# WESTSLOPE CUTTHROAT TROUT PASSAGE

# IN A SCALED DENIL FISHWAY

by

Cole John Buller

A thesis submitted in partial fulfillment
of the requirements for the degree

of

Master of Science

in

Civil Engineering

MONTANA STATE UNIVERSITY
Bozeman, Montana

May 2023

# DEDICATION

This thesis is dedicated to my family and friends for their continuing support in the many ups and downs of life. Thank you for teaching me to appreciate the little things and to always have fun. None of this would have been possible without you.

# ACKNOWLEDGEMENTS

This project would not have been possible without the support and guidance of my graduate committee: Katey Plymesser, Matt Blank, Kevin Kappenman, and Joel Cahoon. The knowledge that I gained from you all is priceless.

Next, I would like to thank the entire staff at the Bozeman Fish and Technology Center. Thank you for welcoming me into your place of work with open arms and teaching me everything I needed to know. A special thanks to Jason Ilgen and Matt Toner for all the work that they put into this project. Thank you for letting me be a constant thorn in your side and never ceasing to make sure I had what I needed to succeed.

Thank you to David Dockery for assisting in the statistical analysis portion of this project. Your knowledge and expertise were critical in completing this project.

I would also like to thank all my peers that assisted in the completion of this project. Whether you assisted me in setting up swim trials or were simply there for me to bounce ideas off, your help was invaluable.

A huge thank you to the USFWS Region 6 Fish Passage Program and Bozeman Fish Technology Center for procuring the funding for this project.

This project took a lot of support, and I am so grateful for the community of people that quite literally made my world go round throughout the course of this project.

# TABLE OF CONTENTS

# TABLE OF CONTENTS CONTINUED

# LIST OF TABLES

Table Page

# LIST OF FIGURES

Figure Page

# ABSTRACT

Westslope Cutthroat Trout (*Oncorhynchus clarkii lewisi*) are a species of concern in the state of Montana and has become the focus of conservation efforts and research. Habitat fragmentation, caused by structures such as dams, culverts, and weirs, is one of the largest threats to Westslope Cutthroat Trout. Denil fishways have been installed at low-head diversions to facilitate their movement past these structures and maintain habitat connectivity. Recent research has focused on scaled Denil fishways, which require less water for operation than standard sized Denil fishways and leave more water for competing uses such as agricultural irrigation. The purpose of this study was to examine the passage of Westslope Cutthroat Trout in a 0.6-scale Denil fishway to determine the hydraulic conditions that best allow for passage. To do this, we prescribed twelve treatments of headwater and downstream approach depth combinations. Each treatment was replicated three times for a total of 36 trials with 10 fish in each trial. Fish movements and passage efficiencies were tracked using PIT tag telemetry. Overall, 68% (256/379) of the fish successfully passed through the fishway. Mixed effects statistical modeling was used to relate passage success to hydraulic variables and fish length. Results from this analysis indicate headwater to tailwater depth ratio and bulk tailwater velocity (as measured at the downstream end of the fishway) are the best metrics to predict the passage efficiency of Westslope Cutthroat Trout in a scaled Denil fishway. In general, passage success increased with lower headwater to tail water depth ratios (i.e., depths at the up and downstream ends of the fishway are similar) and lower tailwater velocities.

# CHAPTER ONE

# LITERATURE REVIEW

## Introduction

Fishways are structures used to facilitate the movement of fish past natural and artificial barriers to migration and have frequently been the focus of research and experimentation. Some researchers have focused on understanding fishway hydraulics to optimize design and provide safe fish passage. Studies have also been conducted on a wide variety of fish species to better quantify swimming abilities used in fishway design criteria. Technologies such as fish tracking devices and hydraulic simulation software have been developed to facilitate this research. Taken together these results have been used to improve criteria for fishway design and to support fish conservation. Of the many threatened fish species, salmonids have been of particular focus for fish passage because of their cultural, commercial, and recreational value. Identified as an at-risk salmonid species needing special attention, Westslope Cutthroat Trout (*Oncorhynchus clarkii lewisi)* are a focus of many conservation efforts and research (Shepard et al. 2005; Maxell 2020). The major subjects of this literature review include Westslope Cutthroat Trout life history, distribution, and swimming ability as well as Denil fishway hydraulics, passage studies, and hydraulic modelling of fishways.

## Westslope Cutthroat Trout

Westslope Cutthroat Trout are a subspecies of inland Cutthroat Trout that are a part of the Salmonid family (Young 1995). Red stripes near the lower jaw and black spots along the spine are some of the identifying characteristics of these fish. They are typically 6 to 16 inches, and rarely exceed 18 inches (MNHP and MFWP 2023). Westslope Cutthroat Trout can be adfluvial, fluvial or resident (Young 1995). Adfluvial fish spawn in streams, then migrate to lakes where they live the rest of their life. Fluvial fish spawn in tributaries but migrate to and exist in larger rivers. Resident fish are fish that spawn and live their entire life cycle in a tributary stream (MNHP and MFWP 2023).

The historic range of Westslope Cutthroat Trout spans both sides of the continental divide. Their range consists of rivers and lakes in Montana, Idaho, Washington, Oregon, Wyoming, and South-West Canada (Alberta and British Columbia). Major rivers in this range include the upper Columbia River, the upper Missouri River, and the John Day River (Western Native Trout Initiative n.d.; Shepard et al. 2005). Historically, this range spanned 90,800 km (56,500 mi) of riverine habitat but has decreased to 54,600 km (33,500 mi) (Western Native Trout Initiative n.d.; Shepard et al. 2005). This decline in historic range can be attributed to habitat loss and degradation, introduction of non-native species, and overfishing (Young 1995; MNHP and MFWP 2023). Hybridization with Yellowstone Cutthroat (*O. clarkia bouvieri*) and Rainbow Trout (*O. mykiss*) is believed to be one of the most significant factors in the decline of Westslope Cutthroat Trout (Allendorf and Leary 1988; Young 1995; Shepard et al. 2005). Allendorf and Leary (1988) found evidence of genetic introgression in 40% of Westslope Cutthroat Trout populations and Shepard et al. (2005) found evidence of genetic introgression in 42% of fish tested.

The swimming ability of Westslope Cutthroat Trout is relatively undefined. To better design fishways, swimming ability must be investigated to understand the capabilities of the fish relative to the hydraulic challenge of the structure. Blank et al. (2020) reported that the average swim speed of Westslope Cutthroat Trout was 0.84 ± 0.03 m/s (FL=15.0-29.0 cm). The maximum observed swim speed was 3.55 m/s. This data was obtained by observing and tracking the swimming ability of 30 Westslope Cutthroat in an open channel flume over the course of three observational trials. No experiments have been performed to analyze the swimming ability of Westslope Cutthroat in fishways or swim chambers.

Although the swimming ability of Westslope Cutthroat is limited in scope, there is literature that provides insight to a similar species, Coastal Cutthroat Trout (*O. clarkii clarkii*). Hawkins and Quinn (1996) performed a study in which the critical swim velocity of Coastal Cutthroat was observed in a Blazka-type swim chamber. The study found that Coastal Cutthroat had a critical swim speed of 5.58 ± 0.15 bl/s (n=23; FL=89.6 ± 12.0 mm) and 6.69 ± 0.23 bl/s (n=13; FL=88.6 ± 7.7 mm), varying between different stocks that were examined. This corresponds to 5.00 m/s and 5.93 m/s if the average reported fork lengths are used. It should be noted that the reported numbers for the Coastal Cutthroat were for juvenile fish (4-5 months old) and may not represent the swimming abilities of an adult fish (Hawkins and Quinn 1996).

## Denil Fishway Hydraulics

Fishways are hydraulic structures intended to assist fish and other aquatic organisms in passing obstructions such as dams, weirs, diversion structures or waterfalls (Clay 1995). There are a wide variety of fishway types and installations. Fishways can be broadly classified as either nature-like or technical fishways. Nature-like fishways use materials such as rocks or trees to simulate conditions that would occur in a natural stream or river. Technical fishways use common construction materials (such as concrete, metal, wood, or fiberglass) to create conditions favorable to fish passage (Katopodis et al. 2001). Technical fishways can be divided into four groups: 1) pool and weir, 2) Denil, 3) vertical slot and 4) modified culverts (Rajaratnam and Katopodis 1984; Katopodis 1992). Design of these fishways depends on the intended hydraulic conditions as well as the biological requirements of the target species.

One common type of technical fishway is the Denil fishway. This fishway was initially designed by the Belgian civil engineer G. Denil in 1909 (Fulton et al. 1953). This fishway was further developed over the next thirty years by various researchers. From 1936-1938 the British Institution of Civil Engineers experimented with physical Denil fishway models having baffles of varying geometry and complexity. They found the most practical was a single-plane baffle angled upstream (Figure 1b), which is the configuration used today. This baffle configuration creates circulating flow with areas of high and low velocity (Fulton et al. 1953). Denil fishways also exhibit high energy dissipation and momentum transfer with significant turbulence (Katopodis 1992). They are typically shorter and steeper than other fishways and are therefore less expensive to construct and maintain (Clay 1995; Haro et al. 1999; Noonan et al. 2012).

Denil fishways can be separated into two general types, simple Denil and Alaska steeppass. Simple Denils have areas of low velocity close to or along the bottom of the fishway (Rajaratnam and Katopodis 1984) while Alaska steeppass fishways create zones of low velocity near or at the water surface (Rajaratnam and Katopodis 1991). Differences in baffle type and geometry creates the difference in velocity profiles through each type of Denil fishway. In both designs the low velocity zones facilitate fish passage through the fishway.

Flow through a Denil can be classified into two hydraulic conditions: plunging flow and streaming flow (Triano 2020; Conley 2021). In plunging flow, the water cascades over each baffle, creating a stair-step water surface profile in the fishway. This occurs at low flows or conditions where the headwater is significantly greater than the tailwater (Rajaratnam et al. 1988; Conley 2021). Streaming flow is characterized by a more linear water surface profile with a stream (non-circulating region) occurring near the water surface (Rajaratnam et al. 1988). This condition occurs at higher flow rates and when the headwater depth is close to the tailwater depth.

Denil fishways can exhibit several tailwater conditions. Backwater conditions occur when the downstream water depth is greater than the water depth at the exit of the fishway. This condition encompasses submerged fishways, which occur when the downstream water depth overflows the fishway, therefore partially or fully engulfing it in water (Conley 2021). Backwatered fishways have lower downstream velocities and may reduce fish attraction (Rajaratnam and Katopodis 1984). Although attraction is reduced, backwatered fishways may increase entrance efficiency (Triano 2020). The other tailwater condition that is often seen in Denil fishways is drawdown. Drawdown occurs when the downstream depth is less than the depth through the fishway, therefore creating a drop in water surface at the exit of the fishway.

Simple Denil fishways are rectangular in cross section (Figure 1). They have varying height (depending on expected water surface elevations), a width of 0.90 m (3.0 ft), and are typically installed at slopes of less than 16.7 % (1:6) to maintain high enough depth and low enough velocity within the fishway (U.S. Fish and Wildlife Service 2017). Denil fishway baffles have a vee shaped notch with baffle legs that extend to the top of the fishway. They slant upstream, at a 45° angle with the fishway bed (Fulton et al. 1953). Denil fishways are recommended to be no longer than 10.0 m without turning pools between sections to provide opportunities for fish to recover (FAO and DVWK 2002). The typical layout and baffle geometry of a simple Denil is shown in Figure 1.

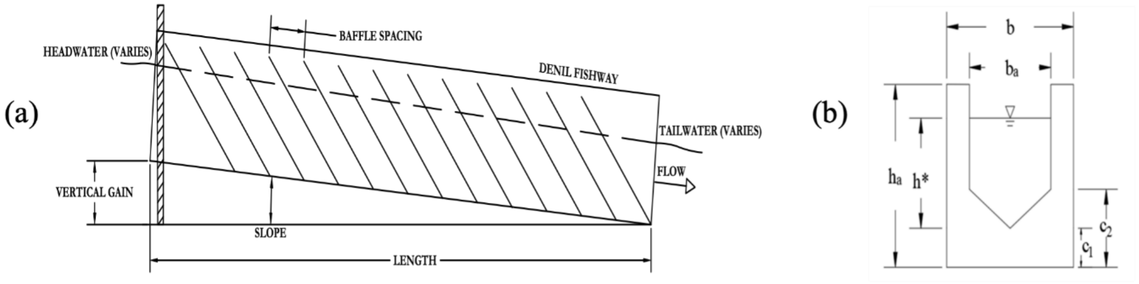

Figure 1: Plan view (a) and baffle detail (b) of a simple Denil Fishway. Baffle height is represented by $h_a$, $h^*$ is depth from water surface to baffle crest, b is width, $b_a$ is clear width, $c_1$ is v-notch depth, and $c_2$ is the depth to the full baffle slot.

Previous researchers have developed Denil fishway rating curves to describe the relationship between flow rate, water depth and velocity (Rajaratnam and Katopodis 1984; Katopodis 1992; Katopodis et al. 1997; FAO and DVWK 2002; Odeh 2003). These studies used various combinations of slope, fishway width (b), baffle clear width ($b_a$), depth to baffle notch ($h^*$), and baffle spacing (a) to define rating curves for Denil fishways. Rajaratnam and Katopodis (1984) and Katopodis et al. (1997) examined the effect of both width ratio ($b/b_a$) and baffle spacing ratio (a/b) on hydraulic conditions. A width ratio of $b/b_a$ equal to 1.58 and baffle spacing ratio of a/b equal to 0.72 are considered standard (Rajaratnam and Katopodis 1984). Rajaratnam and Katopodis (1984) and Katopodis et al. (1997) found that the rating curve for standard Denil fishways was valid for nonstandard Denil fishways (i.e., dimensions different from standard) for width ratios of up to 2.0 and baffle spacing ratios of up to 3.0. The Food and Agriculture Organization of the United Nations (FAO) and Deutscher Verband für Wasserwirtschaft und Kulturbau e.V. (DVWK) (2002) developed rating curves that are based off clear width, fishway slope and depth to baffle crest. Odeh (2003) examined how different combinations of slope, upstream depth, and width ratio impacted the flow capacity of a Denil fishway, and presented rating curves for widths between 0.46 m and 1.22 m. The vertical velocity profile within the baffles has been described by Rajaratnam and Katopodis (1984) and Kamula and Bärthel (2000). These studies showed that there is a zone of low velocity that occurs near the bottom of the fishway with a higher velocity region near the water surface. The highest velocity zones were found to occur along the sides of the Denil fishway rather than along the centerline (Kamula and Bärthel 2000).

## Fish Passage Through Denil Fishways

Artificial barriers cause natural habitat to become fragmented, which prevents fish from completing their upstream or downstream movements. In impacted systems, fish can no longer move through rivers to spawn, escape predators, or search for food  (Silva et al. 2018). Factors such as swimming ability, motivation, and migration timing must be considered in the design of a fishway to overcome the negative effects these barriers create (Katopodis 1992; Bunt et al. 2001).

In general, fishways must produce sufficient attraction flow in the correct location for fish to be able to find the entrance. Fishway entrances must be placed in locations (typically near the shoreline or edge of the river obstruction) where they can generate adequate velocity gradients to attract fish and not be hidden by the hydraulics of the river obstruction (Bunt et al. 2001; Williams et al. 2012). Fish tend to prefer attraction flow that is not too turbulent and is somewhat stable (Liao 2007).

Denil fishways have shown the potential to pass a wide range of fish sizes and species (Schmetterling et al. 2002; Mallen-Cooper and Stuart 2007). Previous experiments have shown that Denil fishways can pass Arctic Grayling (*Thymallus arcticus*), Alewife (*Alosa pseudoharengus*), Bony Herring (*Nematalosa erebi*), Golden Perch (*Macquaria ambigua*), and others (Mallen-Cooper and Stuart 2007; Nau et al. 2017; Triano 2020; Conley 2021; Plymesser et al. 2022). In general, fish pass at higher rates at lower slopes with higher headwater depths (Haro et al. 1999; Mallen-Cooper and Stuart 2007; Blank et al. 2021). Smaller fish pass at higher rates at narrower widths, but if width is reduced too much, then larger fish may have issues passing through them since they require larger areas to be able to swim (Mallen-Cooper and Stuart 2007). Constricting the width also prevents the Denil fishway from being able to operate over as wide of a range of hydraulic conditions (Mallen-Cooper and Stuart 2007). Optimizing fish passage through a Denil fishway must balance the capabilities of the target species with the expected hydraulic conditions within the fishway. If designed incorrectly, Denil fishways (as well as fishways in general) can lead to significant differences in species and size distribution between upstream and downstream fish populations (Baumgartner 2006).

Recent studies of Denil fishways have focused on dimensional scaling. Smaller scale Denil fishways utilize less water to provide fish passage, and therefore leave water available for other uses. This is important in rivers or streams where water is prioritized for other uses, such as agriculture or irrigation, or is limited, such as in small streams (Conley 2021; Plymesser et al. 2022). Plymesser et al. (2022) used the rating curves developed by Rajaratnam and Katopodis (1984), Katopodis et al. (1997) and Katopodis (1992) to create an overall rating curve for 0.60 and 0.75 scaled Denil fishways; the standard Denil discussed in Rajaratnam and Katopodis

(1984) was scaled by Froude number. These fishways were tested for passage efficiency with Arctic Grayling at various headwater and tailwater conditions, with greater passage success rates occurring at deeper tailwater conditions. Unfavorable passage conditions were found to occur when the headwater was significantly greater than the tailwater, causing a steep hydraulic grade line. Over all trials, the passage success rate was 91%, showing that scaled Denils have the potential to effectively pass fish, while utilizing less water (Plymesser et al. 2022).

Although Denil fishways have shown strong potential for successful fish passage, a recent meta-analysis by Hershey (2021) yielded they exhibit poor passage efficiency compared to other fishways. This analysis reviewed 60 articles containing information pertaining to 100 species of fish passing through 75 unique fishways. Nature-like (55.74%, n=76 fishways), pool and weir (50.36%, n=63 fishways), vertical slot (63.39%, n=78 fishways) and lock and lift (64.13%, n=27 fishways) fishways all exhibited higher passage efficiency than Denil Fishways (44.17%, n=8 fishways) (Hershey 2021). An earlier meta-analysis done by Bunt et al. (2012) yielded different results than Hershey (2021). Nature like fishways (70%, n=21 fishways) were the only fishway that exhibited higher passage efficiency than Denil fishways (51%, n=7 fishways). Vertical slot (45%, n=29 fishways) and pool and weir (40%, n=44 fishways) fishways exhibited poorer passage efficiency when compared to Denil fishways (Bunt et al. 2012). In both studies, Denil fishways were the least observed type of fishway, and therefore must be further examined to truly quantify their passage capabilities.

## Hydraulic Modelling

Physical and computational models enable the observation or prediction of hydraulic conditions within fish passage structures and in natural channels. They are useful for predicting variables such as depth, velocity, pressure, turbulence parameters and flow rate. Observations from models of fishways and channels are used by researchers to understand hydraulic conditions either broadly or within specific areas of interest in a fishway. Measured characteristics from physical models are used to develop mathematical relationships that can be used to predict fish passage or hydraulic conditions within the fishway. Models can be broadly separated into one dimensional (1-D) and three dimensional (3-D) categories. The complexity of data and results generally increase as more dimensions are observed.

Previous 1-D physical model studies of Denil fishways focused on developing rating curves and velocity profiles, as previously described (Rajaratnam and Katopodis 1984; Katopodis 1992; Katopodis et al. 1997; Odeh 2003). Physical 3-D models produce more detailed results than most 1-D physical models. More complex variables can be considered due to the multi-dimensionality of the results. The methods of collection are often complicated and require more advanced technology. Tools such as acoustic doppler velocimeters (ADV) are required to record multidimensional observations. Using these observations, variables such as turbulent kinetic energy (TKE) or turbulent intensity (TI) can be calculated and used to better define the hydrodynamics within the fishway (Amaral et al. 2016; Dockery et al. 2017).

Previous three-dimensional physical models focused on describing turbulence and fish movement within Denil, w-weir and vertical slot fishways. Wada et al. (2000) analyzed velocity fields and how they related to Ayu (*Plecoglossus altivelis*) movement within simple Denil and Alaskan steeppass fishways. This study found that for both types of fishway, Ayu tended to ascend through the bottom portion of the fishway where velocity and entrained air was at a minimum. Liu et al. (2006) used three-dimensional modelling to examine velocity and turbulence (TKE, TI, and Reynolds shear stress) in flow through vertical slot fishways. Shahabi et al. (2021) used multidimensional velocity measurements to calculate TKE and TI within W-weir fishways and examine how those parameters related to the stress levels of fish passing through the fishway.

Computational models of technical fishways are typically three dimensional (3-D) computational fluid dynamics (CFD) models. CFD models use the Navier-Stokes equations and turbulence models to predict or describe fishway conditions (Plymesser 2014; Platt 2019). CFD models use discretized forms of the fundamental laws of fluid mechanics to simulate hydraulic conditions. Previous CFD models have focused on vertical slot fishways, C-type fishways, turning pools, as well as others (Marriner et al. 2014; Fuentes-Pérez et al. 2018; Baharvand and Laskar-Ara 2021). When applied to fishways, CFD models can provide important insights to hydraulic conditions and associated fish behavior through the fishway. Physical measurements, such as water depth or flow rate, are used to define the boundary conditions and are used to calibrate and validate the results of CFD models (Feurich et al. 2012; Fuentes-Pérez et al. 2018; Baharvand and Laskar-Ara 2021). Once the model is calibrated and validated, it can be used to predict hydraulic variables at any point within the model space. Results can yield a more in-depth understanding of fish passage and fluid motion throughout the fishway.

Few Denil fishway CFD modelling studies have been published. Mahmoudian et al. (2019) used a Flow-3D CFD model to assess the effect of different baffle angles on velocity profiles. This study used expirmental data from Rajaratnam and Katopodis (1984) in order to confirm model results. The model results compared well to the the expirmental results. Plymesser (2014) used a Flow-3D CFD model to analyze an Alaska Steppass Denil fishway. This model investigated energy expenditure and passage efficiency of American Shad (*A. sapidissima)*; results from the CFD model were used to analyze fish fatigue levels through different swimming paths within the fishway. The results allow for fish fatigue levels to be derived for any given length of fishway, therefore helping designers determine maximum lengths of fishways or maximum length between resting pools within fishways. The CFD model for this study was further used to examine pressure gradients within Alaska Steppass Denil fishways. The results indicated that pressure gradients can be of significant magnitude and should be examined for the effect they have on fish passage (Plymesser and Cahoon 2017).

## Conclusion

This literature review examined Westslope Cutthroat Trout life history, distribution, and swimming ability as well as Denil fishway hydraulics, passage studies, and hydraulic modelling of fishways. Key findings include:

- The swimming behavior and ability of Westslope Cutthroat Trout is relatively unknown. Only one study has been performed to date to quantify the swimming abilities of this fish.
- Denil fishways yield variable passage metrics depending on fish species, hydraulic conditions, and physical constraints.
- Compared to other fishways types Denil fishways exhibited mixed passage metrics but are often the most economical option (Noonan et al. 2012).
- There have been many 1-D physical model studies and relatively few 3-D or CFD model studies of Denil fishways.

- There are no published passage studies of Westslope Cutthroat Trout in Denil fishways.

This literature review highlights the need to better understand Denil fishways, Westslope Cutthroat Trout swimming abilities, and how Westslope Cutthroat Trout utilize Denil Fishways to pass, both upstream and downstream. Three-dimensional physical and CFD models should be developed to further understand of these fishways and to allow for more in-depth analysis of fish passage metrics.

# CHAPTER TWO

# WESTSLOPE CUTTHROAT TROUT (ONCORHYNCHUS CLARKII LEWISI) PASSAGE THROUGH A SCALED DENIL FISHWAY

## Contribution of Authors and Co-Authors

Manuscript in Chapter 2

Author: Cole Buller

Contributions: Collected data, analyzed data, interpreted results, wrote manuscript.

Co-Author: Katey Plymesser Ph.D.

Contributions: Provided intellectual contributions, co-authored proposal to secure funding, reviewed manuscript.

Co-Author: Kevin Kappenman

Contributions: Helped form conceptual basis of project, co-authored proposal to secure funding, reviewed manuscript, oversaw flume study, provided fisheries knowledge.

Co-Author: Matt Blank Ph.D.

Contributions: Helped form conceptual basis of project, co-authored proposal to secure funding, reviewed manuscript.

Co-Author: Joel Cahoon Ph.D.

Contributions: Provided intellectual contributions, reviewed manuscript, co-authored proposal to secure funding, provided hydraulics support.

# Manuscript Information

Cole Buller, Katey Plymesser, Kevin Kappenman, Matt Blank, Joel Cahoon

Journal of Fish and Wildlife Management

Status of Manuscript:

__X__ Prepared for submission to a peer-reviewed journal

______ Officially submitted to a peer-reviewed journal

______ Accepted by a peer-reviewed journal

______ Published in a peer-reviewed journal

Publisher: Allen Press

# Abstract

Westslope Cutthroat Trout (*Oncorhynchus clarkii lewisi*) are a species of concern in the state of Montana and has become the focus of conservation efforts and research. Habitat fragmentation, caused by structures such as dams, culverts, and weirs, is one of the largest threats to Westslope Cutthroat Trout. Denil fishways have been installed at low-head diversions to facilitate their movement past these structures and maintain habitat connectivity. Recent research has focused on scaled Denil fishways, which require less water for operation than standard sized Denil fishways and leave more water for competing uses such as agricultural irrigation. The purpose of this study was to examine the passage of Westslope Cutthroat Trout in a 0.6-scale Denil fishway to determine the hydraulic conditions that best allow for passage. To do this, we prescribed twelve treatments of headwater and downstream approach depth combinations. Each treatment was replicated three times for a total of 36 trials with 10 fish in each trial. Fish movements and passage efficiencies were tracked using PIT tag telemetry. Overall, 68% (256/379) of the fish successfully passed through the fishway. Mixed effects statistical modeling was used to relate passage success to hydraulic variables and fish length. Results from this analysis indicate headwater to tailwater depth ratio and bulk tailwater velocity (as measured at the downstream end of the fishway) are the best metrics to predict the passage efficiency of Westslope Cutthroat Trout in a scaled Denil fishway. In general, passage success increased with lower headwater to tail water depth ratios (i.e., depths at the up and downstream ends of the fishway are similar) and lower tailwater velocities.

# Introduction

## Denil Fishways

A Denil fishway is a flume with rectangular cross section and notched baffles spaced evenly throughout its length (Rajaratnam and Katopodis 1984). Denil fishways can be separated into two general types, simple Denil and Alaska steeppass. Differences in baffle shape and dimensions are what distinguishes the two types from each other. Simple Denil fishways were the focus of this study.

Simple Denil fishways can have varying geometry depending on their intended use or fabrication. The "standard" dimensions referred to herein are b=0.56 m, $b_a$=0.36 m, $c_1$=0.13 m, and a=0.25 m (Figure 3), as discussed in Rajaratnam and Katopodis (1984). Simple Denil fishway baffles have a vee shaped notch with baffle legs that extend to the top of the fishway. They slant upstream, at a 45° angle with the fishway bed (Fulton et al. 1953). The angled baffles cause high energy dissipation and momentum transfer with a significant amount of turbulence (Katopodis 1992). Recirculating regions are created between baffles with high velocities occurring close to or along the water surface and low velocity regions occurring close to or along the bottom of the fishway (Rajaratnam and Katopodis 1984). The low velocity region is what facilitates fish passage through the fishway.

Previous fish passage studies of Denil Fishways have shown their potential to pass a wide range of fish species and sizes (Schmetterling et al. 2002; Mallen-Cooper and Stuart 2007). Experiments have shown that Denil fishways can pass Arctic Grayling (*Thymallus arcticus*), Alewife (*Alosa pseudoharengus*), Bony Herring (*Nematalosa erebi*), Golden Perch (*Macquaria ambigua*), and others (Schwalme et al. 1985; Baumgartner 2006; Mallen-Cooper and Stuart

2007; Nau et al. 2017; Triano 2020; Conley 2021; Plymesser et al. 2022). Laboratory studies of Denil fishways have focused on assessing their hydraulic characteristics (Rajaratnam and Katopodis 1984; Katopodis 1992; Katopodis et al. 1997; Kamula and Bärthel 2000; FAO and DVWK 2002; Odeh 2003). These studies developed rating curves and examined velocity profiles for these fishways but did not use fish to assess passage success.

Recent studies at the United States Fish and Wildlife Service Bozeman Fish Technology Center (BFTC) have focused on assessing the passage of Arctic Grayling through Denil fishways (Conley 2021; Blank et al. 2021; Plymesser et al. 2022). These studies have focused on dimensional scaling of Denil fishways. Smaller scale Denil fishways utilize less water to provide fish passage, and therefore leave water available for other uses. This is important in rivers or streams where water is prioritized for other uses, such as agriculture or irrigation, or is limited, such as in small streams (Conley 2021; Plymesser et al. 2022).

## Westslope Cutthroat Trout

Westslope Cutthroat Trout (*Oncorhynchus clarkii lewisi*), hereafter WCT, are a subspecies of inland Cutthroat Trout that are a part of the salmonid family (Young 1995). The historic range of WCT spans both sides of the continental divide. Their range consists of rivers and lakes in Montana, Idaho, Washington, Oregon, Wyoming, and South-West Canada (Alberta and British Columbia). Major rivers in this range include the upper Columbia River, the upper Missouri River, and the John Day River (Western Native Trout Initiative n.d.; Shepard et al. 2005). Historically, this range spanned 90,800 km (56,500 mi) of riverine habitat but has decreased to 54,600 km (33,500 mi) (Western Native Trout Initiative n.d.; Shepard et al. 2005). This decrease in habitat has resulted in WCT being listed as an at-risk species in the state of Montana (Maxell 2020).

To date, there has only been one published study examining the swimming ability of WCT. Blank et al. (2020) reported that the average volitional swim speed of WCT was 0.84 ± 0.03 m/s (FL=15.0-29.0 cm). The maximum observed swim speed was 3.55 m/s. This data was obtained by observing the swimming ability of 30 Westslope Cutthroat in an open channel flume over the course of three observational trials. To our knowledge, no other experiments have been performed to analyze the swimming ability of Westslope Cutthroat in fishways or swim chambers.

## Overview

The objective of this study was to evaluate upstream passage of WCT in a scaled Denil fishway. We used a 0.6 scale Denil fishway, when compared to the standard size. The fabricated fishway was installed and tested at the BFTC. Fish were allowed to swim volitionally for a period of 18 hours for each swim trial. Flow rate, headwater depth, and downstream approach depth were all varied to create a variation of hydraulic conditions ranging from the minimum to the maximum capacity of the fishway. The goal was to better understand the hydraulics of dimensionally scaled Denil fishways and their relationship to the passage of WCT, a species of special concern.

# Methods

## Fishway Layout and Instrumentation

The study took place in an outdoor flume at the BFTC from July through November of 2021. The flume was 17.0 m long, with an inside width of 0.9 m (Figure 4). The downstream approach depth (Figure 2) in the flume was regulated using outlet control weirs that were built into the holding area at the downstream end the flume. Headwater depth (Figure 2 and Figure 3) was controlled by manipulating the flow rate within the flume. Fresh water lines that were piped into the flume from nearby warm and cool springs were used to control the water temperature. The Denil fishway was placed in the flume such that the downstream end of the fishway was 6.0 m from the tailwater holding area.

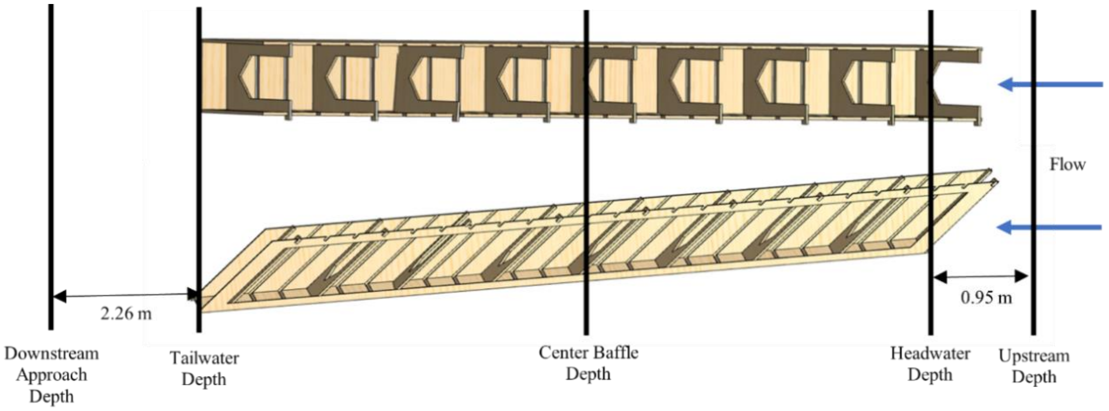

Figure 2: Measured depth locations.

The Denil fishway used for this study was “simple” type in terms of baffle shape. It was 0.6 scale (scaled by Froude number) when compared to the standard Denil fishway described in Rajaratnam and Katopodis (1984). The scaling factor was based on a previous study by Plymesser (2022), which used a similar experimental process and examined Arctic Grayling passage. The scaled Denil fishway was designed to significantly reduce water flow, while still maintaining enough width to allow for the movement of adult WCT. The scaling factor was applied to all dimensions shown in Figure 3, except overall height, $h_a$. The constructed fishway had a length of 3.67 m with a slope of 8.3% (nominally 1:12 horizontal: vertical), therefore having a vertical gain of 0.30 m. The baffle spacing (a) was 25.0 cm. The constructed baffles had dimensions of total width (b) of 35.5 cm, slot width ($b_a$) of 21.5 cm, height ($h_a$) of 61.2 cm, a V-notch depth ($c_1$) of 9.0 cm, and a depth to full baffle slot width ($c_2$) of 16.7 cm (See Figure 3).

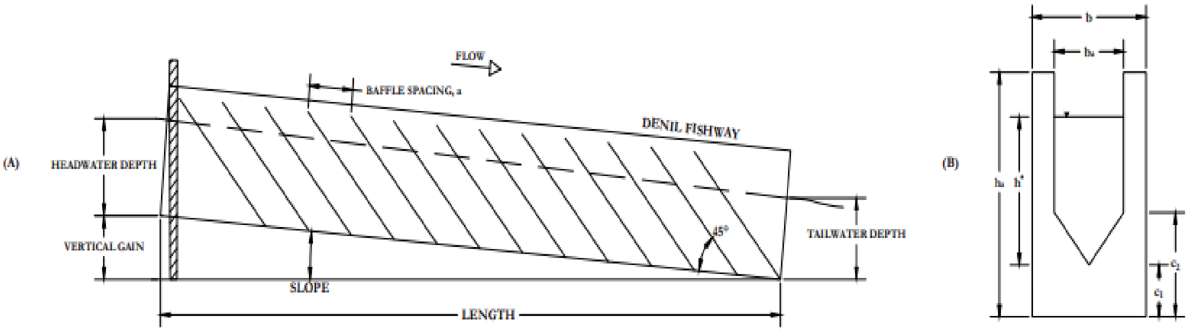

Figure 3: Side view (A) and baffle detail (B) of a Denil fishway. The dimensions used were b=35.5 cm, $b_a$= 21.5 cm, $h_a$= 61.2 cm, $c_1$=9.0 cm, and $c_2$= 16.7 cm.

A Multi-Antenna HDX Reader (Oregon RFID, Portland, OR) passive integrated transponder (PIT) system was used to track fish movement throughout trials. The system utilized four antennas placed at locations significant to fish passage. Antenna A1 was placed 1.27 m downstream of the Denil fishway. This antenna was used to determine participation rate in the trial. Any fish that was detected by this antenna was approaching the Denil fishway and was therefore an active participant in the trial. Antenna A2 was placed 0.65 m upstream of the downstream end of the fishway to detect passage attempts (fish that entered the fishway). Antenna A3 was placed at the upstream end of the fishway, and Antenna A4 was placed 2.44 m upstream of the fishway. These two antennas were used to detect fish that successfully ascended the fishway (passage success). Detection probability was tested (Triano, 2020) and the system was calibrated until 100% single tag detection and 85% multi-tag detection was achieved. The PIT antenna layout and general flume layout is shown in Figure 4.

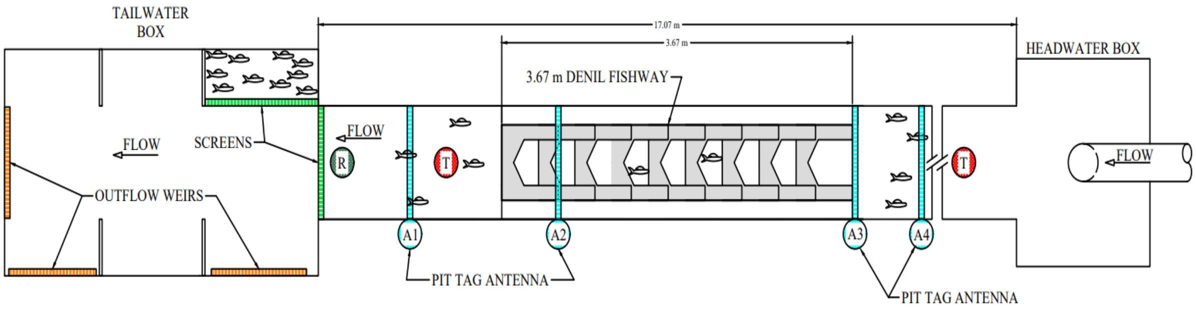

Figure 4: Flume layout schematic. T denotes where temperature readings were taken. R indicates where WCT were released at the start of each trial. A1, A2, A3, and A4 denote where PIT tag antennas were placed.

## Test Fish

We used 382 WCT in this study. The study fish were offspring from brood stock collected from tributaries of Hungry Horse Reservoir and the lower Clark Fork drainage and maintained at MTFWP Washoe Park Trout Hatchery in Anaconda, MT. The test fish were reared to fingerling stage (50-100 mm) at Washoe and then transferred to the BFTC in Bozeman, MT. During transport, the live-well temperature was 12 °C (±2 °C) and the oxygen maintained at 8 mg/L. At BFTC the WCT were reared at 12 °C and fed daily via a timed belt with floating feed (Classic Trout; Skretting, Tooele, UT). Fish were gradually moved to larger tanks to maintain a fish density below 0.023 kg/L as they grew. A few weeks before the trials, fish were moved to 1.83 m diameter tanks fitted with recirculating pumps. To identify and track fish throughout the study, 12 mm preloaded HDX PIT tags (OregonRFID, Portland, OR) were inserted into the abdominal cavity prior to conducting the experiment. Fish were anesthetized with 25 mg/L of tricaine methane sulfonate (MS-222) during the tagging process. The insertion wounds were small and did not require sutures. All fish were allowed a minimum of 6 days to heal before being included in a trial.

### Experimental Treatments/Swimming Studies

Volitional WCT passage trials were performed at specific headwater and downstream approach depths. We used a combination of four headwater depths (61.0 cm, 51.0 cm, 40.5 cm, and 30.5 cm) and three downstream approach depths (61.0 cm, 30.5 cm, and 15.2 cm) throughout twelve treatments, with each treatment having a unique combination of headwater depth and downstream approach depth. Each treatment was replicated at least three times yielding a total of 39 trials, with ten WCT used in each trial. The trial order was determined using a random number generator. A summary of the treatments and trials is shown in Table 1. Some trials were performed more than three times to ensure that good data was collected (Table 4).

Table 1: Summary of treatments and trials for the study.

| Treatment number | Trial Number | Target Number of Fish | Target Headwater Depth (cm) | Target Downstream Approach Depth (cm) |
|---|---|---|---|---|
| 1 | 22 | 10 | 30.5 | 61.0 |
| | 12 | 10 | 30.5 | 61.0 |
| | 29 | 10 | 30.5 | 61.0 |
| 2 | 35 | 10 | 30.5 | 30.5 |
| | 28 | 10 | 30.5 | 30.5 |
| | 38 | 10 | 30.5 | 30.5 |
| | 6 | 10 | 30.5 | 30.5 |
| 3 | 16 | 10 | 30.5 | 15.2 |
| | 15 | 10 | 30.5 | 15.2 |
| | 37 | 10 | 30.5 | 15.2 |
| | 39 | 10 | 30.5 | 15.2 |
| | 17 | 10 | 30.5 | 15.2 |
| 4 | 2 | 10 | 40.5 | 61.0 |
| | 10 | 10 | 40.5 | 61.0 |
| | 24 | 10 | 40.5 | 61.0 |
| 5 | 25 | 10 | 40.5 | 30.5 |
| | 23 | 10 | 40.5 | 30.5 |
| | 14 | 10 | 40.5 | 30.5 |
| 6 | 13 | 10 | 40.5 | 15.2 |
| | 36 | 10 | 40.5 | 15.2 |
| | 26 | 10 | 40.5 | 15.2 |
| 7 | 7 | 10 | 51.0 | 61.0 |
| | 3 | 10 | 51.0 | 61.0 |
| | 33 | 10 | 51.0 | 61.0 |
| 8 | 9 | 10 | 51.0 | 30.5 |
| | 18 | 10 | 51.0 | 30.5 |
| | 21 | 10 | 51.0 | 30.5 |
| 9 | 5 | 10 | 51.0 | 15.2 |
| | 32 | 10 | 51.0 | 15.2 |
| | 31 | 10 | 51.0 | 15.2 |
| 10 | 20 | 10 | 61.0 | 61.0 |
| | 19 | 10 | 61.0 | 61.0 |
| | 8 | 10 | 61.0 | 61.0 |
| 11 | 34 | 10 | 61.0 | 30.5 |
| | 11 | 10 | 61.0 | 30.5 |
| | 4 | 10 | 61.0 | 30.5 |
| 12 | 1 | 10 | 61.0 | 15.2 |
| | 27 | 10 | 61.0 | 15.2 |
| | 30 | 10 | 61.0 | 15.2 |

### Trial Process

Twenty-four hours prior to the start of a trial, we arbitrarily netted 10 WCT from the circular holding tanks and moved them into holding pens in the tailwater box of the open channel flume. Each fish was scanned using a Destron Fearing 601 Handheld reader (Destron Fearing, DFW Airport, Texas, USA) or a HPR Lite (Biomark, Boise, Idaho, USA) PIT tag reader to ensure a functioning PIT tag. During the holding period, food was withheld to ensure a post-absorptive state.

At the start of the trial, water flow rate and depths were established near the treatments target values. Fish were placed into the downstream portion of the flume and allowed to acclimate. Screens were placed at the downstream end of the flume to create a 2.44 meter long holding area. The screens prevented fish from swimming up into the fishway or down into the tailwater box. After fish placement, the water flows and depths were fine tuned to the treatment target values and allowed to stabilize.

While the hydraulic system was stabilizing the PIT array was turned on and tested by moving a 12 mm HDX tag through the array to ensure proper function of each PIT antenna. After the 30-minute hydraulic stabilization, a preliminary set of hydraulic measurements were recorded (flow rate, headwater depth and downstream approach depth). The downstream holding screen was then removed, allowing fish to move volitionally through the flume, officially beginning the trial.

Trials lasted 18 hours, beginning in the afternoon, and then concluding the following morning. At the end of the trial, the PIT tag array was turned off. We then collected a second set of hydraulic measurements. Screens were inserted into the upstream and downstream baffles of the fishway, and the pump was turned off. Fish were caught using a net. Their PIT tag number and location was recorded (either as below, within, or above the Denil fishway). Test fish were only used in one trial.

### Hydraulic Data Collection

Before the start and after the end of each trial hydraulic measurements were taken. At the start of the trial the headwater and the downstream approach depths were recorded. At the end of the trial the same water depths were recorded as well as upstream water depth, center baffle depth, and tailwater depth. See Figure 2 for measured depth locations, and Figure 3 for a sideview of headwater and tailwater depth measurements. We measured water depth using a depth rod. Water and air temperatures were measured using a Ertco-Eutenchnics Model 4400 digital thermometer (Alpha Technics, Oceanside, CA). A temperature reading was taken in both the headwater and tailwater portion of the flume at the beginning and end of each trial. Water flow rate was measured using a Signet 2540 paddle wheel flow sensor (GF Piping Systems, Schlaffhausen, Switzerland) installed into the recirculation pipe. A summary of the measured hydraulic conditions across all trials is shown in Table 4.

### Data Analysis

The PIT data from the Multi-Antenna HDX reader was summarized to indicate the presence of individual fish at each antenna. Several fish made multiple passes through the fishway, but only the first detection at each antenna was used to analyze passage success. A fish was considered a participant if it was scanned at antenna A1. If a fish was scanned at A2, then it was considered to have entered the fishway. A fish was considered to have successfully passed through the fishway if it was scanned at either A3 or A4, since both antennas are upstream of the fishway. The measure of passage success in the trial was the total number of fish that passed through the fishway divided by the number of participants in the trial. A summary of passage and hydraulic results are presented in Table 4.

There were several detection malfunctions (i.e., a fish being scanned at A1, A3, and A4, but not scanned at A2, or being randomly scanned at A4 after being repetitively scanned at A1). These malfunctions were compensated for using logic. The time of detection at each antenna was considered and scan locations were either assumed or removed using previous antenna scans. For example, if a fish was scanned at A1 at 8:05:22 p.m. and then scanned at A3 at 8:06:45 p.m. and A4 at 8:07:14 p.m., then a detection was manually added at A2. If a fish was scanned at A1 at 10:30:31 p.m., then scanned at A4 at 10:30:32 p.m., then re-scanned at A1 at 10:30:33 p.m., then the A4 scan was removed from the data set as it was physically impossible for a fish to move in that manner.

## Statistical Analysis

The summarized PIT detection data was analyzed in the program R (R Core Team, 2023). Data was analyzed by both a by-trial basis, and a by-fish basis. Binomial logistic regression was used to analyze the data on a by-trial basis. Mixed effects logistic regression was used to analyze the binary response (pass/fail) on a by-fish basis using the lme4 package (Bates et al. 2015). A random effects intercept term was added to models to account for the effects of group behavior among trials.

### Temperature.

The observed water temperature varied from 10.95 °C to 12.71 °C across all trials. The mean water temperature was 11.87 ± 0.34 °C. Water temperature did not exhibit any correlation with trial date, indicating that seasonal temperature variations were negated by controlling the amount of the warm or cool spring water entering the flume. Exploratory analysis did not indicate any trends among temperature and passage success among trials or treatments. A one-way ANOVA indicated no evidence (*p* value=0.3465; from a one-way ANOVA f-test; F=1.178 on 11 and 27 degrees of freedom) that temperature varied among treatments. For these reasons, temperature was not considered for exploratory models of passage success.

Fish Length. Fish were measured at the end of a trial and total length (TL) ranged from 77.0 mm to 277.0 mm, with a mean TL of 155.6 ± 32.9 mm. All fish were adult fish that were two to three years old. Results from a Kruskall-Wallis test (to account for unequal variances in TL among trials) indicate that there is inconclusive evidence ($p$=0.0635, $X^2$=51.939, df=38) that fish length among trials was different. Among treatments, a one-way ANOVA did not indicate any evidence (two-sided $p$=0.1737 from one way ANOVA f-test; f=1.393 on 11 and 370 degrees of freedom) in difference between mean total lengths. For these reasons, we did not initially consider fish length as a candidate for exploratory logistic regression models.

By-Trial Analysis. Binomial logistic regression was used to analyze how hydraulic conditions affected the probability of passage success on a by-trial basis. Linear logit was applied to passage rate to develop models. We examined nine hydraulic variables: 1) headwater depth, 2) tailwater depth, 3) downstream approach depth, 4) flow rate, 5) headwater to tailwater (HW to TW) ratio, 6) slope of the hydraulic grade line (HGL), 7) center baffle bulk velocity, 8) tailwater bulk velocity, 9) downstream approach velocity. HW to TW ratio was calculated by dividing the headwater depth by the tailwater depth. HGL was calculated by dividing the difference between the headwater depth and tailwater depth by the length of the fishway. Bulk velocities were calculated by dividing the flow rate by the respective cross-sectional area of the region of interest. Models were only developed using one hydraulic variable due to high correlations among hydraulic variables.

Results from this analysis did not indicate that any of the models fit the data well. The highest *p* value obtained from goodness of fit tests was 0.0078 for the downstream approach velocity model. All other models had *p* values of <0.0001 from goodness of fit tests. To put this in perspective, a *p* value of >0.05 would be needed to provide inconclusive evidence that the observed values differed from the predicted values. The smaller the *p* value, the better a model fits the observed data. See Table 2 for a summary of the goodness of fit tests for all the models that were examined. When the models were plotted, most of the collected data points did not fall within the 95% confidence interval. This indicates that none of the models fit the data very well, and that a different method of analysis was needed. Figure 5 shows examples of this for some of the models that were developed.

Table 2: Summary of goodness of fit tests for logistic regression models.

| Model | *p* value |
|---|---|
| Headwater Depth | <0.0001 |
| Tailwater Depth | <0.0001 |
| Downstream Approach Depth | <0.0001 |
| Flow Rate | <0.0001 |
| HW to TW ratio | <0.0001 |
| HGL | <0.0001 |
| Center Baffle Velocity | <0.0001 |
| Tailwater Velocity | <0.0001 |
| Downstream Approach Velocity | 0.0078 |

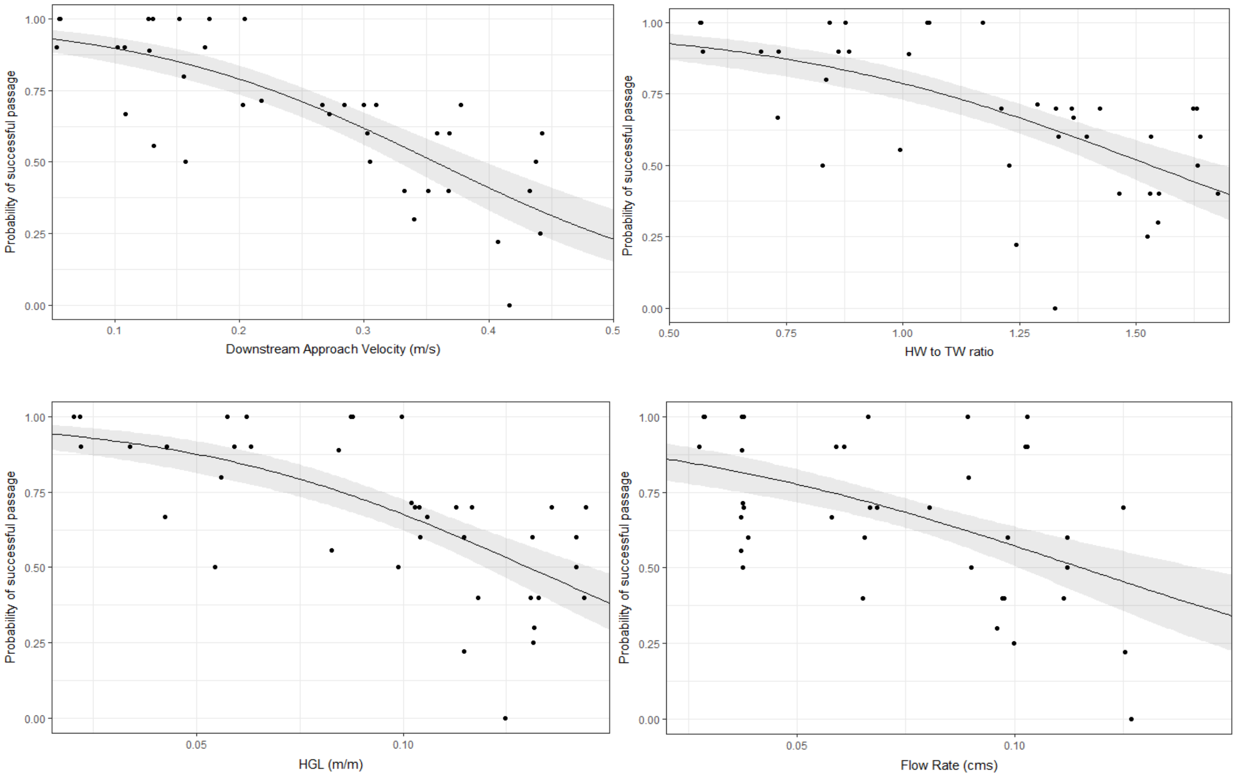

Figure 5: Summary plots of the logistic regression models (Upper Left – Downstream Approach Velocity, Upper Right - HW/TW Ratio, Lower Left - HGL, Lower Right - Flow Rate).

By-Fish Analysis. Because logistic regression analysis by trial did not yield any well-fitting models, the data was analyzed using a binary by-fish approach. Mixed effects models were developed with a random effects term for the trial number used as the model intercept (to account for group behavior among trials, as previously stated). A fish length term was added to the models. Although differences in fish length was not observed among treatments, differences in fish length were observed between fish that did not pass and fish that did pass, justifying the addition of the term to models. The input variables were centralized (i.e., the mean was subtracted) to reduce multicollinearity and variance inflation factors (VIF's) that were observed in preliminary model development.

The hydraulic variables that were examined were: HW to TW ratio, tailwater velocity, and tailwater depth. These values were selected from the wider range of recorded values because they are the most applicable, easy to measure, and simple to implement in a field setting. Each of these hydraulic variables, in conjunction with fish length, was then used to create a series of models. A total of 3 models were created for each hydraulic variable, along with two extra models that only accounted for the intercept and fish length, yielding a total of 11 models. The general form of all the models is summarized below in Table 3.

Table 3: Mixed effects model notation.

| Model Description | Model Notation |
|---|---|
| Fish Length * Hydraulic Variable | $\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_{1,2}(X_1 * X_2)$ |
| Fish Length + Hydraulic Variable | $\beta_0 + \beta_1 X_1 + \beta_2 X_2$ |
| Hydraulic Variable | $\beta_0 + \beta_2 X_2$ |
| Fish Length | $\beta_0 + \beta_1 X_1$ |
| Intercept | $\beta_0$ |

Akaike’s information criterion corrected for small sample sizes (AICc) was used to assess the models. This methodology accounts for the number of input variables to the model as well as the ability of the model to estimate the data (Burnham et al. 2011; Symonds and Moussalli 2011). The smaller the AICc score, the better the model fit. Any models that were within two AICc values of the best model were considered essentially as good as the best model (Burnham et al. 2011; Symonds and Moussalli 2011). We used AICc to assess models due to the relatively small number of observations in this study.

## Table 4: Summary of trials/treatments.

| Treatment | Trial | Date | Number of Fish in Trial | Number of Participants | Total that Passed | Passage Rate | Fish Length (mm) | Fish Weight (g) | Water Temperature (˚F) | Downstream Approach Depth (cm) | Headwater Depth (cm) | Tailwater Depth (cm) | Flow Rate (cms) | DS Denil Velocity (m/s) | HW to TW Ratio |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 12 | 9/13/2021 | 10 | 10 | 9 | 0.90 | 144.7 | 28.59 | 11.90 | 55.95 | 29.90 | 52.30 | 0.03 | 0.32 | 0.57 |
| 1 | 22 | 9/29/2021 | 10 | 10 | 10 | 1.00 | 162.5 | 45.95 | 11.21 | 56.00 | 29.65 | 52.20 | 0.03 | 0.34 | 0.57 |
| 1 | 29 | 10/13/2021 | 10 | 10 | 10 | 1.00 | 162.1 | 37.75 | 12.02 | 56.40 | 29.95 | 53.00 | 0.03 | 0.33 | 0.57 |
| 2 | 6 | 9/2/2021 | 10 | 9 | 5 | 0.56 | 144.6 | 28.90 | 12.16 | 31.00 | 30.40 | 30.60 | 0.04 | 0.97 | 0.99 |
| 2 | 28 | 10/12/2021 | 9 | 9 | 8 | 0.89 | 149.6 | 32.46 | 11.82 | 32.05 | 30.20 | 29.80 | 0.04 | 1.03 | 1.01 |
| 2 | 35 | 10/26/2021 | 9 | 9 | 9 | 1.00 | 168.7 | 45.82 | 11.76 | 32.00 | 30.20 | 28.70 | 0.04 | 1.09 | 1.05 |
| 2 | 38 | 11/4/2021 | 10 | 10 | 10 | 1.00 | 182.2 | 63.79 | 12.09 | 31.60 | 30.30 | 28.70 | 0.04 | 1.11 | 1.06 |
| 3 | 15 | 9/16/2021 | 9 | 9 | 6 | 0.67 | 156.2 | 35.52 | 11.81 | 14.95 | 30.85 | 22.60 | 0.04 | 1.77 | 1.37 |
| 3 | 16 | 9/20/2021 | 8 | 7 | 5 | 0.71 | 157.3 | 34.55 | 10.95 | 18.90 | 30.65 | 23.80 | 0.04 | 1.60 | 1.29 |
| 3 | 37 | 11/1/2021 | 10 | 10 | 6 | 0.60 | 167.0 | 35.09 | 11.50 | 14.05 | 30.40 | 22.80 | 0.04 | 1.82 | 1.33 |
| 3 | 39 | 11/3/2021 | 10 | 10 | 5 | 0.50 | 171.6 | 46.54 | 11.69 | 13.45 | 30.70 | 25.00 | 0.04 | 1.43 | 1.23 |
| 3 | 17 | 9/21/2021 | 10 | 10 | 7 | 0.70 | 153.8 | 36.84 | 11.38 | 14.50 | 30.30 | 22.80 | 0.04 | 1.76 | 1.33 |
| 4 | 2 | 8/26/2021 | 10 | 9 | 6 | 0.67 | 136.3 | 24.10 | 11.82 | 58.35 | 40.85 | 55.80 | 0.06 | 0.63 | 0.73 |
| 4 | 10 | 9/8/2021 | 10 | 10 | 9 | 0.90 | 157.6 | 38.29 | 12.17 | 65.05 | 41.40 | 59.50 | 0.06 | 0.61 | 0.70 |
| 4 | 24 | 10/4/2021 | 10 | 10 | 9 | 0.90 | 149.5 | 32.99 | 11.69 | 60.00 | 40.95 | 55.80 | 0.06 | 0.64 | 0.73 |
| 5 | 14 | 9/15/2021 | 10 | 10 | 10 | 1.00 | 150.1 | 28.42 | 12.24 | 35.60 | 41.10 | 35.10 | 0.07 | 1.39 | 1.17 |
| 5 | 23 | 9/30/2021 | 10 | 10 | 7 | 0.70 | 148.9 | 31.40 | 11.59 | 28.10 | 40.95 | 28.80 | 0.07 | 1.99 | 1.42 |
| 5 | 25 | 10/5/2021 | 10 | 10 | 7 | 0.70 | 149.9 | 29.25 | 12.13 | 36.80 | 41.15 | 34.00 | 0.07 | 1.50 | 1.21 |
| 6 | 13 | 9/14/2021 | 10 | 10 | 4 | 0.40 | 147.4 | 29.89 | 12.04 | 19.40 | 40.10 | 27.40 | 0.07 | 2.08 | 1.46 |
| 6 | 26 | 10/6/2021 | 10 | 10 | 6 | 0.60 | 157.0 | 38.23 | 11.93 | 19.50 | 40.45 | 29.00 | 0.07 | 1.89 | 1.39 |
| 6 | 36 | 10/27/2021 | 10 | 10 | 7 | 0.70 | 172.2 | 48.93 | 11.77 | 24.40 | 40.60 | 29.80 | 0.07 | 1.83 | 1.36 |
| 7 | 3 | 8/27/2021 | 10 | 10 | 8 | 0.80 | 136.8 | 21.70 | 11.70 | 63.05 | 50.85 | 60.90 | 0.09 | 0.87 | 0.83 |
| 7 | 7 | 9/5/2021 | 10 | 10 | 5 | 0.50 | 150.7 | 37.85 | 12.24 | 62.70 | 50.95 | 61.50 | 0.09 | 0.86 | 0.83 |
| 7 | 33 | 10/21/2021 | 10 | 10 | 10 | 1.00 | 159.9 | 38.88 | 12.25 | 64.45 | 50.65 | 60.10 | 0.09 | 0.88 | 0.84 |
| 8 | 9 | 9/7/2021 | 10 | 10 | 4 | 0.40 | 132.3 | 19.74 | 12.31 | 30.40 | 50.95 | 32.90 | 0.10 | 2.26 | 1.55 |
| 8 | 18 | 9/22/2021 | 10 | 10 | 3 | 0.30 | 148.8 | 29.10 | 11.91 | 30.90 | 50.10 | 32.40 | 0.10 | 2.29 | 1.55 |
| 8 | 21 | 9/28/2021 | 10 | 10 | 4 | 0.40 | 148.3 | 35.02 | 11.62 | 32.00 | 50.15 | 32.80 | 0.10 | 2.26 | 1.53 |
| 9 | 5 | 8/31/2021 | 8 | 8 | 2 | 0.25 | 141.5 | 24.63 | 11.49 | 24.75 | 51.20 | 33.60 | 0.10 | 2.24 | 1.52 |
| 9 | 31 | 10/19/2021 | 10 | 10 | 7 | 0.70 | 161.7 | 38.50 | 11.92 | 28.45 | 49.85 | 30.60 | 0.08 | 2.11 | 1.63 |
| 9 | 32 | 10/20/2021 | 10 | 10 | 6 | 0.60 | 162.0 | 38.03 | 12.00 | 30.10 | 50.55 | 33.00 | 0.10 | 2.27 | 1.53 |
| 10 | 8 | 9/6/2021 | 10 | 10 | 10 | 1.00 | 146.0 | 28.21 | 12.23 | 63.95 | 55.15 | 62.90 | 0.10 | 0.96 | 0.88 |
| 10 | 19 | 9/23/2021 | 10 | 10 | 9 | 0.90 | 153.3 | 38.16 | 11.81 | 65.50 | 56.05 | 63.40 | 0.10 | 0.95 | 0.88 |
| 10 | 20 | 9/27/2021 | 10 | 10 | 9 | 0.90 | 154.6 | 33.60 | 11.95 | 65.15 | 54.95 | 63.80 | 0.10 | 0.94 | 0.86 |
| 11 | 4 | 8/30/2021 | 9 | 9 | 2 | 0.22 | 134.9 | 25.22 | 11.64 | 33.70 | 58.70 | 47.20 | 0.13 | 1.70 | 1.24 |
| 11 | 11 | 9/9/2021 | 10 | 10 | 0 | 0.00 | 158.3 | 46.32 | 12.71 | 33.30 | 61.40 | 46.30 | 0.13 | 1.76 | 1.33 |
| 11 | 34 | 10/25/2021 | 10 | 10 | 7 | 0.70 | 188.6 | 54.04 | 12.10 | 36.25 | 58.10 | 35.80 | 0.13 | 2.53 | 1.62 |
| 12 | 1 | 10/28/2021 | 10 | 10 | 4 | 0.40 | 159.7 | 35.87 | 12.27 | 28.10 | 54.95 | 32.80 | 0.11 | 2.59 | 1.68 |
| 12 | 27 | 10/7/2021 | 10 | 10 | 5 | 0.50 | 163.7 | 47.56 | 11.64 | 28.00 | 55.45 | 34.00 | 0.11 | 2.47 | 1.63 |
| 12 | 30 | 11/2/2021 | 10 | 10 | 6 | 0.60 | 172.7 | 52.69 | 11.49 | 27.70 | 55.00 | 33.60 | 0.11 | 2.51 | 1.64 |

# Results

## Test Conditions

Hydraulic conditions (e.g., flow rate, velocities, etc.) were similar within treatments (Table 4). Amongst all trials the average flow rate was 0.07 $m^3$/s (SD=0.03 $m^3$/s) with a minimum of 0.03 $m^3$/s and a maximum of 0.13 $m^3$/s. The average HW to TW ratio was 1.12 (SD= 0.34). The minimum HW to TW ratio was 0.57 and the maximum was 1.68. The mean tailwater velocity was 1.50 m/s (SD=0.69 m/s) with a minimum of 0.32 m/s and a maximum of 2.59 m/s. The average tailwater depth was 39.6 cm (SD=13.8 cm). The minimum depth measured was 22.6 cm and the maximum depth measured was 63.8 cm. Figure 6 shows the general distribution/spread of each of these variables by treatment. See Appendix A for scatter plots and box plots of all the hydraulic variables examined.

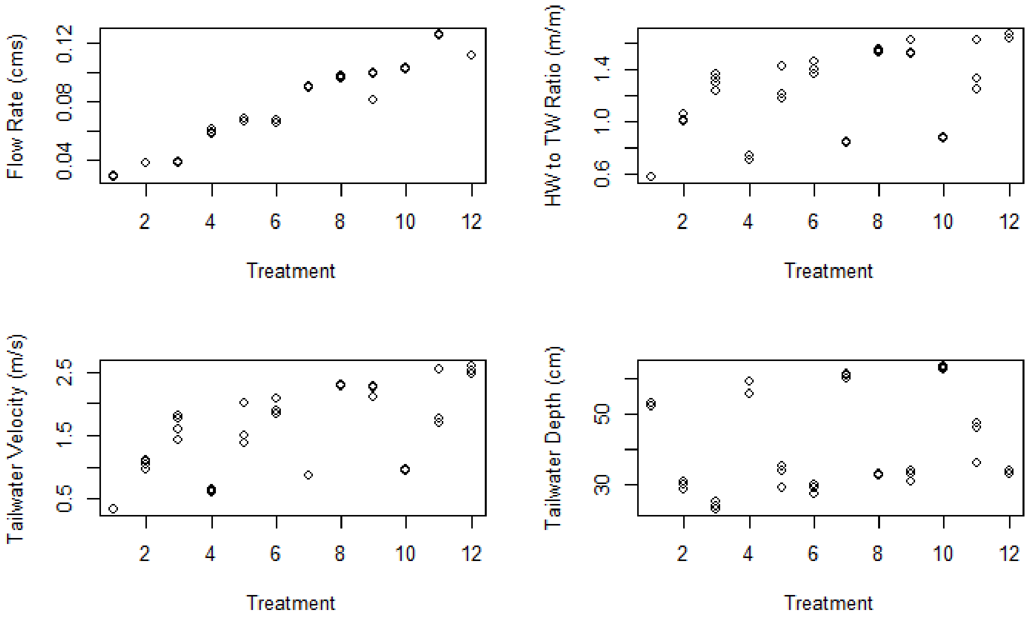

Figure 6: Summary of hydraulic conditions.

Trials using a nominal 61.0 cm headwater depth were within 6.05 cm of the prescribed condition. Headwater depths were within 1.15 cm of the nominal 51.0 cm headwater depth, within 0.90 cm of the 40.5 cm target depth, and within 0.85 cm of the 30.50 cm nominal condition.  Downstream approach depths for the 61.0 cm nominal depth were within 5.05 cm of the target condition. Downstream approach depths were within 6.30 cm of the nominal 30.5 cm condition. Downstream approach depths of nominal 15.2 cm were within 14.9 cm of the prescribed treatments. Tailwater depth was sometimes impossible to adjust to the nominal depth due to the flow rates needed to obtain the prescribed headwater depths.

## Passage Results

A total of 382 fish were used in this study and of that total, 379 participated in experiments, for a total participation rate of 99%. Trial participation rate (i.e., number of fish that participated divided by number of fish that were used in the trial) ranged from 87.5% to 100%. Most trials experienced 100% participation (36 out of 39 trials). Only participants were considered during further data analysis.

Entrance rates (i.e., fish that entered the fishway divided by number of fish that participated) varied from 0 to 100% among trials and from 41.4% to 100% among treatments. Of the total participants, 282 entered the fishway and attempted to ascend, leading to an overall entrance rate of 74.4%.

Passage rates varied from 0 to100% among trials and from 31.0% to 96.7% among treatments. Treatments 11 and 8 had passage rates of 25 to 50%, treatments 3, 4, 5 and 6 had passage rates of 50 to 75%, and treatments 1, 2, 4, 5, 7, and 10 had overall passage rates of 75 to

100%. Of the total participants 256 fish successfully passed through the Denil fishway, leading to a total overall passage rate of 67.6%.

Model Results

Mixed effects models (equation form shown in Table 3), were developed to predict passage through the fishway. The results from AICc model selection are shown in Table 5. Models with a “1” following the name (e.g., DS Denil Velocity 1) correspond to models with only the hydraulic variable term. A “2” following the name denotes that there are terms for the hydraulic variable and fish length in the model. Models with a “FULL” following the name contain terms for the hydraulic variable of interest, fish length, and an interaction term between fish length and the hydraulic variable. In Table 5, K is the number of predictor terms in the model, AICc is the model score using AICc criterion, and Δ AICc is the change in AICc value from the top ranked model.

Table 5: Mixed effects models summary.

| Model Name | K | AICc | Δ AICc |
|---|---|---|---|
| Tailwater Velocity FULL | 5 | 368.52 | 0.00 |
| HW to TW Ratio FULL | 5 | 369.44 | 0.92 |
| Tailwater Velocity 2 | 4 | 369.87 | 1.35 |
| HW to TW Ratio 2 | 4 | 370.28 | 1.76 |
| Tailwater Depth FULL | 5 | 388.49 | 19.96 |
| Tailwater Depth 2 | 4 | 389.82 | 21.29 |
| Fish Length | 3 | 396.09 | 27.56 |
| Tailwater Velocity 1 | 3 | 424.12 | 55.60 |
| HW to TW 1 | 3 | 424.92 | 56.40 |
| Tailwater Depth 1 | 3 | 441.22 | 72.69 |
| Intercept | 2 | 444.87 | 76.34 |

Based on AICc model selection, the best models are: Tailwater Velocity FULL, HW to TW Ratio FULL, Tailwater Velocity 2, and HW to TW Ratio 2. All these models have AICc values that are within two of each other and can therefore be considered of equal value. The results from each model shall be discussed below.

Tailwater Velocity FULL Model Results. The Tailwater Velocity FULL model had the highest AICc score (368.52). This model includes coefficients for a random effect intercept for each trial, fish length, tailwater velocity, and an interaction between fish length and the tailwater velocity. The coefficient estimates are shown in Table 6.

Table 6: Tailwater Velocity FULL model results.

| | Coefficient Estimate | Std. Error | Z-Value | Pr(>\|Z\|) |
|---|---|---|---|---|
| Intercept | 1.0606 | 0.2065 | 5.136 | 2.81e-07 |
| Fish Length | 0.3182 | 0.0559 | 5.693 | 1.25e-08 |
| Tailwater Velocity | -1.5863 | 0.3155 | -5.027 | 4.97e-07 |
| Interaction | 0.1559 | 0.0845 | 1.845 | 0.065 |

The coefficient estimate for fish length is positive (0.3182), indicating that if all else is held constant, the probability of a fish successfully passing through the Denil will increase as the length of the fish increases. The coefficient estimate for tailwater velocity is negative indicating that if fish length is held constant, then the probability of passage success will decrease as the velocity becomes higher. This can be visualized in Figure 7. This figure displays the range of passage probabilities over a range of tailwater velocities. In this figure, fish length is held constant at the mean fish length that was used during the study (155.9 mm). All the variables used to develop the model were centralized (i.e., the mean was subtracted), which is why there are negative values for tailwater velocity in the graph on the left. The graph on the right side displays the results of the model without centralized variables. This graph is strictly a visual aid and uses the actual (non-centralized) values for tailwater velocity.

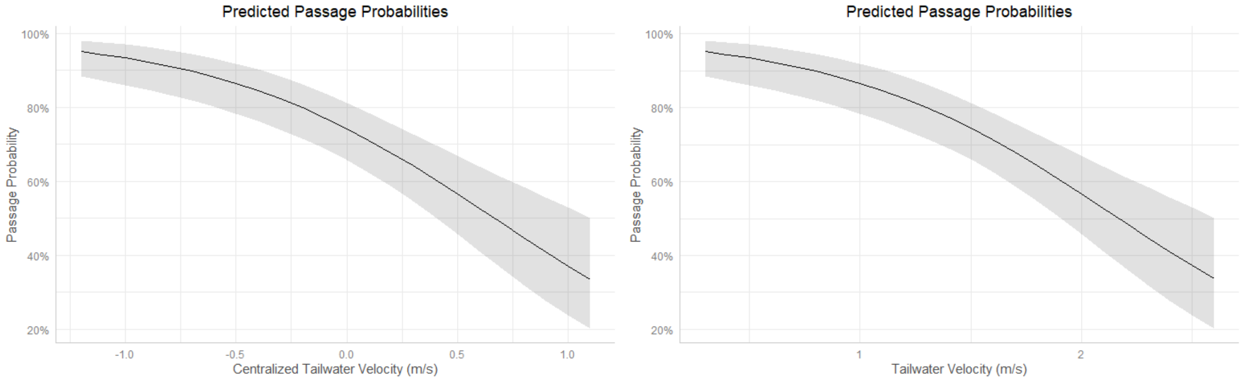

Figure 7: Graphs of Tailwater Velocity FULL model with (left) and without (right) centralized input variables.

<u>HW to TW Ratio FULL Model Results.</u> The HW to TW Ratio FULL model ranked second in AICc score (369.44, Δ AICc=0.92). This model includes terms for fish length, HW to TW ratio, and an interaction term. The coefficient estimates are shown Table 7.

Table 7: HW to TW Ratio FULL model results.

| | Coefficient Estimate | Std. Error | Z-Value | Pr(>\|Z\|) |
|---|---|---|---|---|
| Intercept | 1.0757 | .2105 | 5.110 | 3.22e-07 |
| Fish Length | 0.3217 | 0.0562 | 5.721 | 1.06e-08 |
| HW to TW Ratio | -3.1844 | 0.6535 | -4.873 | 1.10e-06 |
| Interaction | 0.2975 | 0.1733 | 1.716 | 0.0861 |

The coefficient estimates indicate that as HW to TW ratio increases, the probability of passage success decreases. As fish length increases, so does the probability of passage success. These results are shown in Figure 8.

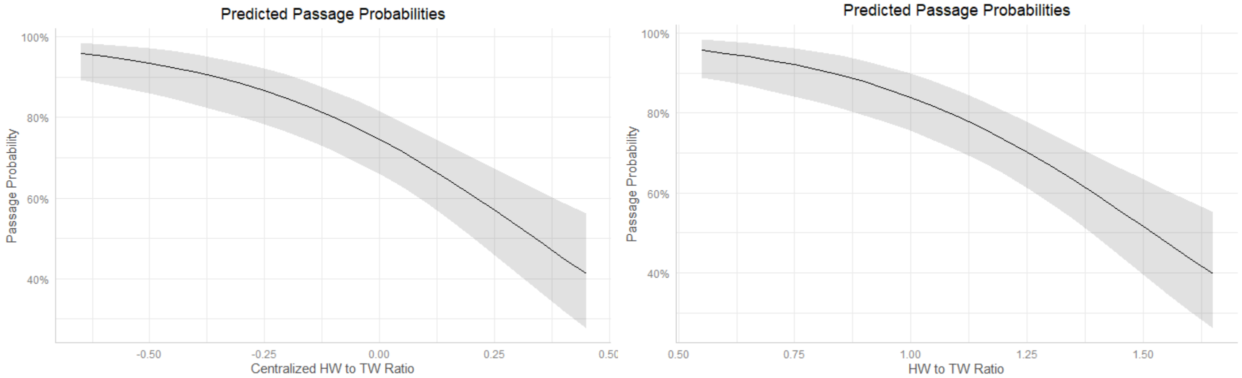

Figure 8: Graphs of HW to TW Ratio Full model with (left) and without (right) centralized input variables.

<u>Tailwater Velocity 2 Model Results.</u> The Tailwater Velocity 2 model had an AICc value of 369.87 (Δ AICc=1.35) and can therefore be considered as good to the Tailwater Velocity FULL velocity model. This model has all the same terms as the full model, except the interaction between fish length and tailwater velocity is removed. The estimates for each variable are shown in Table 8.

Table 8: Tailwater Velocity 2 model results.

| | Coefficient Estimate | Std. Error | Z-Value | Pr(>\|Z\|) |
|---|---|---|---|---|
| Intercept | 1.1608 | 0.2066 | 5.618 | 1.93e-08 |
| Fish Length | 0.3498 | 0.0545 | 6.418 | 1.38e-10 |
| Tailwater Velocity | -1.7403 | 0.3150 | -5.524 | 3.31e-08 |

This model yields a similar trend to the Tailwater Velocity FULL model. The fish length has a positive coefficient, indicating that as a fish becomes larger, so will the probability of passage success. The velocity term has a negative coefficient, indicating higher velocities in the downstream end of the fishway reduce passage success. The results from this model are shown in Figure 9.

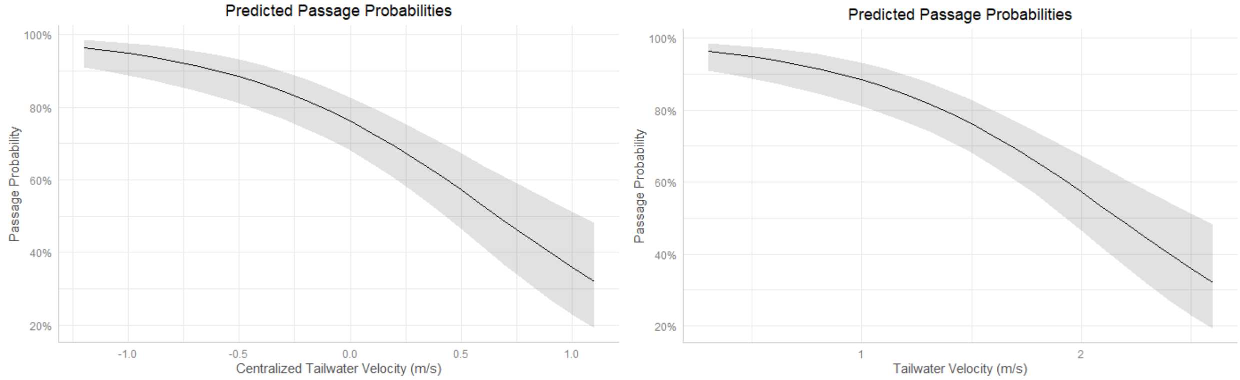

Figure 9: Graphs of DS Denil Velocity 2 model with (left) and without (right) centralized input variables.

<u>HW to TW Ratio 2 Model Results.</u> The reduced HW to TW ratio model (i.e., the interaction term was removed) also had an AICc score within two of the top ranked model (370.28, Δ AICc= 1.76), and can therefore be considered equally as good. The parameter estimates for this model (HW to TW Ratio 2) are shown in Table 9. The results for this model are displayed in Figure 10. As the HW to TW ratio increases, the probability of passage success decreases.

Table 9: HW to TW Ratio 2 model results.

| | Coefficient Estimate | Std. Error | Z-Value | Pr(>\|Z\|) |
|---|---|---|---|---|
| Intercept | 1.1719 | 0.2083 | 5.626 | 1.85e-08 |
| Fish Length | 0.3520 | 0.0547 | 6.441 | 1.19e-10 |
| HW to TW Ratio | -3.5159 | 0.6441 | -5.459 | 4.79e-08 |

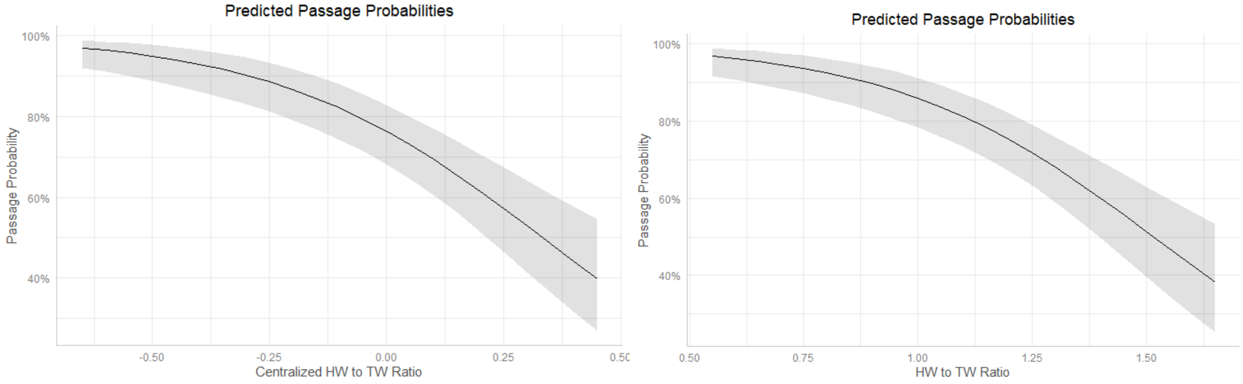

Figure 10: Graphs of HW to TW Ratio 2 model with (left) and without (right) centralized input variables.

## Discussion

The goals of this study were to examine if WCT could successfully pass through a 0.6 scale Denil fishway in a laboratory setting, and to determine the hydraulic conditions that allow passage. The scaling factor was selected based on previous studies by Plymesser (2022) and was intended to balance a reduction in flow, while still accommodating for the passage of adult WCT. Overall, this study demonstrated the ability of scaled Denil fishways to pass WCT. This study demonstrates that these fishways can yield high passage rates and have the potential to be implemented as conservation tools.

Mixed effects modelling was used to relate passage success to hydraulic variables and fish length. AICc model selection yielded the four best models for consideration were Tailwater Velocity FULL, Tailwater Velocity 2, HW to TW Ratio FULL, and HW to TW Ratio 2 (see Table 3 and Table 5). Although all the observed models yield pertinent information on passage metrics, we recommend using the simplified HW to TW ratio model (HW to TW Ratio 2) for all field and design applications. Measuring the depths within the fishway is simple to do in the field, making this model an easy tool to apply. This model indicates fish passage success will increase as HW to TW ratio decreases. The more similar the depths at the up and downstream ends of the fishway are, the higher the probability for passage success. Although all the models that were examined yielded compelling results, we recommend that they be used as conceptual guidelines rather than as strict mathematical or design requirements.

When compared with a meta-analysis performed by Hershey (2021), our study of a scaled Denil yielded a higher passage rate than had been observed for full sized Denil fishways, suggesting that the scaled Denil performed well for WCT passage. Hershey (2021) reported a total passage rate of 44% (n=8 fishways), whereas we obtained a total passage rate of 68%. Hershey (2021) observed a much broader range of fish species than this study, so swimming abilities cannot be compared well, but it is promising to see that the experimental passage rate was greater than that of previously observed studies.

This is the second study demonstrating the potential for scaled Denil fishways to meet the needs of fish conservation and water resource management. Plymesser et al. (2022) performed a similar scaled Denil study using Arctic Grayling as the test species. That study yielded an overall passage rate of 91% as compared to 68% for WCT in this study. The Arctic Grayling were a slightly larger average size (214 mm, SD=2.3mm) compared to the WCT in this study (155.9 mm, SD=32.9 mm) and their greater size may have provided greater swimming ability. Also, this study had two lower water depth treatments that were not tested in the Plymesser et al. (2022) study, which may be the cause of the lower passage rate. In general, lower depths at the tailwater of the fishway cause increases in velocity and turbulence, which can create hydraulic barriers to fish.

Our study yielded consistent results with previous studies showing increases in passage rate with increases in tailwater depth. As the tailwater depth decreased, we observed that the water near the exit of the Denil fishway became more turbulent and chaotic. As the water depth decreased, so did the passage success, which was also observed in Slatick (1975), Plymesser et al. (2022), Triano (2020) and Blank et al. (2021). As the tailwater depth decreased, the velocity at the exit of the Denil increased. Increase in velocity had a negative effect on passage rate, which is comparable to trends observed in Bunt et al. (1999).

One difference between this study and previous studies is that the passage rate tended to decrease as the flow rate through the Denil increased (Figure 11). Blank et al. (2021) observed increases in passage rate with increases in flow rate for Arctic Grayling. This difference may be caused by the scale of fishway used. Blank et al. (2021) used a full scale Denil fishway, whereas we used a 0.6 scale fishway. Full scale fishways are designed to accommodate more flow, and therefore may exhibit different trends between passage rate and flow rate. Triano et al. (2020) did not observe any trends between flow rate and fish passage but did observe increases in attraction efficiency with increases in flow rate, which should be considered when applying these fishways in a field setting.

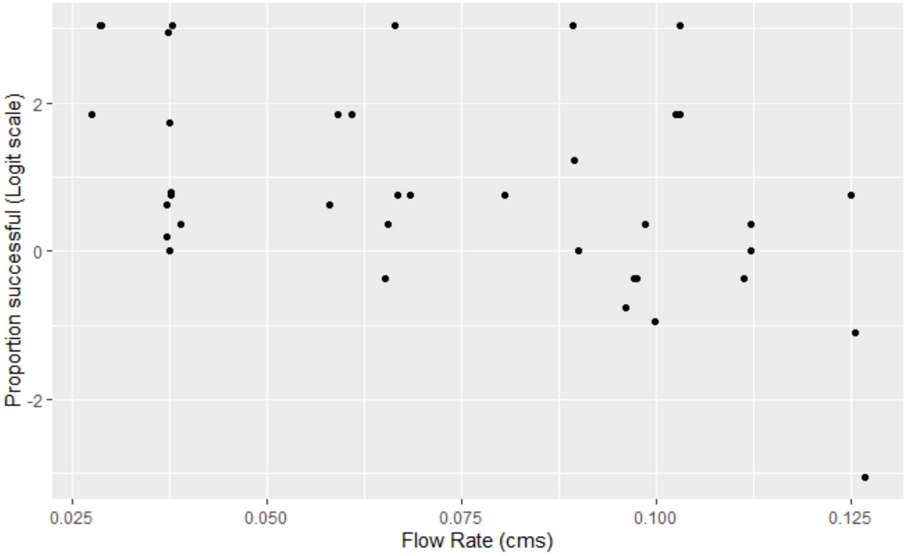

Figure 11: Flow Rate vs. Passage Success.

This study evaluated the effects of varying hydraulic conditions on passage success of WCT in a scaled Denil fishway. Over a test range that included optimal and suboptimal hydraulic conditions (U.S. Fish and Wildlife Service 2017; Triano 2020; Blank et al. 2021; Plymesser et al. 2022) the overall passage rate was 68% (with six of the 12 treatments having over 75% passage rate), indicating that scaled Denil fishways have the potential to pass WCT over varying hydraulic conditions. We presented a mixed effects model (HW to TW Ratio 2) to describe passage success for different fish lengths and HW to TW ratios. Generally, we observed that lower HW to TW ratios (i.e., depths at the up and downstream ends of the fishway are similar) resulted in increases in passage success. This statistical model could be refined further by performing field studies to validate the laboratory results. The mixed effects model may be useful to practitioners installing or retrofitting Denil fishways. The HW to TW Ratio 2 model can be used as a guideline to determine the best depths at which to install or retrofit these fishways, or when adjusting water depths to improve passage during monitoring or fishway maintenance activities. While the results are best applied to WCT, the model could be used for fish of similar swimming abilities, life history, and motivation.

Some limitations to this study are that we used fish that reared in a hatchery, and they may not have exhibited the same characteristics of wild fish. This study also did not test attraction to the fishway because fish were placed near the downstream fishway entrance at the beginning of each trial, and the entire flume flow passed through the fishway and approach.

Future studies should focus on field applications of Denil fishways and how approach conditions (i.e., flow rate, depth, and turbulence) influence attraction to, and passage success through the fishway. Further laboratory and experimental studies should be performed to optimize the fishway scaling factor for different species and size classes and to broaden the understanding of passage through Denil fishways. Additional studies should focus on pairing representations of turbulence (e.g., TKE) with passage results to better understand the hydraulic variables that effect fish passage.

# REFERENCES CITED

## REFERENCES CITED

Allendorf, F. W., and R. F. Leary. 1988. Conservation and Distribution of Genetic Variation in a Polytypic Species, the Conservation and Distribution of Genetic Variation in a Polytypic Species, the Cutthroat Trout. Conservation Biology 2(2):170–184.

Amaral, S. D., P. Branco, A. T. da Silva, C. Katopodis, T. Viseu, M. T. Ferreira, A. N. Pinheiro, and J. M. Santos. 2016. Upstream passage of potamodromous cyprinids over small weirs: the influence of key-hydraulic parameters. Journal of Ecohydraulics 1(1–2):79–89.

Baharvand, S., and B. Laskar-Ara. 2021. Hydraulic design criteria of the modified meander C-type fishway using the combined experimental and CFD models. Ecological Engineering 164.

Bates, D., M. Mächler, B. M. Bolker, and S. C. Walker. 2015. Fitting linear mixed-effects models using lme4. Journal of Statistical Software 67(1).

Baumgartner, L. J. 2006. A preliminary assessment of fish passage through a Denil fishway on the Edward River, Australia. Narradera, NSW.

Blank, M. D., K. M. Kappenman, K. Plymesser, K. Banner, and J. Cahoon. 2020. Swimming performance of rainbow trout and westslope cutthroat trout in an open-channel flume. Journal of Fish and Wildlife Management 11(1):217–225.

Blank, M., K. M. Kappenman, E. Ryan, and K. Banner. 2021. The effect of water depth on passage success of arctic grayling through two Denil fishways. Journal of Ecohydraulics:1–13.

Bunt, C. M., T. Castro-Santos, and A. Haro. 2012. Performance of fish passage structures at upstream barriers to migration. River Research and Applications 28(4):457–478.

Bunt, C. M., C. Katopodis, and R. S. McKinley. 1999. Attraction and Passage Efficiency of White Suckers and Smallmouth Bass by Two Denil Fishways. North American Journal of Fisheries Management 19(3):793–803.

Bunt, C. M., B. T. van Poorten, and L. Wong. 2001. Denil fishway utilization patterns and passage of several warmwater species relative to seasonal, thermal and hydraulic dynamics. Ecology of Freshwater Fish:212–219.

Burnham, K. P., D. R. Anderson, and K. P. Huyvaert. 2011, January 1. AIC model selection and multimodel inference in behavioral ecology: Some background, observations, and comparisons. Springer Verlag.

Clay, C. H. 1995. Design of Fishways and Other Fish Facilities. CRC Press, Inc., Boca Raton.

Conley, M. E. 2021, May. SMALL SCALE DENIL DEVELOPMENT FOR USE IN HEADWATER STREAMS IN SOUTHWEST MONTANA. Master of Science, Montana State University, Bozeman, MT.

Dockery, D. R., T. E. McMahon, K. M. Kappenman, and M. Blank. 2017. Evaluation of swimming performance for fish passage of longnose dace Rhinichthys cataractae using an experimental flume. Journal of Fish Biology 90(3):980–1000.

FAO, and DVWK. 2002. Fish passes : design, dimensions and monitoring. Page D. d'Enno, G. Marmulla, and R. Welcomme, editors. Food and Agriculture Organization of the United Nations (FAO) and Deutsher Verband für Wasserwirtschaft und Kulturbau e.V. (DVWK), Rome.

Feurich, R., J. Boubée, and N. R. B. Olsen. 2012. Improvement of fish passage in culverts using CFD. Ecological Engineering 47:1–8.

Fuentes-Pérez, J. F., A. T. Silva, J. A. Tuhtan, A. García-Vega, R. Carbonell-Baeza, M. Musall, and M. Kruusmaa. 2018. 3D modelling of non-uniform and turbulent flow in vertical slot fishways. Environmental Modelling and Software 99:156–169.

Fulton, L. A., H. A. Gangmark, and S. H. Bair. 1953. Trial of Denil-Type Fish Ladder on Pacific Salmon. Washington D.C.

Haro, A., M. Odeh, T. Castro-Santos, and J. Noreika. 1999. Effect of Slope and Headpond on Passage of American Shad and Blueback Herring through Simple Denil and Deepened Alaska Steeppass Fishways. North American Journal of Fisheries Management 19(1):51–58.

Hawkins, D. K., and T. P. Quinn. 1996. Critical swimming velocity and associated morphology of juvenile coastal cutthroat trout (Oncorhynchus clarki clarki), steelhead trout (Oncorhynchus mykiss), and their hybrids. Canadian Journal of Fisheries and Aquatic Sciences 53:1487–1496.

Hershey, H. 2021. Updating the consensus on fishway efficiency: A meta-analysis. Fish and Fisheries 22(4):735–748.

Kamula, R., and J. Bärthel. 2000. Effects of modifications on the hydraulics of Denil fishways. Boreal Environment Research 5:67–79.

Katopodis, C. 1992. INTRODUCTION TO FISHWAY DESIGN.

Katopodis, C., J. A. Kells, and M. Acharya. 2001. Nature-like and conventional fishways: Alternative concepts? Canadian Water Resources Journal 26(2):211–232.

Katopodis, C., N. Rajaratnam, S. Wu, and D. Tovell. 1997. Denil Fishways of Varying Geometry. Journal of Hydraulic Engineering 123(7):624–631.

Liao, J. C. 2007, November 29. A review of fish swimming mechanics and behaviour in altered flows. Royal Society.

Liu, M., N. Rajaratnam, and D. Z. Zhu. 2006. Mean Flow and Turbulence Structure in Vertical Slot Fishways. Journal of Hydraulic Engineering 132(8):765–777.

Mahmoudian, Z., S. Baharvand, and B. Lashkar-Ara. 2019. Investigating the Flow Pattern in Baffle Fishway Denil Type. Irrigation Sciences and Engineering (JISE) 42(3):179–196.

Mallen-Cooper, M., and I. G. Stuart. 2007. Optimising Denil fishways for passage of small and large fishes. Fisheries Management and Ecology 14:61–71.

Marriner, B. A., A. B. M. Baki, D. Z. Zhu, J. D. Thiem, S. J. Cooke, and C. Katopodis. 2014. Field and numerical assessment of turning pool hydraulics in a vertical slot fishway. Ecological Engineering 63:88–101.

Maxell, B. A. 2020. Animal Species of Concern. Helena.

Montana Natural Heritage Program, and Montana Fish Wildlife and Parks. 2023. Westslope Cutthroat Trout — Oncorhynchus clarkii lewisi.

Nau, G. S., A. D. Spares, S. N. Andrews, M. L. Mallory, N. R. McLellan, and M. J. W. Stokesbury. 2017. Body size, experience, and sex do matter: Multiyear study shows improved passage rates for alewife (Alosa pseudoharengus) through small-scale Denil and pool-and-weir fishways. River Research and Applications 33(9):1472–1483.

Noonan, M. J., J. W. A. Grant, and C. D. Jackson. 2012. A quantitative assessment of fish passage efficiency. Fish and Fisheries 13(4):450–464.

Odeh, M. 2003. Discharge Rating Equation and Hydraulic Characteristics of Standard Denil Fishways. Journal of Hydraulic Engineering 129(5):341–348.

Platt, N. C. 2019, April. DESIGNING AND ASSESSING THE EFFECTIVENESS OF DENIL FISHWAYS USING HYDRAULIC MODELING-BASED APPROACHES. Master of Science, Montana State University, Bozeman, MT.

Plymesser, K., M. Blank, M. Conley, K. Kappenman, J. Cahoon, D. Dockery, and A. Zale. 2022. A scaled Denil fishway for upstream passage of Arctic Grayling. Journal of Ecohydraulics:1–11.

Plymesser, K., and J. Cahoon. 2017. Pressure gradients in a steeppass fishway using a computational fluid dynamics model. Ecological Engineering 108:277–283.

Plymesser, K. E. 2014, January. MODELING FISH PASSAGE AND ENERGY EXPENDITURE FOR AMERICAN SHAD IN A STEEPPASS FISHWAY USING A COMPUTATIONAL FLUID DYNAMICS MODEL. Doctor of Philosophy, Montana State University, Bozeman.

Rajaratnam, N., and C. Katopodis. 1984. HYDRAULICS OF DENIL FISHWAYS. Journal of Hydraulic Engineering 110(9):1219–1233.

Rajaratnam, N., and C. Katopodis. 1991. Hydraulics of steeppass fishways. Canadian journal of civil engineering 18(6):1024–1032.

Rajaratnam, N., C. Katopodis, and A. Mainali. 1988. Plunging and Streaming Flows in Pool and Weir Fishways. Journal of Hydraulic Engineering 114(8):939–944.

Schmetterling, D. A., R. W. Pierce, and B. W. Liermann. 2002. Efficacy of Three Denil Fish Ladders for Low-Flow Fish Passage in Two Tributaries to the Blackfoot River, Montana. North American Journal of Fisheries Management 22(3):929–933.

Schwalme, K., W. C. Mackay, and D. Lindner. 1985. Suitability of vertical slot and Denil fishways for passing north- temperature, nonsalmonid fish. Canadian Journal of Fisheries and Aquatic Sciences 42(11):1815–1822.

Shahabi, M., M. Ghomeshi, J. Ahadiyan, T. Mohammadian, and C. Katopodis. 2021. Do fishways stress fish? Assessment of physiological and hydraulic parameters of rainbow trout navigating a novel W-weir fishway. Ecological Engineering 169.

Shepard, B. B., B. E. May, and W. Urie. 2005. Status and Conservation of Westslope Cutthroat Trout within the Western United States. North American Journal of Fisheries Management 25(4):1426–1440.

Silva, A. T., M. C. Lucas, T. Castro-Santos, C. Katopodis, L. J. Baumgartner, J. D. Thiem, K. Aarestrup, P. S. Pompeu, G. C. O’Brien, D. C. Braun, N. J. Burnett, D. Z. Zhu, H. P. Fjeldstad, T. Forseth, N. Rajaratnam, J. G. Williams, and S. J. Cooke. 2018. The future of fish passage science, engineering, and practice. Fish and Fisheries 19(2):340–362.

Slatick, E. 1975. Laboratory Evaluation of a Denil-Type Steeppass Fishway with Various Entrance and Exit Conditions for Passage of Adult Salmonids and American Shad. Marine Fisheries Review 37(9):17–26.

Symonds, M. R. E., and A. Moussalli. 2011, January 1. A brief guide to model selection, multimodel inference and model averaging in behavioural ecology using Akaike’s information criterion. Springer Verlag.

Triano, B. L. 2020, April. Attraction, Entrance, and Passage Efficiency of Arctic Grayling, Trout, and Suckers at Denil Fishways in the Big Hole River Basin, Montana. Master of Science, Montana State University, Bozeman, MT.

U.S. Fish and Wildlife Service. 2017. Fish Passage Engineering Design Criteria. Hadley, MA.

Wada, K., N. Azuma, and S. Nakamura. 2000. Migratory Behavior of Juvenile Ayu in Denil and Seeppass Fishways in Japan. Page M. Odeh, editor. American Fisheries Society, Bethesda, MD.

Western Native Trout Initiative. (n.d.). West Slope Cutthroat Trout.

Williams, J. G., G. Armstrong, C. Katopodis, M. Larinier, and F. Travade. 2012. Thinking like a fish: A key ingredient for development of effective fish passage facilities at river obstructions. River Research and Applications 28(4):407–417.

Young, M. K. 1995. Conservation assessment for inland cutthroat trout. Fort Collins, CO.

# APPENDICES

# APPENDIX A

## DISTIBUTION/SPREAD OF HYDRAULIC VARIABLES

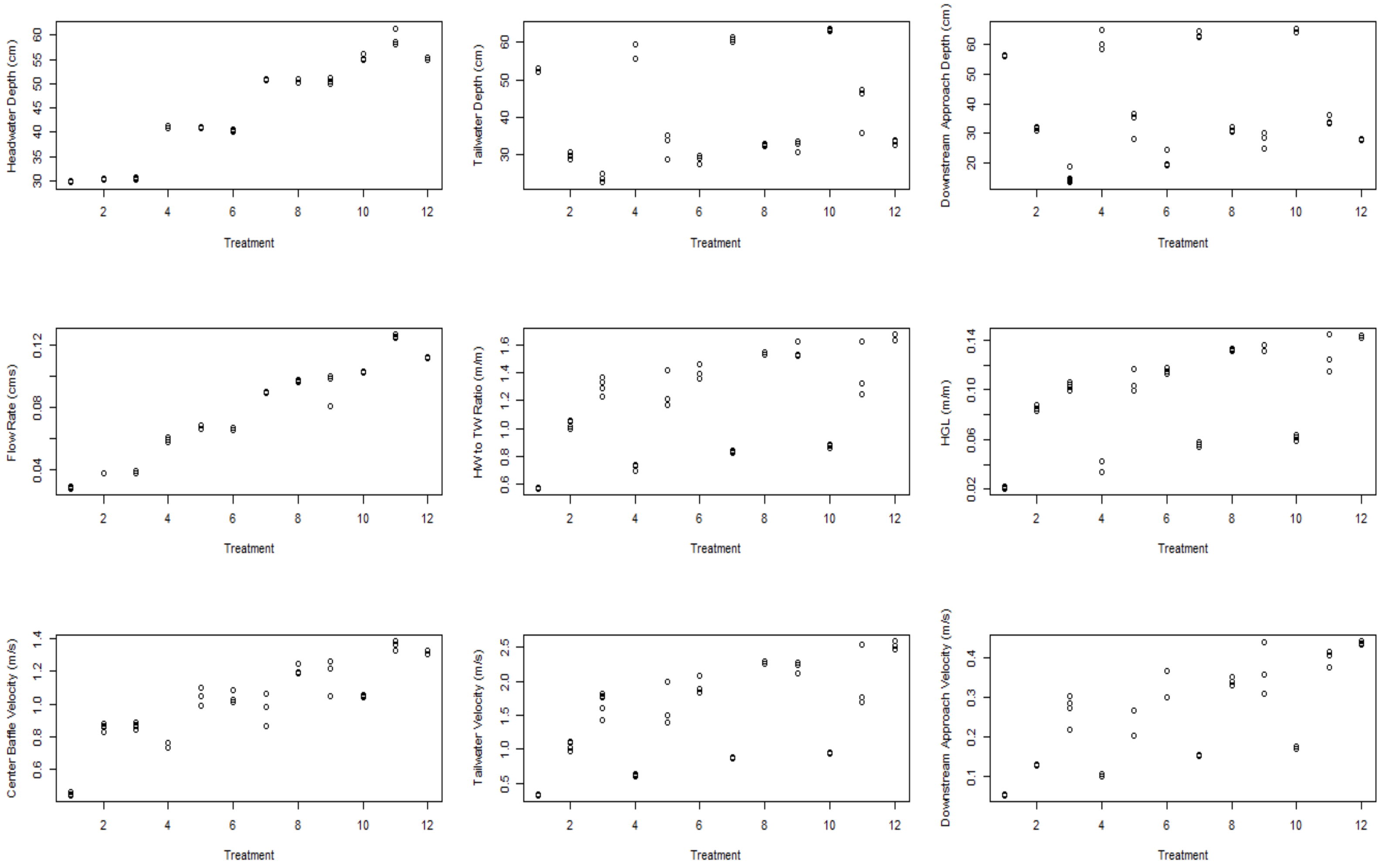

Figure 12: Scatter plots of hydraulic variables vs. treatments.

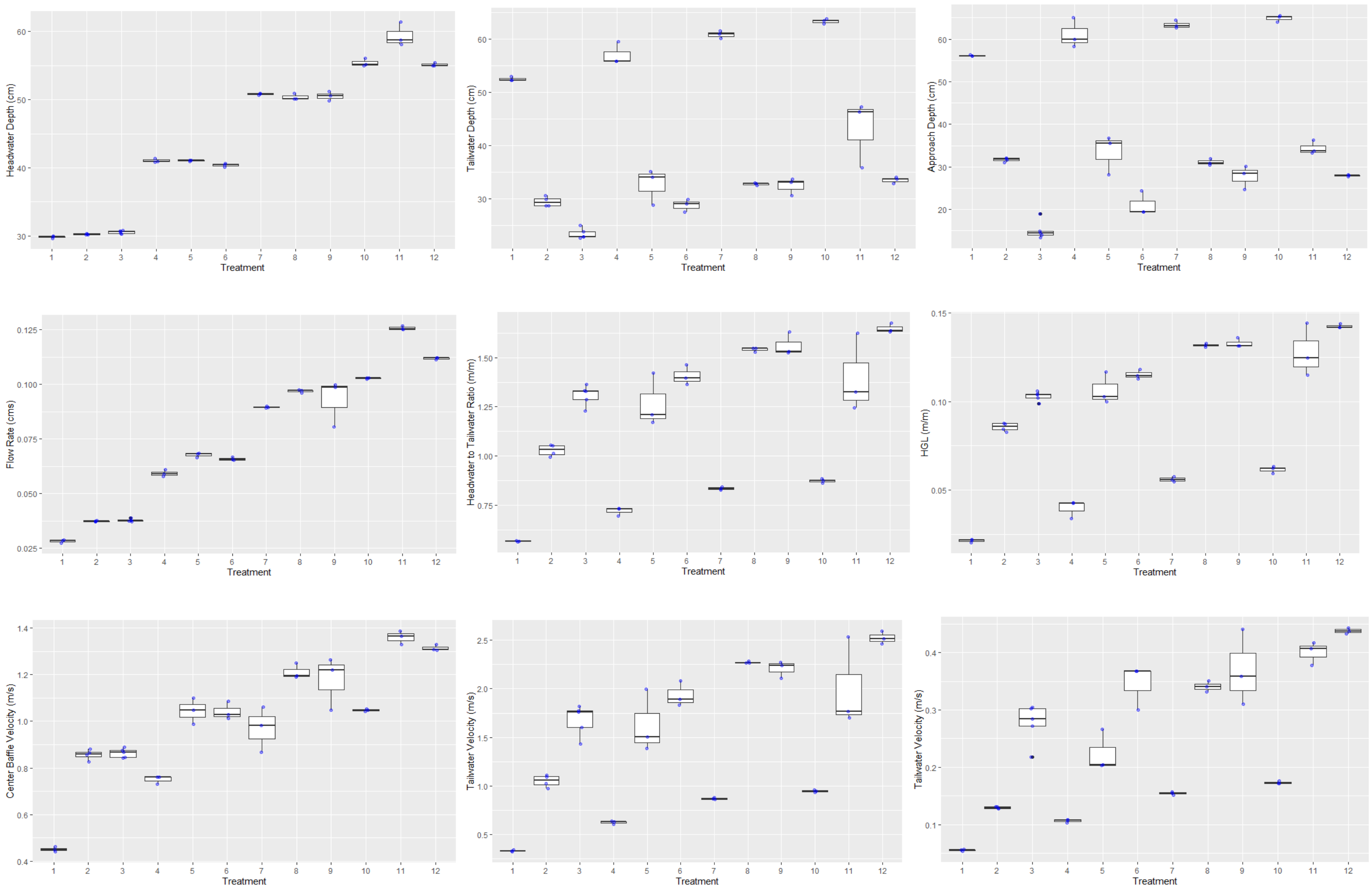

Figure 13: Box plots of measured hydraulic variables.