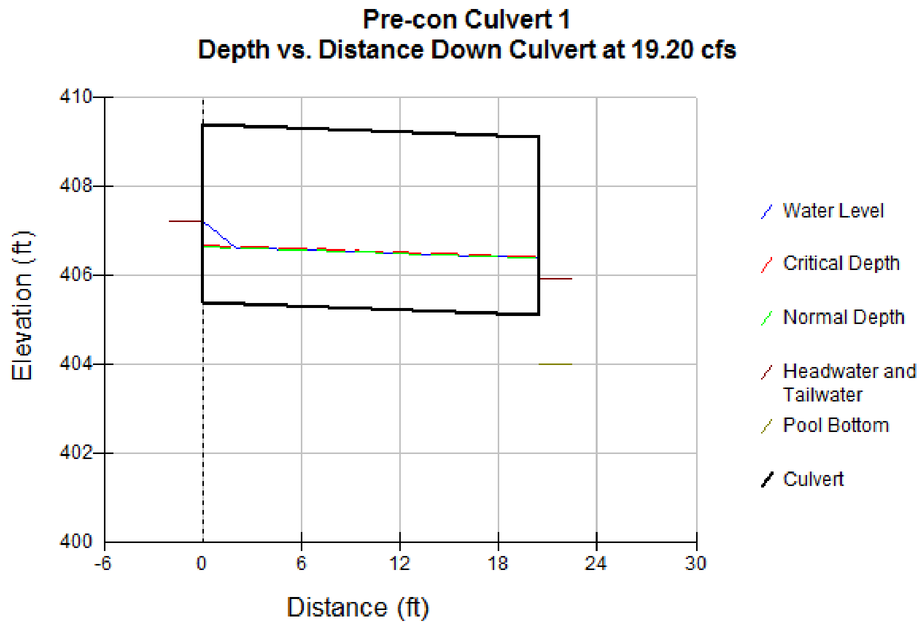

Figure 16. FishXing water surface profile for Culvert 1 of array

3.5.1.2 Arch

After the arch was constructed, multiple measurements were taken in 2015 and 2016, including survey of cross-sections, discharges, water surface elevations, depths, and spot velocities within the culvert. Measured depths and spot velocities within the structure at associated discharges were used for model validation.

Measurements varied significantly throughout the inside of the culvert, especially during low flows. The bank constructed within the culvert created multiple areas of high turbulence and then areas of transient flow on the downstream side of the barb as shown in Figure 17. Also worth noting is the stream adjustments upstream and downstream of the structure from summer 2015 to summer 2016. Sediment accumulated just upstream of the structure and formed a gravel bar as shown in Figure 18 and in the comparative longitudinal profiles in Figure 19. These adjustments could affect the accuracy of comparing measured data from 2015 and 2016 with the model using 2016 data; however, models were developed for both conditions. It is assumed that this bar mostly formed during September 2015 during the flooding event (over 200 cfs), as shown in the hydrograph in Figure 6.

Figure 17. Flow variations inside structure at installed bank

Figure 18. Stream adjustments: A. 7/28/15 looking upstream (Q=14.1 cfs—11% bankfull); B. 8/27/16 looking upstream (Q=25.2 cfs—20% bankfull)

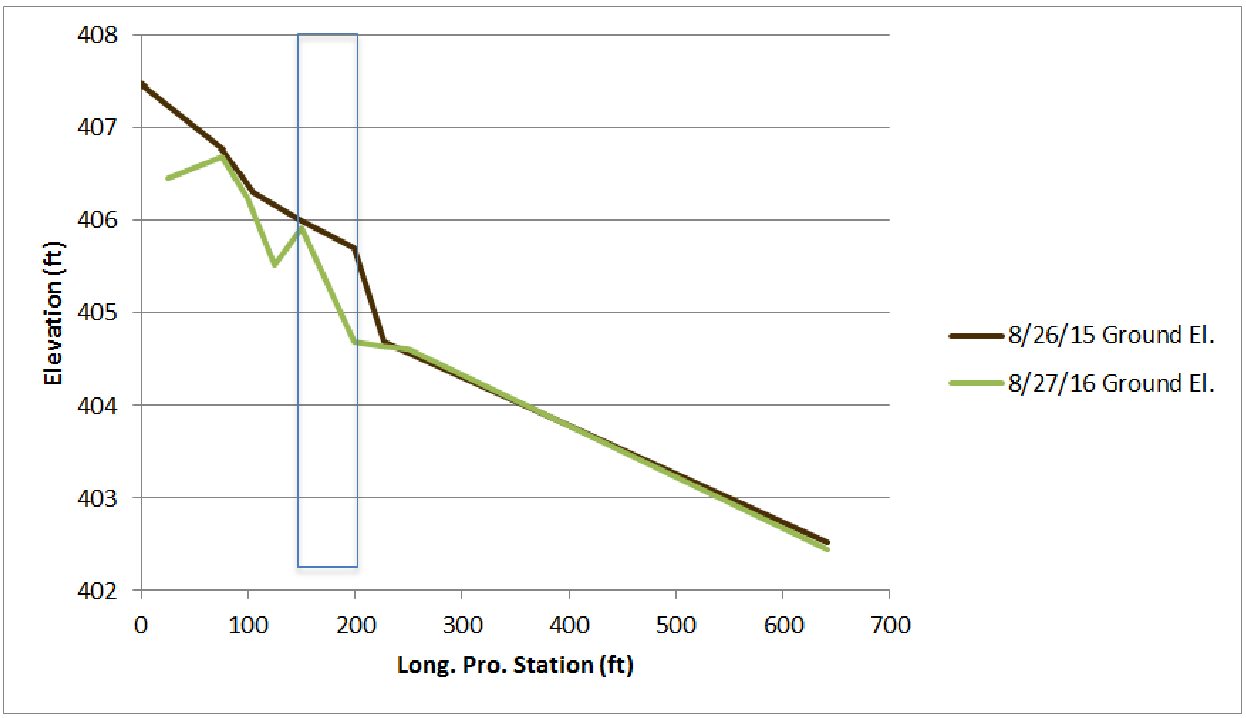

Figure 19. Longitudinal profile of Buddy Creek August 2015 and August 2016

The arch's constructed size, slope, and placement was input into FishXing. The culvert was noted as being embedded, with a Manning's n of 0.04 inside the structure, similar to input in the other models. Cross-sectional information from 25 feet downstream of the arch's outlet was used as tailwater conditions. The average percent difference for depth was 18% and for velocity, 51%. Measured depths and velocity varied greatly throughout the structure due to large substrate and varying flow throughout the cross section due to the constructed banks and barbs. Measured and modeled values were not as close as ideal; however surrounding measurements put modeled values within an acceptable range (approximately 20%). No other reasonable modifications could be made to the models to calibrate them better (e.g., adjusting Manning's n to unreasonable values or adjusting geometry or unrealistic tailwater conditions).

Figure 20 shows a sample of FishXing's animated output at a discharge of 14.1 cfs, and shows the design fish operating in "prolonged" mode in of the culvert.

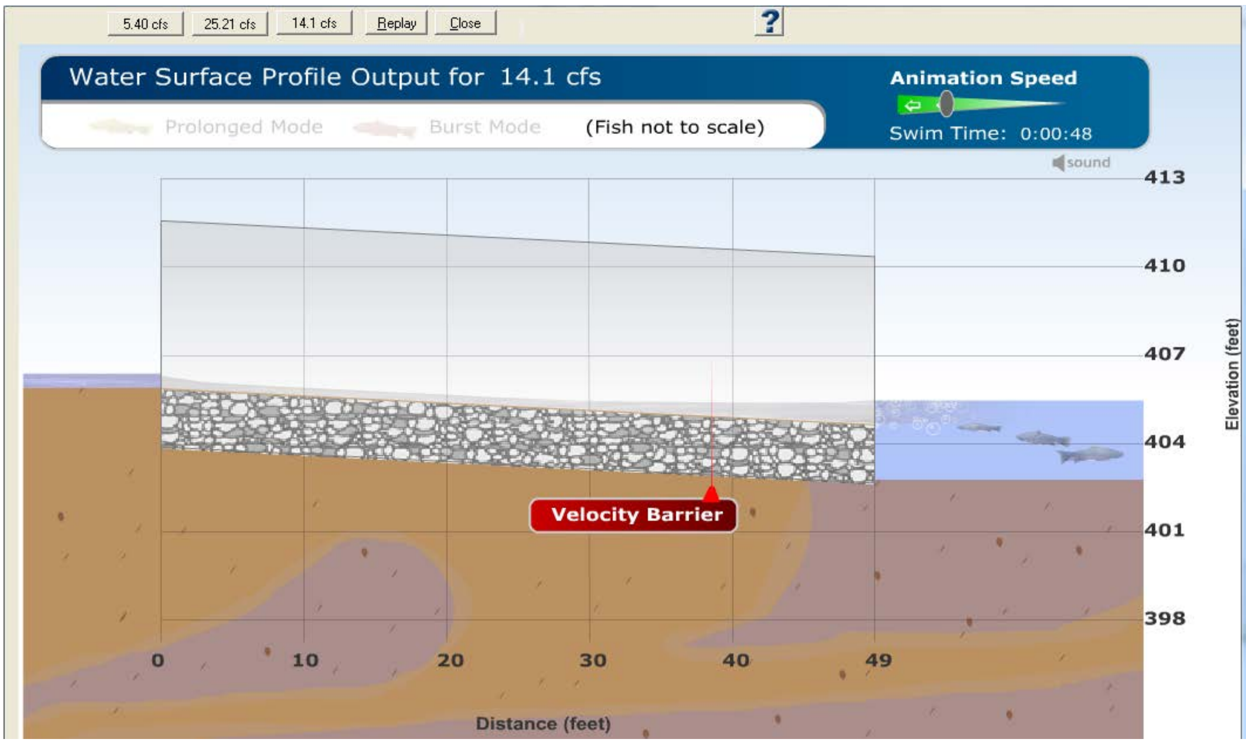

Figure 20. Arch FishXing animation for Q=14.1 cfs

FishXing's input does not allow the user to make certain custom adjustments. Modifications to better validate the model included increasing roughness by adjusting the Manning's n; however, this would still just provided an average depth and velocity through the cross-section and does not account for two-dimensional variations.

3.5.2 River2D

Due to the difficulties with modeling an array of culverts within River2D, such as input of the culvert walls and tops, it was not attempted. River2D is not designed to model setups such as this, or structures for that matter.

The arch culvert was modeled in a way such that it resembled a stream with high vertical banks (culvert walls). This model was only run at flows where the stream was not constricted by the culvert, and therefore was an appropriate assumption for flows where fish would be passing in most cases. The boundary was marked at the culvert edge on either side. Embedded or open-bottom structures that have a rise that is unlikely to be overtopped at the modeled flows (such as in this case), may be modeled in River2D as the height would be negligible and flow would resemble a normal stream. Flow rates observed and modeled were low enough that overtopping was nonexistent.

The full surveyed reach was modeled in River2D. The surveyed cross-sections, manually input cross-sections (based on design drawings) inside of the culvert at a tighter scale, and Manning's n values for each point (or node) were entered into a text file and imported into a River2D BED file. This bed information was then imported into the River2D MESH module to construct a mesh throughout the reach that was realistic. This was then converted to a River2D input file using the known downstream water surface elevation and inflow discharge as boundary conditions. Figure 21 and Figure 22 display the velocity and depth results inside the structure for a discharge of 14.1 cfs. Note the gravel bar is displayed at the entrance to the culvert. Due to formation of this bar between 2015 and 2016 around the culvert, multiple meshes were constructed: one using 2015 survey for modeling 2015 measured discharges, and one with 2016 survey for modeling 2016 measured discharges; however, after running the model with both meshes, it was found that they both provide similar results within the structure.

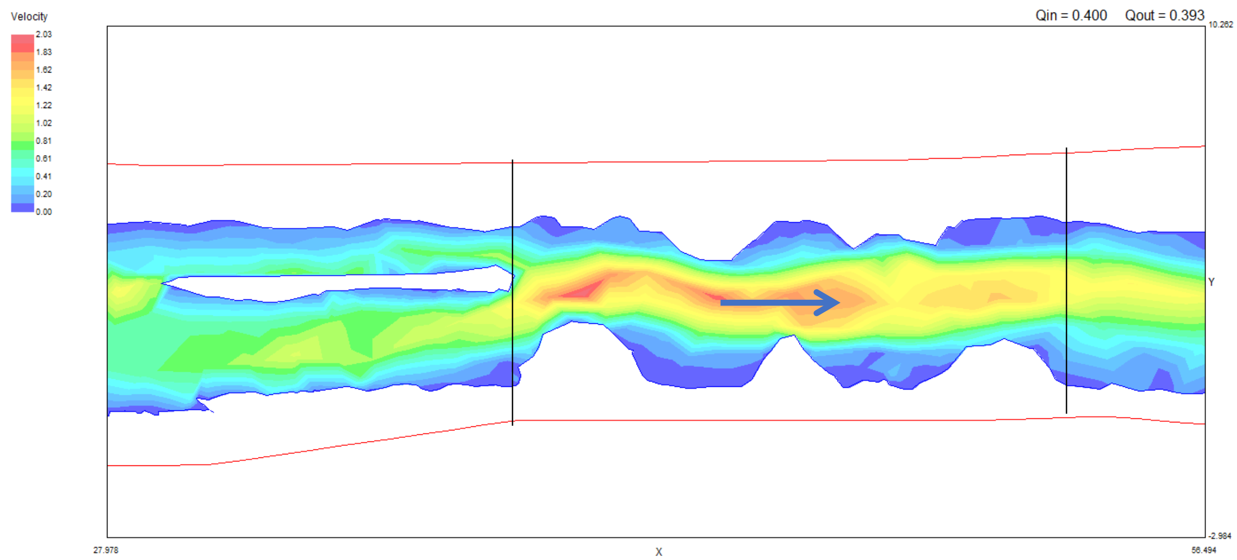

Figure 21. River2D velocity in culvert for Q=14.1 cfs (legend in meters per second)

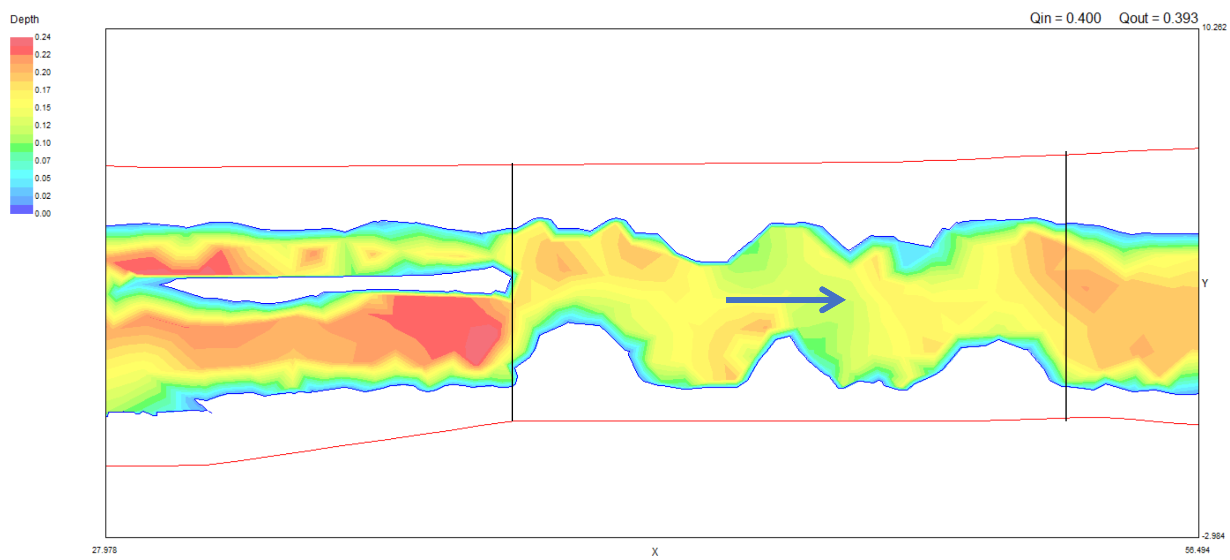

Figure 22. River2D depth in culvert for Q=14.1 cfs (legend in meters)

Depths and velocities were compared, as was done for the one-dimensional models. The average percent difference for depth was 15%, and for velocity it was 31%. Velocities and depths varied within inches inside the culvert due to roughness features and large substrate.

4 Results and Discussion

ADF&G had collected data on fish passage of juvenile coho and Chinook salmon, and rainbow trout between the sizes of approximately 55 mm to 120 mm between 2013 and 2016 with two different structures: the culvert array and the arch. This data was provided by ADF&G, and passage rates at the gaged discharges were used to compare against the developed algorithm passage results as well as FishXing results.

Fish passage data provided by ADF&G included: fish species, size at tagging, date(s) and time(s) of detection by the upstream and downstream antennas, time period between detections, and flow. Passage data was not used if the range of flows while the fish was in between antennas was more than 5 cfs, if the fish spent more than 5 days within the structure/between antennas, or if the fish passed through the structure outside of the season that it was tagged (e.g., 2014 data was not used if a fish tagged in 2013 passed the structure in 2014). Discarding the aforementioned passage data was to ensure that fish weren't able to rest for extended periods of time that may throw off the swimming ability data, and to account for lack of a growth model. There was insufficient data for ADF&G to develop a growth model as they were not able to recapture enough of the tagged fish to conduct measurements. If a tagged fish passed the structure months after tagging, it was likely much larger than when it was tagged and ultimately possesses better swimming abilities. In order to account for this, fish were modeled within groups of 1 cm (10 mm), and only within the summer that they were tagged and measured.

The modeled passage events for each passage structure are presented in Table 6. This includes the total successful passage events that were modeled (excluding those events mentioned above), the species modeled (note Chinook were modeled using coho abilities), the range of sizes modeled, and the range of flows modeled.

Table 6. Modeled passage events

Structure	Species	No. of Passage Events	Size Range (*mm*)		Flow Range (*cfs*)			
			Min	Max	Min	% BF	Max	% BF
Culvert Array	Coho & Chinook	121	65	110	6	5%	72	58%
	Rainbow Trout	17	94	134	11	9%	56	45%
Arch	Coho & Chinook	291	55	124	3	2%	91	73%
	Rainbow Trout	58	70	95	3	2%	38	30%

Fish swimming ability references used were displayed in Table 3. The following tables (Table 7 and Table 8) provide actual prolonged and burst speeds for coho/Chinook and rainbow trout used in the algorithm and FishXing.

Table 7. Coho/Chinook swim speeds

Swim Type	Rounded Length (*mm*)	**V** (*m/s*)	**V** (*fps*)
Prolonged	60	0.39	1.3
	70	0.43	1.4
	80	0.47	1.6
	90	0.51	1.7
	100	0.55	1.8
	110	0.59	1.9
	120	0.63	2.1
Burst	60-120	0.8	2.6

Table 8. Rainbow trout swim speeds

Swim Type	Rounded Length *(mm)*	**V** *(m/s)*	**V** *(fps)*
Prolonged	60-120	0.80	2.6
Burst	60	0.95	3.1
	70	1.04	3.4
	80	1.13	3.7
	90	1.22	4.0
	100	1.30	4.3
	110	1.38	4.5
	120	1.45	4.8

4.1.1 Algorithm Results

Upon completion of model validation and collection of field measurements and fish passage results, the generated two-dimensional fish passage algorithm was tested against real data collected by ADF&G. Passage rates collected from PIT tag studies over a variety of flows were compared against the algorithm results for these various flows.
Fish abilities used included those displayed in Table 3.

A total of 243 coho and 48 Chinook (291 aggregate), between the sizes of 55 mm and 124 mm (at tagging), successfully passed the arch with discharges ranging from 3 cfs to 91 cfs, as shown above. As discussed earlier, data for juvenile Chinook is severely lacking and initial results showed 0% congruency in the models compared to actual passage results, so it is commonly assumed that coho swimming data could also be applied to Chinook. With this assumption, the two-dimensional algorithm passed just 200 (68%) of the juvenile coho and Chinook salmon that were documented to pass from downstream to upstream according to the ADF&G PIT tag studies. For rainbow trout, the algorithm provided 100% congruency.

Within the algorithm, most of the barriers were combined high velocity in the middle of the structure where fish were not able to swim close enough to the stream banks due to inadequate depth, and therefore failures existed at higher flows. However, at certain higher flows, water levels would increase to overtop some of the streambanks. This allowed the fish to swim over these areas of higher roughness and resulted in more successful attempts.

4.1.2 FishXing Results

4.1.2.1 Culvert Array

A total of 103 coho and 18 Chinook, between the sizes of 65 mm and 110 mm at tagging, successfully passed through one or more of the culverts in the array between the flows of approximately 6 cfs to 72 cfs according to ADF&G's PIT tagging study. More passed at flows over 72 cfs, but it was assumed that these fish could traverse over the overtopped roadway (flows over approximately 80 cfs) at these higher flows and were therefore not considered. The modeled passages were simulated in each of the three culverts portioning the flow as discussed in the methodology section and applying velocity reduction factors of 0.8 in the inlet, barrel, and outlet for the outer culverts, and 0.8 for the inlet and outlet and 0.6 for the barrel for the middle culvert, as recommended for a culvert that has some substrate in it. The results showed that the middle culvert appeared to be favored for passage which appears to coincide with observations made by ADF&G in the field. FishXing still only allowed 2% of coho and Chinook through the structure. Seventeen rainbow trout also passed through the culvert array at flows ranging from 11 cfs to 56 cfs. FishXing passed 16 of these trout, with the 56 cfs event modeled as impassible, resulting in a congruency of 94%.

Some of these FishXing runs were very close to success with slight velocity barriers right at the inlet of the culvert. If slight adjustments were made allowing these fish to pass, it would bring the coho and Chinook passage success to 12% congruency with the passage data. With the modeled culverts being extremely dilapidated, it was difficult to model actual conditions in FishXing.

4.1.2.2 Arch

The arch was input into FishXing based on design drawings, and recommended velocity reduction factors were used (0.8 at the inlet and outlet, and 0.6 in the barrel). Similar to the algorithm, FishXing passed approximately 62% of the juvenile coho and Chinook and 100% of the rainbow trout that actually passed through the structure according to ADF&G

PIT tag studies. Without the use of velocity reduction factors (using a value of 1.0), congruency was just 22% for coho and Chinook and 72% for rainbow trout.

Barriers in FishXing were all velocity barriers at higher flows, mostly near the inlet of the culvert where the fish could swim through most of the barrel, switch to burst speed, and then become exhausted prior to exiting the structure.

4.1.3 Discussion

FishXing and the algorithm provided similar results across a range of rounded sizes (rounded to the nearest 10 millimeters) for the arch. This is shown in Figure 23 by percent congruency (i.e., percent of successful modeled passage events compared to field passage events). This only shows coho and Chinook (modeled together) as all rainbow trout passed at all size ranges.

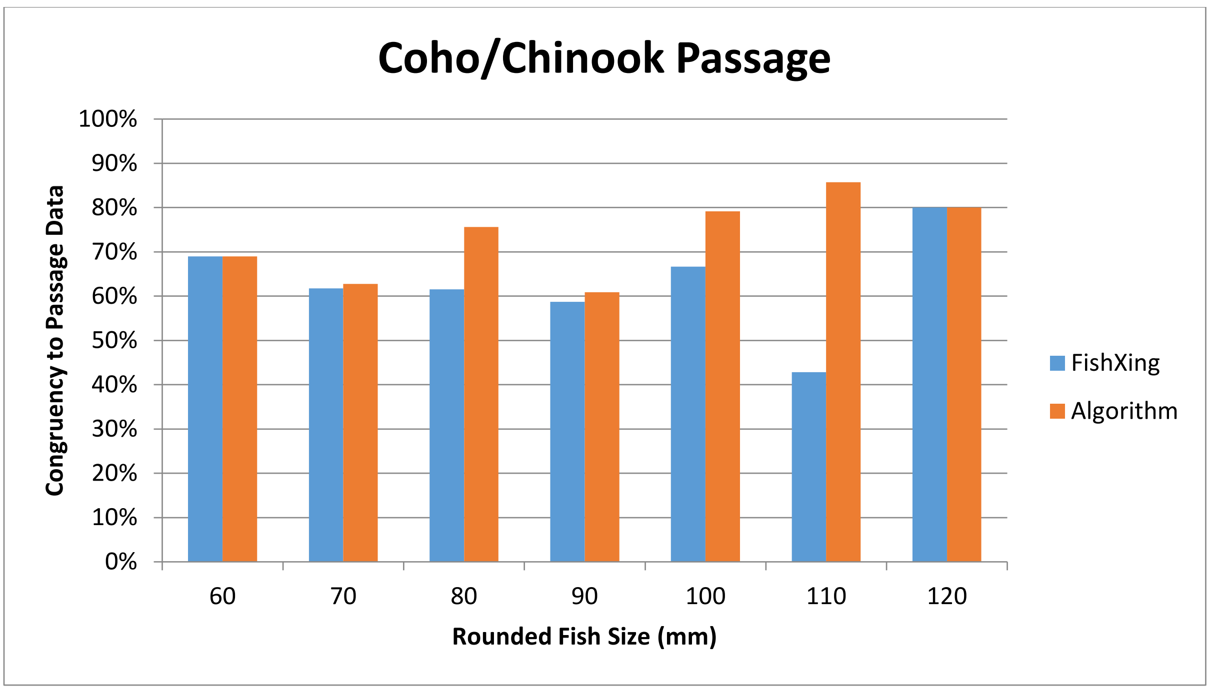

Figure 23. Modeled percent passage versus rounded fish size

Figure 24 displays the same data but provides actual quantity of passage events by rounded fish size, and also provides the total field-measured actual passage events by size.

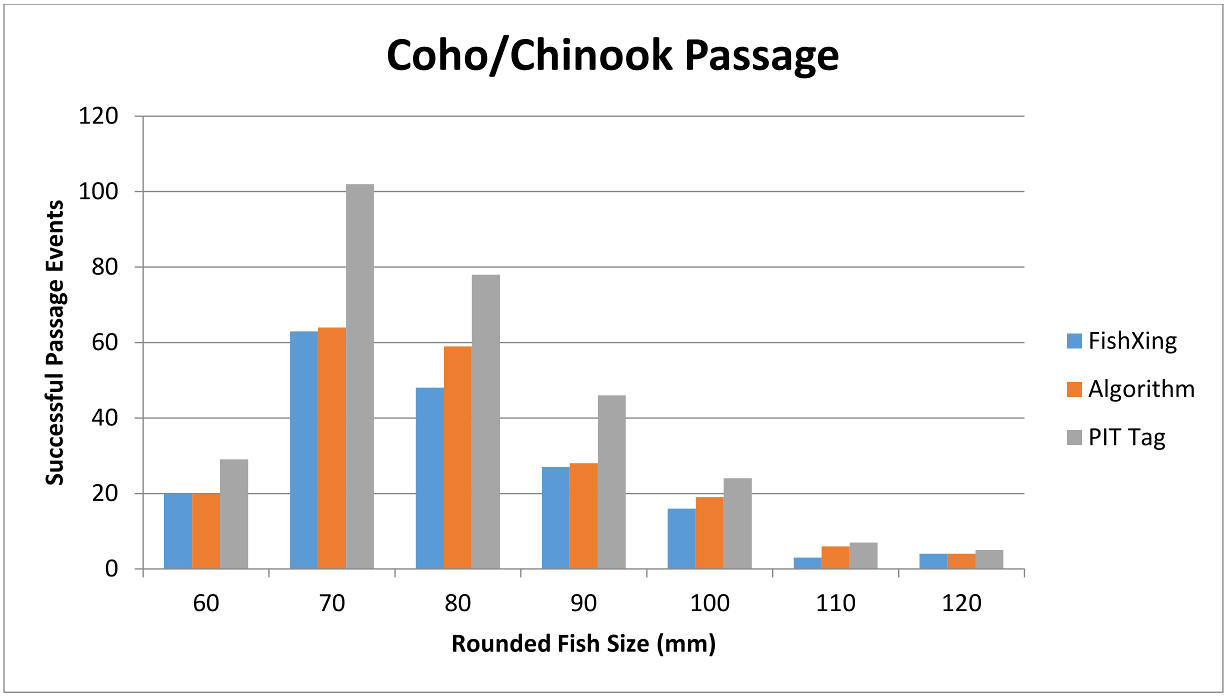

Figure 24. Success passage events versus rounded fish size

The maximum flows passed in each model for the rounded size group for coho and chinook is displayed in the following table. Actual passage flows for the arch ranged from 2% to upwards of 73% bankfull. No tagged fish passed at a flow greater than bankfull.

Table 9. Maximum flow at modeled passage for coho/Chinook

Rounded Size *(mm)*	**FishXing**		**Algorithm**	
	Q (cfs)	**% BF**	**Q** (cfs)	**% BF**
60	13	10%	20	16%
70	14	11%	23	18%
80	17	14%	91	73%
90	19	15%	20	16%
100	22	18%	88	70%
110	23	18%	23	18%
120	27	22%	20	16%

As previously discussed for the arch, FishXing presented exhaustion barriers at flows much lower than barrier flows for the algorithm. This is likely due to the ability to swim over, or in between the roughened areas along the sides of the culvert within the rock. Figure 25 displays the inside of the arch culvert at an approximate flow of 90 cfs (upward limit of passage). Note the submersed banks on the edges.

Figure 25. Flow inside arch culvert at Q=90 cfs

5 Conclusions and Recommendations

5.1 Conclusions

It was expected that the two-dimensional algorithm would provide more accurate results than the one-dimensional model, FishXing. The two-dimensional algorithm utilized the same fish swimming studies as were modeled in FishXing, but instead of relying on an estimated velocity reduction factor to approximate occupied velocity in the structure (like FishXing allows), the algorithm used output from a two-dimensional hydraulic model (River2D) that appeared to accurately model the variance in velocities throughout the cross-section of the structure. Conceptually, this approach could simulate low-velocity areas around boundaries, which fish (especially juveniles) utilize while traversing a structure. However, both models resulted in approximately the same passage results (only passing an average 65% of coho and Chinook that actually passed through the structure from downstream to upstream, and both passing all modeled rainbow trout).

Both models resulted in overly conservative results, and without the use of velocity reduction factors, FishXing would be much more conservative and unrealistic.

Since both models resulted in an accurate prediction of passage only 65% of the time for both coho and Chinook, and success was for approximately the same fish, one reason for low congruency could be studied physical abilities of fish for juvenile salmon. This conclusion has been stated by others (Mahlum, 2014; Bourne, 2011; Burford, 2009); however, other components may also contribute, and are discussed below.

FishXing for the culvert array also only passed 2% of the coho and Chinook and 94% of the rainbow trout that actually traversed through the crossing; however, due to the dilapidated nature of the culvert array, not many conclusions can be made from this exercise.

5.2 Limitations

This study found that FishXing is sensitive to user inputs such as the culvert structure, tailwater conditions, and velocity reduction factors. The designer is able to input culvert dimensions, type, and ideally will has a good understanding of the culvert environment, such as the roughness and tailwater conditions; although, accurate tailwater conditions (post-construction) for input into the model could be somewhat difficult to predict for a new structure. Velocity reduction factors are more or less chosen by the user and may have little, to no basis, but are extremely important. Based on this study, even with proper use of velocity reduction factors, FishXing may lack the ability to accurately model velocity barriers for juvenile salmonids.

Other modeling limitations could include lack of consideration of a depth component, and varying Manning's "n" values. The two-dimensional algorithm modeled velocities and depths on an x-y plane and did not account for any variance in the water column; whereas, in reality, the fish may be swimming near the streambed (where it is rougher) rather than at the average velocity within the water column. Additionally, Manning's "n" values were calculated for this study and used in the model. Roughness varies at different flows and flow depth. Only one value for each roughness component (i.e., streambed, banks, banks within culvert, etc.) was used for all flows.

The largest limitation appears to be studied swim speeds for juvenile coho and especially Chinook. Water temperature can also play a large roll on the fish swimming abilities. Only one equation was used for the algorithm and the one-dimensional model, but in reality temperature varied more than 20°C throughout the PIT tagging study.

Other study limitations that may have affected results include the amount of time fish spent within the structure and the size of the fish at time of passage. Passage events that took more than five days between antennas were removed from the study; however, the five days may have still allowed sufficient resting time for the fish to overcome barriers with burst speed over multiple days. This would only affect several fish within this specific study. Additionally, ADF&G was unable to create a growth model due to lack of significant recapture of tagged fish for measurements. Fish were modeled within a range of 10 mm of their tagged size and were only modeled if they were tagged within the same summer that the passage event took place. This was assumed to account for their passage size and associated swimming abilities related to their size; however, some fish may have been larger than modeled and therefore would have better swimming abilities than what was modeled.

5.3 Recommendations

The ultimate recommendation resulting from this thesis is that the designer should utilize stream simulation design wherever possible. In areas where stream simulation is not possible (i.e., where funds or space constraints do not allow for the size of structure required), FishXing is an easy, user-friendly tool to model fish passage. This study showed that utilizing a one-dimensional model may be adequate as the two-dimensional model did not provide a substantial increase in accuracy. With use of recommended velocity reduction factors, the one-dimensional model appears to fairly accurately model the occupied velocity within the structure (based on similarity in passage between this model and the two-dimensional algorithm that models occupied velocity well). Velocity reduction factors are extremely important, but even then, FishXing is still conservative for juvenile salmonids. Although conservative, the goal of FishXing is to model a structure that will successfully pass fish. This precautionary approach may overestimate the size of the structure, resulting in additional cost, but will likely easily pass the design fish at flows higher than designed providing a factor of safety.

5.4 Areas of Further Study

Results show that there is a clear need to better understand juvenile salmonid swimming abilities and fish movement through passage structures. Many studies have been completed, but most are inside a flume and may only test a few fish, and are typically at a forced velocity in a laboratory setting at only certain water temperatures. Additionally, very little data was uncovered regarding juvenile salmonid burst speeds, and swimming ability data for juvenile Chinook was only on a small range of sizes and a tight range of velocities applied in a flume. Further studies should be made under field conditions so that barrier assessment (such as FishXing) can be refined.

If further modeling is desired, a three-dimensional model could be developed that could account for, not only velocity variations in the longitudinal and transverse direction, but also within the water column. Juvenile salmon may utilize the boundary layer at the bottom of the structure, and a two-dimensional model only captures the average depth-velocity; therefore, the depth component may increase predicted passage accuracy.

Lastly, for designers using FishXing, velocity reduction factors should be studied more thoroughly. An appropriate reduction factor can make all the difference in whether the design fish can pass through the modeled flow. Not using velocity reduction factors would result in an extremely conservative structure, but using velocity reduction factors that are too low could ultimately unrealistically model a structure that, in reality, may not be able to pass the design fish. FishXing should be used where needed, but as with any model, proper engineering judgement is a necessity.

6 References

Alaska Department of Fish & Game. (2014). Fish Passage Inventory Database. Accessed 10/20/2014 at: http://www.adfg.alaska.gov/index.cfm?adfg=fishpassage.database

Alaska Department of Fish & Game. (2017). Buddy Creek Hydrograph.

Alaska Department of Fish & Game, and Alaska Department of Transportation and Public Facilities. (2001). *Memorandum of Agreement Between Alaska Department of Fish and Game ad Alaska Department of Transportation and Public Facilities for the Design, Permitting, and Construction of Culverts for Fish Passage.*

Behlke, C. E. (1991). Power and Energy Implications of Passage Structures for Fish. *American Fisheries Society, Symposium 10: Fisheries Bioengineering Symposium*. Bethesda, Maryland. Pp. 289-298.

Behlke, C.E., Kane, D.L, McLean, R.F, and Travis, M.D. (1993). *Economic Culvert Design Using Fish Swimming Energy and Power Capabilities.* Pages 95-100 in K. Bates, editor. Proceeding of a symposium on fish passage and technology. American Fisheries Society, Bioengineering Section, Portland, OR.

Behlke, C.E., Kane, D.L, McLean, R.F, and Travis, M.D. (1991). *Fundamentals of Culvert Design for Passage of Weak Swimming Fish (FHWA-AK-RD-90-10).* State of Alaska Department of Transportation and Public Facilities in cooperation with US Department of Transportation Federal Highway Administration. February. 178 pp.

Bell, M. C. (1991). Fisheries handbook of engineering requirements and biological criteria. U.S. Army Corps of Engineers, Fish Passage Development and Evaluation Program. Portland, OR.

Bourne, C. M., Kehler, D. G., Wiersma, Y. F., & Cote, D. (2011). *Barriers to fish passage and barriers to fish passage assessments: the impact of assessment methods and assumptions on barrier identification and quantification of watershed connectivity*. Aquatic Ecology, Vol 45, pp. 389-403

Burford, D. D, McMahon, T. E., Cahoon, J. E., & Blank, M. (2009). *Assessment of trout passage through culverts in a large Montana drainage during summer low flow*. North American Journal of Fisheries Management Vol 29, pp. 739-752

Curran, J. H., Meyer, D. F., & Tasker, G. D. (2003). *Estimating the Magnitude and Frequency of Peak Streamflows for Ungaged Sites on Streams in Alaska and Conterminous Basins in Canada*. US Geological Survey Water Resources Investigations report 03-4188.

DOWL-HKM. (2014). Buddy Creek survey data. Anchorage, Alaska.

DOWL-HKM. (2014). Buddy Creek 95 percent design drawings. Anchorage, Alaska.

DOWL-HKM. (2014). Buddy Creek Hydrology & Hydraulic Report. Anchorage, Alaska.

DOWL-HKM. (2013). Buddy Creek Field Photos. Anchorage, Alaska.

Eisenman, M. & O'Doherty, G. (2014). *Culvert inventory and assessment manual for fish passage in the State of Alaska: A guide to the procedures and techniques used to inventory and assess stream crossings 2009-2014*. Alaska Department of Fish and Game, Special Publication No. 14-08, Anchorage, AK.

Firor, Susan. (2000). Th*esis: Sensitivity Analysis and Comparison of the Velocity Method with the Power and Energy Method for Assessing Fish Passage through Culverts*. Department of Environmental Systems: Environmental Resources Engineering. Humboldt State University.

Flosi, G., Downie, S., Hopelain, J., Bird, M., Coey, R., & Collins, B. (2010). *Part IX: Fish Passage Evaluation at Stream Crossings*. California Salmonid Stream Habitat Restoration Manual, 2010 4th Edition. p. 42

Forest Service Stream-Simulation Working Group. (2008). *STREAM SIMULATION: An Ecological Approach to Providing Passage for Aquatic Organisms at Road-Stream Crossings*. National Technology and Development Program, San Dimas, California.

Furniss, M., Love, M., Firor, S., Moynan K., Llanos, A, Guntle, J., & Gubernick, R. (2006). *FishXing Version 3 User Manual and Reference*, sponsored by Pacific Northwest Research Station, Forest Service Engineering Technology & Development Program, Federal Highway Administration, Stream Systems Technology Center, Rocky Mountain Research Station, US Fish and Wildlife Service. San Dimas, CA: USDA Forest Service.

Gubernick, R. (n.d.) Information for FishXing input and assessing barrierity and red pipe analysis for the Tongass National Forest Fish Passage Program. Notes provided by Gillian O'Doherty (ADF&G).

Jensen, K. M. (April 2014). *Thesis: Velocity Reduction Factors in Near Boundary Flow and the Effect on Fish Passage through Culverts*. Department of Civil and Environmental Engineering, Brigham Young University.

Jones, D. R., Kiceniuk, J. W., & Bamford, O.S. (1974). *Evaluation of the swimming performance of several fish species from the Mackenzie River.* J. Fish. Res. Bd. Canada, Vol. 31. pp. 1641-1647

Hunter, L. A. & Mayor, L. (1986). Analysis of fish swimming performance data. North-South Consultants and city Lights Engineering Consultants. Prepared for the Department of Fisheries and Ocean and the Alberta Department of Transportation. Winnipeg, Manitoba.

Kerr, J. E. (1953). Studies on fish preservation at the Contra Costa stream plant of the Pacific Gas and Electric Company. State of California, Dept. of Fish and Game Fish Bulletin 92.

Mahlum, S., Cote, D., Wiersma, Y., & Clarke, K.D. (2013). *Evaluating the Barrier Assessment Technique Derived from FishXing Software and the Upstream Movement of Brook Trout through Road Culverts*. Transaction of the American Fisheries Society, 143(1).

Milhous, R. T., and T.J. Waddle. (2012). *Physical Habitat Simulation (PHABSIM) Software for Windows (v.1.5.1)*. Fort Collins, CO: USGS Fort Collins Science Center.

National Fish Habitat Partnership. (2014). *Montana Creek, Alaska: A Waters to Watch Project for 2014*. Accessed 10/20/2014 at: http://fishhabitat.org/content/montana-creek-alaska

NMFS (National Marine Fisheries Service). (2008). Anadromous Salmonid Passage Facility Design. NMFS, Northwest Region, Portland, Oregon.

O'Doherty, G. (2017). Personal communication.

Powers, P. D. September 1997. Culvert hydraulics related to upstream juvenile salmon passage. Unpublished report. Washington State Department of Fish and Wildlife Habitat Program.