

SMALL SCALE DENIL DEVELOPMENT FOR USE IN HEADWATER STREAMS IN  
SOUTHWEST MONTANA

by

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DEDICATION

This thesis is dedicated to my family, for supporting me in all my endeavors in life, pushing me to be my best self, and for teaching me to appreciate nature whenever possible.

To Jackson, Corry, and McNally, for welcoming me to Bozeman with open arms and providing me with endless laughs.

And to Graham and Baker, the dream team, for being my biggest cheerleaders, always providing smiles (even Baker's snarly, snorty kind) and love and words of encouragement whenever I needed it, and for always believing in me to pursue my dreams, even if they took me hundreds of miles away.

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## ABSTRACT

The Big Hole River is located in an agricultural valley in Southwest Montana and is home to the last fluvial (river dwelling) population of Arctic grayling (*Thymallus arcticus*) in the contiguous United States. Grayling mostly populate the tributary streams in the upper portion of the watershed, where there are many irrigation diversions, which greatly fragments grayling's natural habitat. While many of these irrigation diversions have fish ladders installed at them to assist with habitat reconnection, these ladders become impassable when the water levels get too low in the system or irrigators chose to block the fish ladders in order to divert more water. This study investigated and characterized a smaller scale Denil fish ladder that would use less water while providing adequate fish passage. Three different flow rate calculations were applied to a series of scaled Denils to compare to the expected flow rates of the full scale Denil to determine the scaled sizes to construct. A 0.6 scale and a 0.75 scale Denil were selected and hydraulic lab testing confirmed that 25.4 cm baffle spacing was the best for both scaled models. The fish swimming study, conducted at the outdoor flume at the Bozeman Fish Technology Center, used eight hatchery-raised grayling in each of the eight treatments. Each treatment was repeated 3 times using the 0.6-scale model for a total of 24 trials with 192 fish. Each treatment used a different combination of headwater depth (between 30.5 cm and 61.0 cm) and tailwater depth (between 15.2 cm and 61.0 cm). The grayling passed with near perfect success at all headwater and tailwater combinations except when the head difference between the headwater and tailwater was at its greatest (61.0 cm headwater and 15.2 cm tailwater). This preliminary study showed that grayling are willing to pass smaller-scale structures at a variety of flow rates but did not test a wide range of slopes, age classes or fish sizes. These results should be useful to water managers when looking to modify or install new Denil fishways in the Big Hole River Basin and around the western United States.

## INTRODUCTION

Fish ladders have been used for decades to assist aquatic organisms in all life stages as they navigate natural and artificial barriers (Katopodis 1992). There are many types of fish ladders, each having unique characteristics best suited to certain settings and hydraulic structures. In low-gradient river valleys with numerous irrigation diversions for agriculture uses, fishways may be used to help fish negotiate low-head dams or irrigation diversions. Fishways commonly used at low-head obstructions are bypass channels, such as nature-like fishways, or technical fishways, such as that developed by Denil (Clay 1995).

A Denil fishway encourages fish passage by creating a zone of lower velocity near the floor of the fishway using baffles set at even intervals along its length (Rajaratnum & Katopodis 1984). Figure 0.1 shows cross section view of a typical Denil that uses baffles set at a 45-degree angle in the upstream direction to slow flow and assist in fish passage.

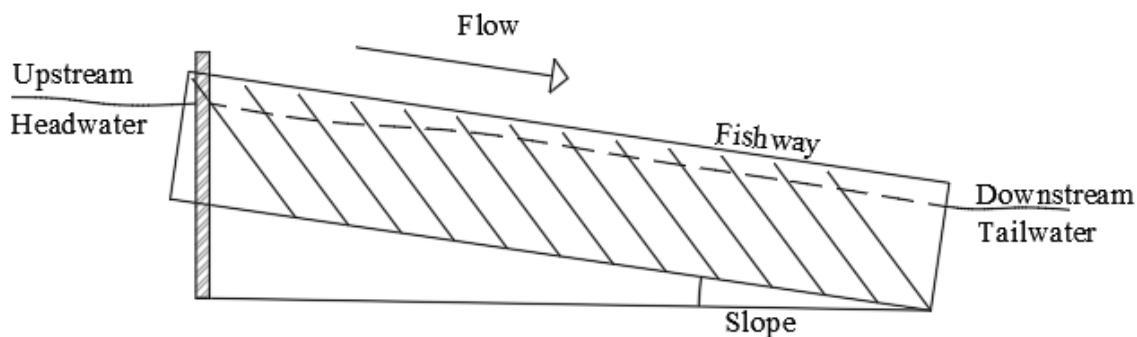


Figure 0.1: A cross section view of a Denil fishway showing the baffles spaced evenly along the length, set at a 45 degree angle against flow.

This study was inspired by fisheries and irrigation management observations in the Big Hole River and its tributaries, a productive agricultural area in Southwest Montana. The Big Hole River and its tributaries are mostly surrounded by private farmland and these farms draw

irrigation water from natural streams according to the Montana Water Use Act of 1973 (Duffield et al. 1992). In recent years, more than 60 Denil-style fishways have been installed at irrigation diversions in the Big Hole River Valley. The most common Denil fishway used in the Big Hole River Valley is the standard size, measuring 0.56m wide (Platt 2019). When streamflow is low but water demand is still high, typically in the late summer months, some landowners fully or partially block the upstream end of the Denil to divert as much water as possible for irrigation (MFWP and USFWS 2006; Platt 2019). This action effectively closes the stream to both upstream and downstream travel for aquatic species at the diversion, unless the fish have sufficient jumping abilities.

One of the species greatly affected by the fragmentation of stream corridors in the Big Hole River Valley is the native Arctic grayling, *Thymallus arcticus*. The fluvial Arctic grayling of the Big Hole River and its tributaries is the last known population of river dwelling grayling in the contiguous United States (Liknes & Gould 1987). Historically, these fish resided in northern Michigan and in the Missouri river within Yellowstone National Park, as well as southwest Montana (Liknes & Gould 1987).

While grayling are not a federally listed endangered species, they are a Montana species of concern and there are a wide range of conservation efforts in the Big Hole River Valley that are focused on grayling (MFWP and USFWS 2006). Many of these efforts are focused on working with the local private landowners to reconnect habitat and keep more water in the streams (MFWP and USFWS 2006). This project supports these goals by working with fisheries managers and irrigators to design fish passage systems that require less water while maintaining passage (BHWC 2016). In support of this effort, the United States Fish and Wildlife Service

(USFWS) and Montana State University have conducted studies to quantify the amount of water required by the Denil fishways in a typical year, and ways this amount can be reduced without impacting fish passage (Platt 2019, Plymessenger et al. forthcoming). If a new fishway design resulted in less water flowing through the fishway while successfully passing fish, landowners may be able to divert their water right with less impact on fish mobility. Initially, a pilot study was undertaken that placed restrictor plates on the upstream end of the Denil (Plymessenger et al. forthcoming). Results from this study were mixed - the plate designs that reduced flow also generally reduced fish passage. As an alternative to reducing the flow through a standard Denil fishway using a restrictor plate, we investigated the effectiveness of a smaller-scaled designs of the standard Denil fishway.

While the hydraulics of scaled Denils have been assessed in lab settings (Rajaratnam & Katopodis 1984; Katopodis 1992; Rajaratnam & Katopodis 1997; Katopodis et al. 1997), smaller scaled Denils have not been assessed for fish passage. The study presented herein is the first attempt to quantify the fish passage success of a scaled Denil in flume-based swimming study using Arctic grayling. This study started by looking at the theoretical flow rates through smaller-scaled Denil sizes, then a hydraulic analysis was undertaken to decide the correct baffle spacing for these potential sizes. Finally, a fish swimming study was completed using hatchery-raised Arctic grayling to assess the efficacy of the selected smaller-scaled Denil.

## LITERATURE REVIEW

### Denil Fishway History

Fish ladders and bypass systems connect habitat fragmented by dams and diversions and allow migrations for spawning, feeding and preferred habitat (Katopodis 1992). These obstructions can be built for hydroelectric power production, flood control, irrigation, or a combination of these and other reasons (Clay 1961). There are many types of fish passage structures installed at these dams and diversions, and the technical passes are typically delineated into three categories: pool and weir, vertical slot and Denil fishways (Rajaratnam & Katopodis 1984; Katopodis 1992). The type of fishway used in different instances depends on the space available, head to overcome and native species that are expected to use the fish passage structure (Katopodis 1992).

The technical fishway often used when space is limited is the Denil fish ladder (Odeh 2003). The Denil fishway was developed in 1906 by a Belgian scientist of the same name and has been used widely in Europe and the United States over the past century (Fulton et al. 1953). Denil fishways are often selected for remote or hard to access locations because they are relatively low cost, easy to install and require little maintenance to provide adequate fish passage (Haro et al. 1999; Noonan et al. 2011). Denil fishways are also commonly used in locations where the local hydrograph is snow-driven and causes the water level to drastically change throughout the year (Sladek 2013). Denil fishways are useful in these environments because they are believed to allow passage at a wide range of water depths. Denil fishways function when submerged as well as when water levels are lower and the Denil may only run partially full (Fulton et al. 1953). Denil fish ladders have also been found to work well in parallel, with

adjacent Denils being installed at different elevations to allow for passage at an increased range of water depths (Katopodis 1992).

A Denil fishway is recognized by its square or rectangular sloping channel, and upstream pointing baffles distributed evenly along its length (Rajaratnum & Katopodis 1984). The most widely used Denil fishway is the standard Denil fishway, which measures 0.56 m (22 in) wide with 0.25 m (10 in) baffle spacing, as shown in Figure 1.1 (Rajaratnam & Katopodis 1984). The baffles of the standard Denil fishway are set at a 45-degree angle from the floor and slanted in the upstream direction toward flow (Fulton et al. 1953).

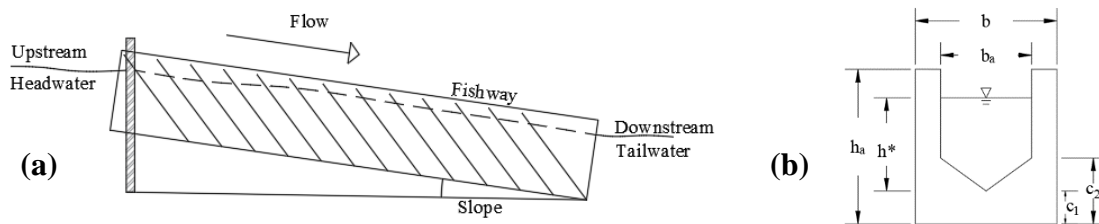


Figure 1.1: A plan view (a) and a baffle detail (b) of a Denil. The plan section shows the single plane baffles at a 45 degree angle from the Denil floor. The standard Denil dimensions are as follows:  $b = 0.56\text{m}$ ,  $b_a = 0.36\text{m}$ ,  $c_1 = c_2 = 0.13\text{m}$ .

In Denil's initial experiments from 1909 to the mid 1930's, the baffles were multidimensional, complicated, and difficult to construct (Larinier 2002). In a study commissioned by the Committee on Fish Passes from 1936-1938, many iterations of small-scale models of Denil-type fishways were tested. A single-plane baffle was found to be the most practical to construct while still causing enough energy dissipation and velocity reduction for viable fish passage (Fulton et al., 1953). While the standard Denil cross sectional dimensions are most often used in practice, there have been a few studies done on larger and smaller scaled Denil type fishways. A field study performed on a larger scale Denil fishway showed fish in an Iowa river would pass a Denil with an expanded width, but the standard size was still preferred

1.75 to 1 (McLeod & Nemenyi 1941; Katopodis & Rajaratnam 1983). A one-third Froude-number-scaled Denil was also studied in a lab and a rating curve was developed (Rajaratnam & Katopodis 1984). The current review found no evidence of fish passage trials being completed with reduced-scale Denil fishways to date.

### Denil Hydraulics and Lab Testing

The Denil fishway creates an environment that is hydraulically suitable for fish passage by using the baffles to disrupt the flow of water and dissipate energy (Rajaratnam & Katopodis 1984). Denil fishways create low velocity zones along the lower portion of the structure due to the v-notched baffles that are spaced along the length (Rajaratnam & Katopodis 1984). Extensive lab studies have been completed on the standard size, as well as a few on Froude-number-scaled equivalent models and nonstandard models (the Simple and Steeppass fishways). These studies showed that as water depth increases, the highest velocity areas shift closer to the water surface, creating lower-velocity zones near the v-notches close to the fishway floor (Katopodis & Rajaratnam 1983; Rajaratnam & Katopodis 1984; Katopodis 1992). Even with this lower-velocity zone, a single segment of Denil fishway is recommended to only be a maximum of 10 m in length without a resting pool for salmonids, as the space between the baffles is typically not large enough for fish to rest in before returning to the swimming channel (Rajaratnam et al. 1997; FAO 2002).

The hydraulic characteristics of a Denil fishway has been described by multiple researchers using rating curve equations that predict flow rates based on the depth of water at the upstream end of the fishway, slope, slot width, and height (Katopodis 1992; Rajaratnam et al. 1997; Katopodis et al. 1997; FAO/DVWK 2002; Odeh 2003). These five studies each defined

similar rating curves for a standard Denil fishway (and its scaled equivalents to an extent) but there were variations in the approach to creating these discharge equations. Each study used unique combinations of fishway slopes, flow rates and d/b ratios (where d is water depth and b is clear width) to develop their respective rating curves. As for similarities, none of these methods considered horizontal baffle spacing in their calculations. The spacing was assumed to not differ significantly from the standard configuration because a significant change would create a large impact on flow characteristics through the fishway (Katopodis et al. 1997; FAO/DVWK, 2002). Fishway slope and clear width are variables in all the discharge equations, and while the clear width is fixed once the Denil fishway is constructed, the fishway slope can change significantly based on how the Denil is installed. Each rating curve equation was optimized for use, within certain parameters, to estimate flow at a full range of water depths and assist in understanding flow regimes based on river metrics.

One way that rating curve equations assist in the design of fishways is help the designer quantify attraction flow. Attraction flow is the often turbulent and high velocity flow at the downstream end of a fish ladder that enables fish to locate, and eventually pass, a fish ladder (Bunt et al. 2001; Williams et al. 2012). The slope of a fish ladder also influences attraction; increased slope results in an increase in turbulence and velocity at the base of the fish ladder (Fulton et al. 1953). The attraction flow must be significant enough to attract fish to the ladder and oriented as to not be masked by the dam or spillway outlet flow (Katopodis & Rajaratnam 1983; Bunt et al. 2001). Because a Denil fishway is typically installed with the upstream end located at the diversion structure and the fishway length is relatively short, the downstream end (where attraction flow is generated) is often near the diversion overflow, increasing the attraction

flow and attraction rate when the Denil is installed near the river bank (Williams et al. 2012).

Even when fish locate the entrance to a Denil fishway, the flow characteristics within the Denil can still pose as a barrier to passage, especially if flows are low (Katopodis & Rajaratnam 1983).

Hydraulic conditions in a Denil fishway are variable depending on water availability and the physical placement and setting in which the fishway is installed. There are three qualitative descriptions of the hydraulic conditions in a Denil fishway - plunging, streaming, and submerged. Plunging flows are characterized by a waterfall-like condition at each baffle. This occurs when flows are low, or the headwater depth is much greater than the tailwater depth (Rajaratnam et al. 1988). Many aquatic species, especially fish that do not have strong jumping abilities, find plunging flows to be a barrier to entrance as well as passage (Blank et al. forthcoming; Platt, 2019). The velocity and water depth within the fishway when plunging flows are occurring can also affect passage results in jumping fish species, as can downstream water depth (Blank 2008). Streaming flow is characterized as having a nearly linear water surface throughout the length of the fish ladder and is typically deep, with backwater conditions at the downstream end of the Denil being common (Rajaratnam et al. 1988). Streaming flows can have higher velocities than plunging flows, which may be a barrier to passage for fish with lesser swimming abilities. While backwater conditions could create hydraulically simpler passage conditions, the attraction flow is normally reduced in this condition so fish may struggle to find the fishway entrance (Rajaratnum & Katopodis 1984). Submerged fish ladders are characterized as a ladder where the tailwater depth is higher than the downstream end of the fishway and in an extreme case the tailwater and headwater depths are at very similar elevations, causing the full fishway structure to be under water. Submerged fish ladders also have attraction flow concerns,

as a submerged structure has a backwater condition along its entire length, but typically does not create barriers to fish passage, once the entrance to the fishway had been found (Slatick 1975; Platt 2019).

To successfully pass a Denil fish ladder, a fish must be able to swim at a velocity that exceeds the water velocity in the swimming channel (Towler et al. 2015). Additionally, fish must have the endurance to maintain that swimming speed for the time it takes to ascend the fishway (Larinier 2002). A standard Denil fishway, set at a 10 percent slope, has maximum velocities of approximately 1.2 m/s within the main swimming channel (Rajaratnam & Katopodis 1984). The fishway velocity may be significantly higher than the water velocity in the main river channel and prolonged (can be maintained for 15-200 minutes before fatigue) or sprint speeds (can be maintained for 15 seconds) may be required to pass (Katapodis 1992). While the baffles in a Denil fishway reduce the velocity of the water at most water depths, swimming ability is still an important factor in passage success.

### Big Hole River and Arctic Grayling

The Big Hole River flows through southwest Montana, with headwaters beginning in the Beaverhead Mountains and terminating at the confluence with the Beaverhead River near Twin Bridges, Montana. The Big Hole River basin drains an area of approximately 6,413 square kilometers through a mixture of federal, state, and private lands (MFWP 2014). Agriculture, more specifically cattle ranching and hay production, are the dominant activities on the privately held lands that border the main stem of the Big Hole River and its many tributaries (MFWP and USFWS 2006). In times of high water demand for agriculture, the Big Hole River could be reduced to minimum flows (0.566 cms in the upper watershed), which put stress on local fish

species, and contributes to increased water temperatures and fragmented habitats (Sladek 2013; BHWC 2016). These stressors particularly affect the resident population of fluvial Arctic grayling (*Thymallus arcticus*).

The fluvial Arctic grayling is a trout species found in streams in Alaska and Montana and is identified by its large and colorful dorsal fin (Brown 1971). Within the contiguous United States, the fish is endemic to the Big Hole River valley (Lohr et al. 1996; MFWP and USFWS 2006; Peterson & Arden 2009; Sladek 2013). There are other grayling populations in Montana (e.g., Red Rocks Lakes in the Centennial Valley and in Ennis Reservoir on the Madison River) but the grayling of the Big Hole River are genetically different from these lacustrine populations (Peterson & Arden 2009). Historically, there were fluvial grayling populations in Michigan (extirpated in the 1930's) (Peterson & Arden 2009) and throughout the Missouri River drainage, but this population has slowly been reduced to its' current range within the Big Hole River (Shepard & Oswald 1989). Due to pressures from land use and overfishing, fluvial grayling currently survive in 5% of their historic range and their current range is impacted by agriculture activity and habitat degradation (Magee et al. 2004). Within the Big Hole River basin, most grayling reside in the tributaries of the upper portion of the main stem of the Big Hole River (MFWP 2014). Within this range, adult grayling prefer pool habitats and feed mainly on floating invertebrates, while fry prefer backwater and waters near beaver dams for more protection (Cayer and McCullough 2014). These habitats have been widely degraded by dewatering and livestock access throughout the Big Hole River system.

### Arctic Grayling Conservation

In response to the dramatic decline in population in recent decades, Arctic grayling are designated a “species of special concern” by Montana Fish, Wildlife and Parks (MFWP), while the United States Forest Service (USFS) designated the fluvial grayling as a “sensitive species” (Cayer and McCullough 2014). In 2014, the United States Fish and Wildlife Service (USFWS) found that grayling populations in Montana were “either stable or increasing” and did not warrant federally listing grayling through the Endangered Species Act (ESA) (USFWS 2014). Further court proceedings ensued and in February 2018 the 9<sup>th</sup> Circuit Court of Appeals ruled that the 2014 decision about grayling was unlawful and required the USFWS to conduct a further review on the status of Montana fluvial grayling and its possible listing through the ESA (*Center for Biological Diversity v Zinke* 2018). As a result of decades of legal battles surrounding the status of grayling, a Candidate Conservation Agreement with Assurances (CCAA) was created for Montana fluvial Arctic grayling in 2006 (MFWP and USFWS 2006). This document provided an outline of actions that private landowners could partake in to help grayling recover (MFWP and USFWS 2006). The agreement also ensured the landowners that participated and enacted the recommended actions outlined in the agreement would not be required to take further action if grayling was federally listed (MFWP and USFWS 2006). Through the CCAA, landowners have added miles of livestock exclusion fencing, rebuilt riparian areas, and replaced undersized and hanging culverts to aid in the recovery of Arctic grayling (Cayer & McCullough 2014). In addition, more than 60 Denil fish ladders were installed at irrigation diversions to reconnect previously fragmented grayling habitat (Platt 2019).

One of the primary habitat challenges the CCAA was intended to address was the dewatering of tributary streams in the Big Hole River Valley (MFWP and USFWS 2006). When the water level is very low due to seasonal fluctuations and agriculture demands, Denil fishways and other fish passage structures become unusable and habitats become fragmented. During the summer months in the Big Hole River Basin some irrigators will fully or partially block the fishways using wood boards so that water can be diverted for irrigation instead of allowing water to flow through the Denil and continue downstream (MFWP and USFWS 2006; Platt 2019). While this blockage is not permanent, it does greatly inhibit the natural movement of Arctic grayling, which can travel up to 80 km in any given year to feed, spawn and find refuge (Northcote 1995).

In the main stem of the Big Hole River, the Montana Water Use Act of 1973 mandates a minimum flow for aquatic species survival (Duffield et al. 1992). This law also confirmed decades-old water rights to all water sources in the state, including the Big Hole River, for use by private and public entities (MDNR 2014). Due to high water demands in the Big Hole River basin, especially in the summer months, the water level in the main stem and tributaries becomes too low for viable fish passage (MFWP and USFWS 2006; BHWC 2016; Platt, 2019). It should be noted that even though the main stem of the Big Hole River has minimum flow requirements, many of the tributary streams do not (BHWC 2016). Water rights in the western United States are mandated on a state level which complicates aquatic species recovery, especially for those that live in heavily irrigated streams and rivers, such as grayling.

### Denil Fishways and Arctic Grayling Passage

Laboratory and field-based fish passage studies help quantify expected passage rates for different fish species and provide critical data for new or modified fish passage structures. Denil fishway passage studies have been completed with many species, however most were observational studies of fishways already installed at dams and diversions (Fulton et al. 1953; Schwalme et al. 1985; Bunt et al. 1999; Schmetterling et al. 2002; Baumgartner 2006; Mallen-Cooper & Stuart 2007). There have also been many laboratory studies of Denil fishways that assess the hydraulics of the fish ladder as discussed previously, but these studies did not use fish to assess passage success (Rajaratnam & Katopodis 1984; Katopodis 1992; Rajaratnam & Katopodis 1997; Katopodis et al. 1997). There has been a recent effort by Montana State University and USFWS to build on these studies to address the water scarcity and fish passage concerns occurring in the Big Hole River watershed. Field studies of the Denil fishways currently installed in the Big Hole River watershed have been completed, both in terms of hydraulics (Platt 2019) and resident fish species passage (Triano et al. forthcoming) and have provided baseline knowledge of the conditions particular to Denil fishway installations in the valley. Laboratory studies involving grayling were completed at the Bozeman Fish Technology Center (BFTC) to relate hydraulics and grayling passage in Denil fishways (Cahoon et al. 2018; Dockery et al. 2019; Blank et al. forthcoming; Plymnesser et al. forthcoming). These flume and respirometer-based studies quantified grayling swimming ability, optimum water depths for passage, and possible modifications to the standard size Denil fishway to reduce flow in a cumulative effort to support grayling recovery in the Big Hole River Valley.

The fishway modification study is of importance to, and inspired, the current study. The previous study used restrictor plates at the upstream end of a full size simple Denil to reduce flow through the Denil while still allowing continuity for fish passage (Plymesser et al. forthcoming). The reduced flows created by the restrictor plates would have allowed irrigators to divert water without completely blocking fishways but did not provide high enough fish passage rates to be a viable solution. It was found that a full scale Denil fishway requires the full amount of flow to create the proper hydraulic conditions to provide the highest passage (Plymesser et al. forthcoming). A balance between maintaining high fish passage rates while requiring less water to pass through a Denil fishway is the focus of the present research.

In terms of optimal hydraulic scenarios for grayling passage in Denil fishways, studies have suggested that grayling passage success is highest when the tailwater elevation is at the height of the fish ladder walls (Blank et al. forthcoming). Trials completed in a respirometer with fish in the 290 mm size class indicated that grayling's critical swim speed was  $1.66 \text{ m s}^{-1}$  (Cahoon et al. 2018), while previous culvert studies have shown grayling of the same size class to have burst and prolonged swim speeds of  $1.6$  to  $2.1 \text{ m s}^{-1}$  and  $0.4$  to  $1.6 \text{ m s}^{-1}$ , respectively (Kane et al. 1989). A recent study completed in the Big Hole River Valley, applied swim speed and field-based Denil fishway hydraulics to predict passage (Platt 2019). This field study found that hatchery-raised grayling had high passage success when flows through the Denil are high and the fish ladders are not blocked for irrigation reasons (Triano et al. forthcoming). The Big Hole River field studies and BTFC laboratory studies informed the work completed for this thesis and drove the selection of scaled Denil sizes.

## HYDRAULICS OF SMALL SCALE DENILS

### Introduction

This section describes both the computer modeling and laboratory-based analysis of the hydraulic qualities of scaled Denil fishways. The goal of this analysis was to determine a scaled model that would convey substantially less flow rate than the full-scale Denil while still being large enough to not physically impede grayling swimming movement. The computer analysis portion of the scale determination consisted of selecting potential size options, computing the maximum expected flow rate and energy dissipation factor (EDF) for each scale, and comparing these flow rates and EDF values to the full scale Denil hydraulics. The laboratory study primarily assisted in the selection of baffle spacing to be used for the fish swimming study. Average velocity and water surface elevations were measured for further hydraulic analysis. Once designed and verified, a prototype of the scaled Denil fishway was used for fish swimming trials at the Bozeman Fish Technology Center (BTFC) outdoor flume. The swimming trials determined the efficacy of the scaled Denil fishways at passing Arctic grayling (*Thymallus arcticus*). The results of the passage trials are detailed in chapter 3 of this thesis.

### Methods and Results

#### Model Selection Calculations

Table 2.1 summarizes key physical and hydraulic information, such as dimensions, maximum flow rates and turbulent energy dissipation for the scaled Denil fishways. The scaled sizes considered were based on the standard Denil fishway, with dimensions as noted in Rajaratnum and Katopodis (1984) and referenced in Figure 2.1 and Table 2.1. Additionally, this

study assumed that 0.61 meters was the full height of the standard fishway, to match the height of full scale Denil fishways used in previous studies and those installed in the Big Hole River Basin (Platt 2019; Blank et al. forthcoming; Plymesser et al. forthcoming).

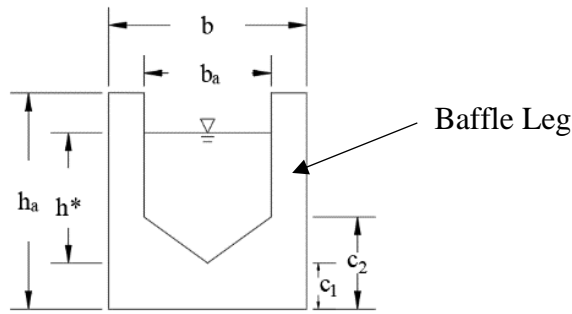


Figure 2.1: Key dimensions of a Denil baffle with notation from Odeh (2003). The standard Denil has the following dimensions:  $b = 0.56\text{m}$ ,  $b_a = 0.36\text{m}$ ,  $c_1 = c_2 = 0.13\text{m}$

Table 2.1: Maximum flow rates for each scaled Denil size tested. The two highlighted sizes (0.75 and 0.60 scale) were constructed for use in laboratory testing. The thicker vertical lines through the table separate the calculations using the scaled heights from the calculations using the full-scale height.

Physical Scale	Fishway Width [b] (m)	Slot Width [b <sub>a</sub> ] (m)	Scaled Maximum Flow w/ Scaled Height (m <sup>3</sup> /s)	% of Standard Max Flow w/ Scaled Height	Expected EDF With Max Flow and Scaled Height (W/m <sup>3</sup> )	Scaled Maximum Flow w/ Full Height (m <sup>3</sup> /s)	% of Standard Max Flow w/ Full Height	Expected EDF With Max Flow and Full Height (W/m <sup>3</sup> )
1.00	0.560	0.360	0.127	100%	70.33	0.127	100%	70.33
0.95	0.532	0.342	0.112	88%	68.55	0.127	100%	72.63
0.90	0.504	0.324	0.097	77%	66.72	0.128	101%	75.20
0.85	0.476	0.306	0.084	67%	64.84	0.126	99%	76.91
0.80	0.448	0.288	0.073	57%	62.90	0.125	98%	78.90
0.75	0.420	0.270	0.061	48%	60.30	0.122	96%	80.46
0.70	0.392	0.252	0.052	41%	58.87	0.117	92%	81.56
0.65	0.364	0.234	0.043	34%	56.73	0.114	90%	83.56
0.60	0.336	0.216	0.035	28%	53.97	0.110	87%	85.19
0.55	0.308	0.198	0.028	22%	52.18	0.106	83%	88.29
0.50	0.280	0.180	0.022	17%	49.76	0.101	80%	90.73
0.25	0.140	0.090	0.004	3%	35.18	0.061	48%	100.67

Table 2.1 provides a physical scale reference in the left-hand column, the overall fishway width ( $b$ ) and slot width ( $b_a$ ) for each of the scales in meters in the next two columns. The scaled maximum expected flow rate columns use an average of three rating curve equations (detailed further below) to find the flow rate when the water depth equals the fishway height. The percent of standard maximum flow compares the given scaled model to the Standard model's expected flow rate when full and the expected EDF with maximum flow uses equation (7) to quantify the turbulence.

There are two scaled maximum flows and the corresponding percent of standard maximum flow shown in Table 2.1: one assumed that the fishway height was also reduced in the same manner as the width and the other used the full scale Denil height for all scales. Initially, the prospective sizes were scaled in height and width and calculations were made using these dimensions and were the basis for model selection. These calculations were edited after installation options were reviewed and a full height wall was used in this study to allow for testing at a wider range of flows. In practice, the wall height is a dimension that is left to the designer's discretion. The following explanation of calculations assumed the height of the fishways scaled the same amount as the width.

Two dimensions were held constant through all scaling iterations - overall fishway length and baffle spacing. The length was held constant to maintain a slope of 8.3% and a drop of 0.3 meter, which are the recommended slope and drop for field installations (personal communication Emily Cayer, former MGRP Coordination). Additionally, most of the Denil fishways in the Big Hole River Valley were 3.65 meters long (Platt 2019). Baffle spacing was analyzed separately and is discussed during the laboratory study portion of this chapter. The

angle of the baffles within the Denil,  $\alpha$ , was maintained at 45 degrees; the angle recommended in all recently published studies involving Denil type fishways (for example: Rajaratnum and Katopodis 1984; Katopodis 1992; Katopodis et al. 1997).

Maximum Expected Flow Rates The scaled fishway sizes to be constructed and water tested were selected based on two parameters: the expected maximum flow rates and the turbulence dissipation. Rating curves were developed for each scaled fishway to understand the difference between the scaled fishway flow rates and those expected in the standard Denil fishway. Initially, five rating curve equations were evaluated to determine which was best suited to the dimensions of the scaled Denils. Two of the equations were omitted due to the recommended size constraints put on the equations that were not compatible with the scaled sizes. The first to be eliminated was the rating curve equation developed by Odeh (2003), which applied to wider fishways, with ideal widths between 0.46 and 1.22 meters. As can be seen in Table 2.1, the widths in this study ranged from 0.14 to 0.56 meters, meaning many of the scaled options were below the recommended range of fishway widths from Odeh (2003). The second equation eliminated was published by the FAO (2002) and was meant for use with a very specific size Denil and most of the scaled sizes did not fit in this range.

The three remaining rating curve equations were all developed for wide ranges of  $h^*/b_a$  (water depth over slot width) ratios and were a better fit for the scaled Denil fishway sizes studied (Rajaratnum and Katopodis 1984; Katopodis 1992; Katopodis et al. 1997). The first equation (Rajaratnum and Katopodis 1984) is based on Manning's equation and an equation that accounts for friction between the main water stream and that of the recirculating flows against the bottom and walls of the fishway. The equation simplifies to:

$$Q = b_a \bar{d} \left[ \frac{2 g I b_a \bar{d}}{b_a + 2 \bar{d}} \right]^{0.5} \frac{1}{\sqrt{C_f}} \quad (1)$$

Where  $Q$  is flow rate in  $\text{m}^3/\text{s}$ ,  $b_a$  is slot width in m,  $g$  is acceleration due to gravity in  $\text{m}/\text{s}^2$ ,  $I$  is the slope of the fishway in dimensionless units, and  $\bar{d}$  is defined as:

$$\bar{d} = h^* - \frac{C_2 - C_1}{2} \quad (2)$$

Where  $h^*$  is the depth of water perpendicular to the channel bottom in m, measured from the V-notch,  $C_1$  is the distance from the Denil floor to the V-notch and  $C_2$  represents the distance from the fishway floor to the full baffle slot width (See Figure 2.1). The term  $C_f$  is the coefficient of friction which can be calculated using the following equation or found through a relationship between  $h^*$  and  $b_a$ . The value of  $C_f$  ranges from 0.7 when  $h^*/b_a$  is 0.5 and decreases in a nonlinear fashion as  $h^*/b_a$  increases (Rajaratnum & Katopodis 1984).

$$C_f = \frac{2gS_0\bar{d}}{V^2(1 + \frac{2\bar{d}}{b})} \quad (3)$$

In equation (3),  $S_0$  is the fishway bed slope in meters/meters,  $V$  is the mean velocity in the fishway in  $\text{m}/\text{s}$ , and the remaining variables are as previously defined. This set of equations applies to Denils with an  $h^*/b_a$  ratio less than 2.0. Because height was scaled at the same rate as the width, the  $h^*/b_a$  ratio has a maximum of 1.33 for all Denil fishway scales, meaning this equation is applicable for all scale sizes investigated herein.

The second equation was developed from the comparison of flows through different fishway types (Denil, culvert, vertical slot, and weir) (Katopodis 1992). Froude-number similitude laws were used to create a general flow equation that is governed by gravity and the ratio of

water depth ( $h^*$ ) and slot width ( $b_a$ ) (Katopodis 1992). The following equation was made specific for Denil fishways by two coefficients ( $\alpha$  and  $\beta$ ) that create a power function:

$$Q = \sqrt{g I b_a^5} \left[ \alpha \left( \frac{h^*}{b_a} \right)^\beta \right] \quad (4)$$

For a standard Denil fishway,  $\alpha$  equals 0.94 and  $\beta$  equals 2. This is based on experiments completed on a Denil fishway with a total width to clear width ( $b/b_a$ ) ratio of 1.58, a baffle spacing to clear width ( $a/b_a$ ) ratio of 0.72 and a water depth to clear width ( $h^*/b_a$ ) ratio range of 0.5 to 5.8. All the scaled models in the current study are scaled equivalents of the standard Denil dimensions so the  $b/b_a$  ratio was always 1.54. The baffle spacing for the current analysis was assumed to be 0.25 meters for all scaled models, creating a range of  $a/b_a$  between 0.71 (for the full-scale model) and 2.82 (for the 0.25 scale model). The  $h^*/b_a$  ratio ranged from 0.37 to 1.33 for the current scaled models, meaning all scales fell within the bounds of this equation.

Finally, the third set of equations published (Katopodis et al. 1997) combined concepts from the first two equations to address a broader range of Denil sizes, including those used in the current study.

$$Q = \sqrt{g I b_a^5} \left[ 1.15 \left( \frac{h^*}{b_a} \right)^{1.8} \right] \quad (5)$$

$$Q = \sqrt{g I b_a^5} \left[ 1.22 \left( \frac{h^*}{b_a} \right)^{1.6} \right] \quad (6)$$

Equations (5) and (6) look very similar to the previous equation developed by Katopodis in 1992 but the coefficients  $\alpha$  and  $\beta$  are different. The reanalysis of coefficients and transition from one equation to two was meant to better represent the  $h^*/b_a$  ratios of over 3.0 (Katopodis et al. 1997).

Katopodis et al. (1997) used the ratio shown in equation (7) to provide guidance for when to use equation (5) and when to use equation (6).

$$r_a = (a/b_a)/(a/b_a)_s \quad (7)$$

Where  $a$  is baffle spacing,  $b_a$  is slot width and the subscript  $s$  denotes the dimensions for the standard Denil configuration. When  $r_a$  is between 0.78 and 1.27, equation (4) should be used to find flow rate and when  $r_a$  is between 1.5 and 2.4, equation (5) should be used (Katopodis et al. 1997). For the scaled models in the current study, only the 0.25 scale model fell outside of this range of  $r_a$  values, with  $r_a$  equal to 4.0. The 0.25 scale model did not fit into any of the three equation's parameters and therefore was only used for comparison purposes, not as a viable option for further testing.

To create a discharge rating curve, the flow rate was determined for a discrete set of water depths using equations (1), (4), (5) and (6). Expected flow rates for each depth were plotted and the results for the 0.60 scale Denil fishway can be seen in Figure 2.2. Rating curves were developed for a range of Denil scales investigated to evaluate the expected flow regimes of each scale. The average of the three points farthest to the right on Figure 2.2, the maximum expected flow, was used for comparison to the full scale Denil and is the number in the maximum expected flow column in Table 2.1.

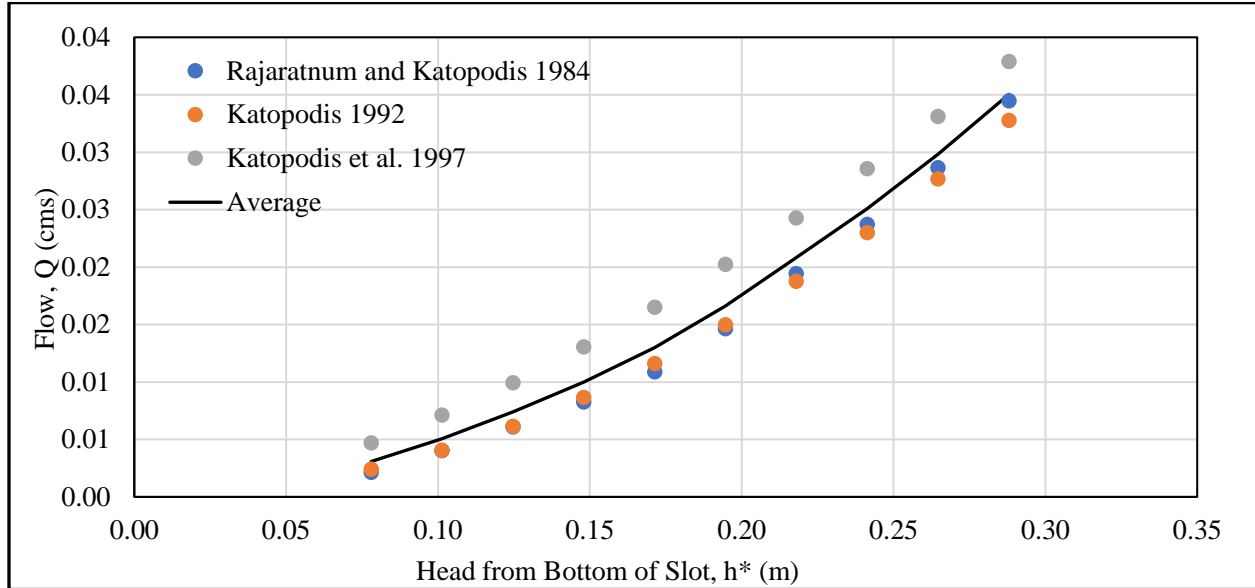


Figure 2.2: Rating curves for the three discharge equations at a series of water depths for the 0.60 scale Denil. The black line represents the average of the three rating curves. A similar graph for each fishway scale can be seen in Appendix A.

Turbulence Turbulence is an important measure in fishways because high turbulence can alter fish swimming performance and reduce passage success (Towler et al. 2015). The turbulence was calculated using the following equation for energy dissipation factor, or EDF (Towler et al. 2015).

$$EDF = \gamma V S_0 \quad (8)$$

Where  $\gamma$  is the unit weight of water,  $V$  is the average velocity in the effective flow area, and  $S_0$  is the channel bottom slope. The EDF was calculated for all scale sizes using their respective maximum flow rates. The EDFs and flow rates were then plotted against each other in Figure 2.3 to better understand the relationship between flow and turbulence in a Denil fishway. As can be seen in Figure 2.3, as the fishway scale reduces, the maximum flow and the EDF value both decrease. As the slot width decreased with smaller scales, less water could be conveyed which causes the velocity and energy dissipation to decrease (Towler et al. 2015).

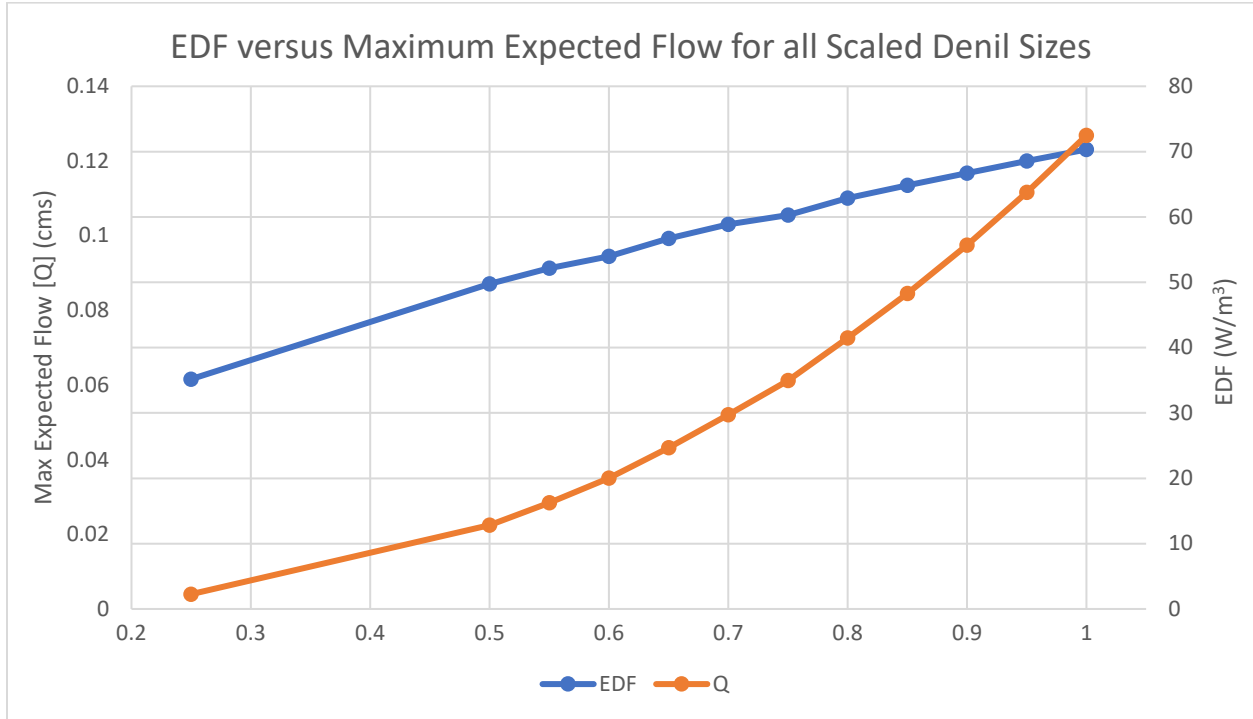


Figure 2.3: EDF plotted against maximum expected flow for each Denil size. As Denil scale decreases, the flow rate and EDF also decrease. This is due to the reduced cross-sectional area of the scale Denil fishways compared to the full scale fishway.

### Installation and its Influence on Flow Rate and Turbulence

Installation layout was also considered during scaled model selection, particularly the height of the fishway walls. In the standard dimensions provided by Rajaratnum and Katopodis (1984), the height was not prescribed and in practice its value is left to the designer. For this study, three options were considered that resulted in different rating curves. The installation options can be seen in Figure 2.4 and the associated rating curves are in Figures 2.5-2.7.

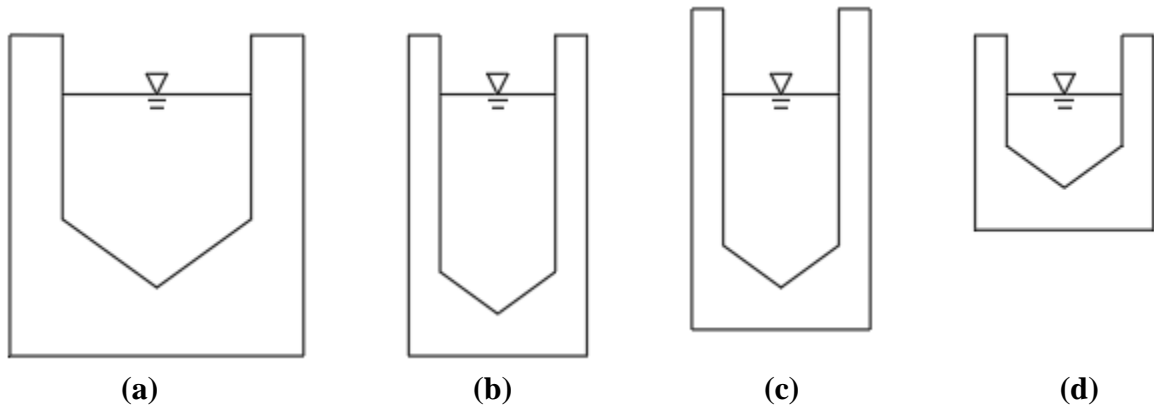


Figure 2.4. A comparison of possible scaled Denil installations considered. (a) represents the full scale Denil. (b) shows the 0.6 scale Denil installed with the same bottom elevation as the full scale and with full height walls. (c) shows the 0.6 scale Denil installed at the same V-notch elevation as the full scale and with full height walls. (d) shows the 0.6 scale Denil installed with the same top elevation as the full scale and with 0.6 scaled walls.

Figure 2.4 (a) shows the full scale fishway and was the basis for scaling. The three installation options for the scaled fishways were:

- Install the scaled Denil at the same invert (bottom) elevation as the full scale Denil and use full height walls for the scaled models (b in Figure 2.4)
- Install the scaled Denil at the same V-notch elevation as the full scale Denil and use full height walls for the scaled models (c in Figure 2.4)
- Install the scaled Denil at the same top elevation as the full scale Denil and use scaled walls (d in Figure 2.4)

This is not an exhaustive list of installation options but provides three of the simplest retrofitting options if a full scale Denil were replaced with a scaled one at an irrigation diversion. Figures 2.5 – 2.7 below provide a comparison between the full scale Denil and three scaled sizes: 0.75, 0.50 and 0.25 for each of the installation options.

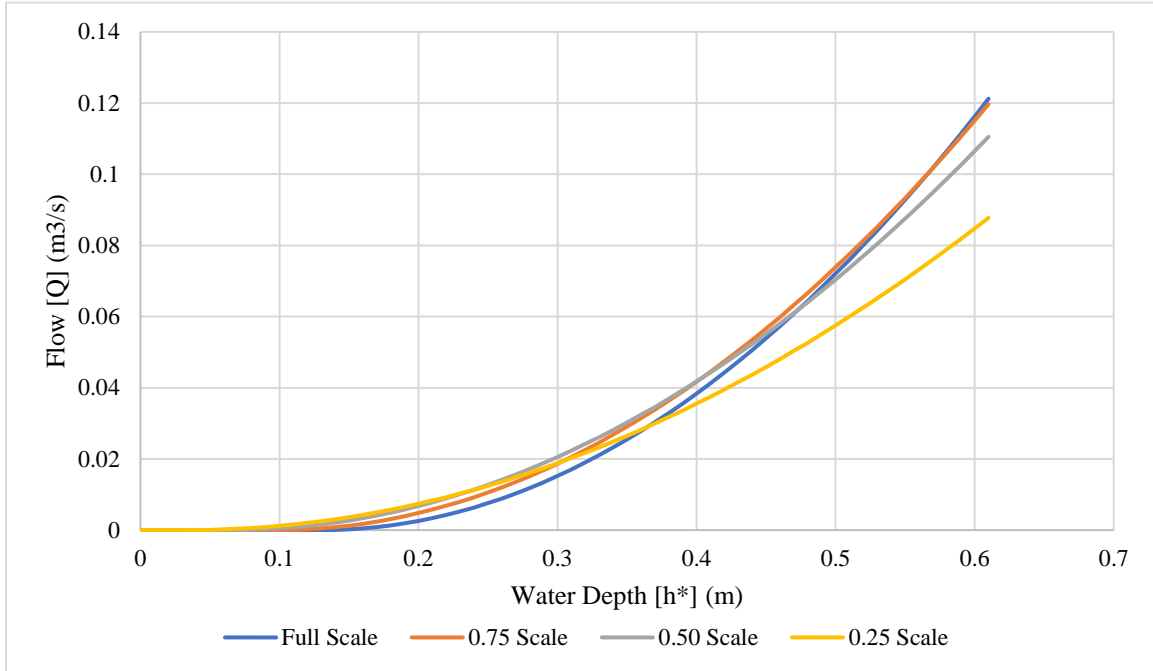


Figure 2.5. Rating curve comparison for installation layout (b), where the invert of the scaled Denil is installed at the same elevation as the full scale fishway and full height walls are used on the scaled models. Each line on the graph represents a different scale: full scale, 0.75, 0.50 and 0.25 scaled models.

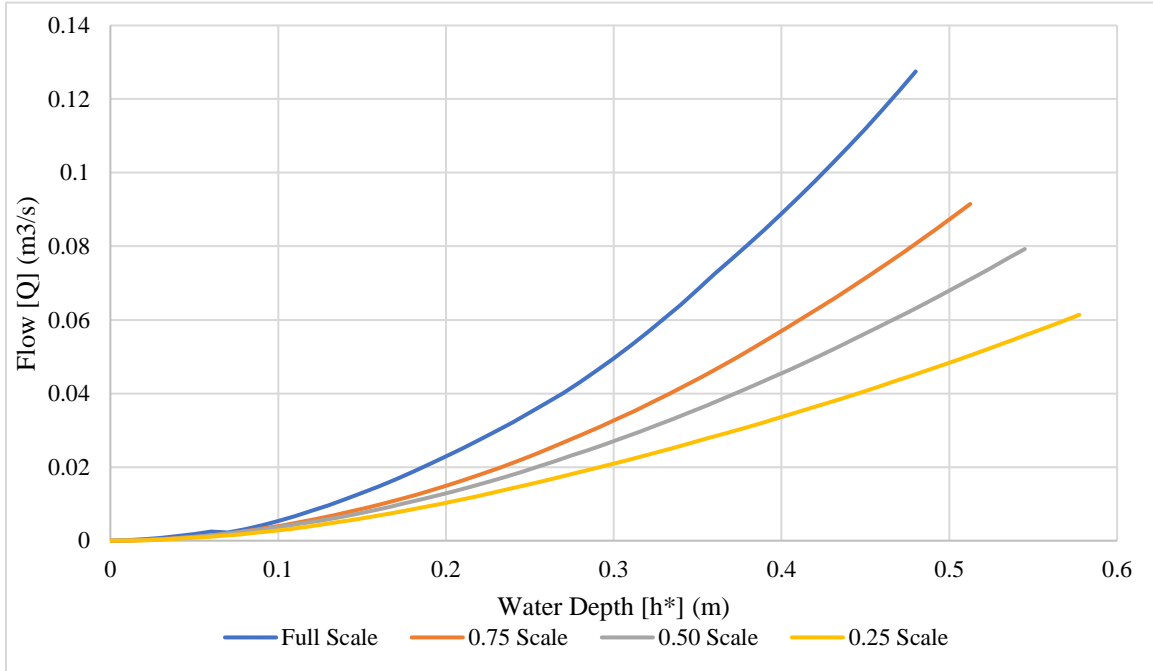


Figure 2.6. Rating curve comparison for installation layout (c), where the V-notch of the scale Denil is installed at the same elevation as the full scale fishway and full height walls are used on the scaled models. Each line on the graph represents a different scale: full scale, 0.75, 0.50 and 0.25 scaled models.

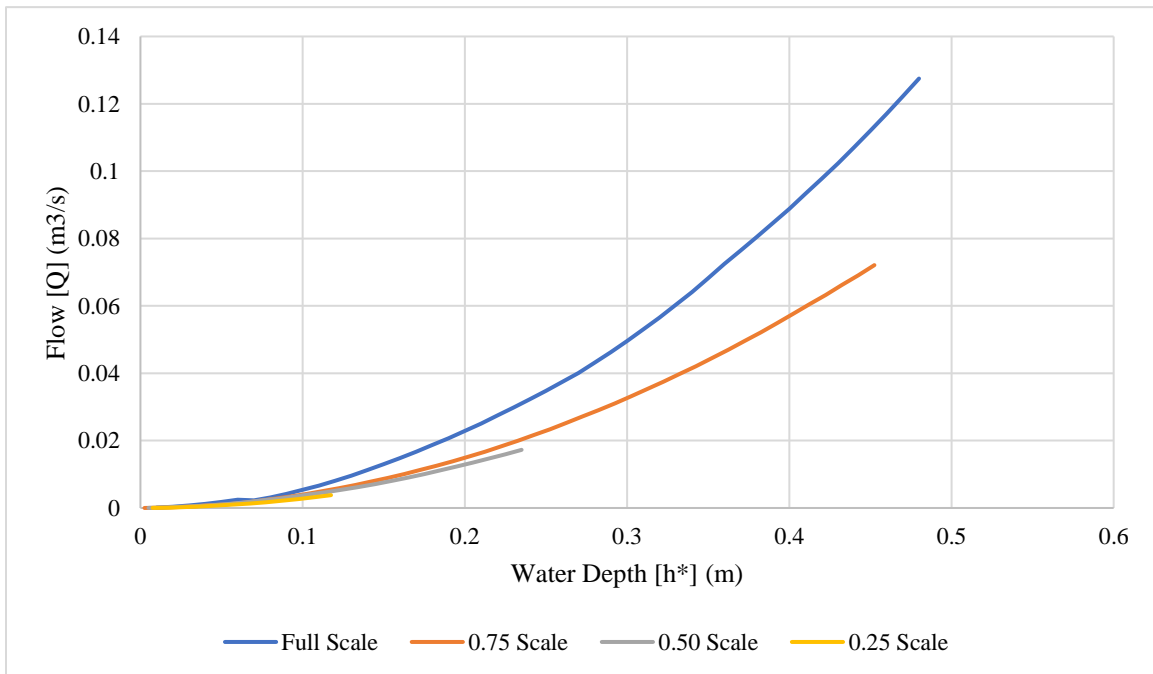


Figure 2.7. Rating curve comparison for installation layout (d), where the top of the scale Denil is installed at the same elevation as the full scale fishway and scaled height walls are used on the scaled models. Each line on the graph represents a different scale: full scale, 0.75, 0.50 and 0.25 scaled models.

Figures 2.5 – 2.7 show that the way scaled Denils are installed greatly effects their performance. Figure 2.5 (installation option (b)) indicates almost zero reduction in flow between the different model sizes, regardless of the water depth. This is because smaller scales have a smaller  $c_1$  dimension (the distance between the V-notch and the fishway flow), which results in relatively larger flow areas, and, therefore larger flows, when the water depth is low. Figure 2.6 (installation option (c)) shows the greatest reduction in flow between the scale sizes. This configuration requires the same upstream water depth for operation as the full scale (due to the V-notch having the same elevation for all scales), but the flow is greatly reduced as the water depth above the notch increases. Finally, Figure 2.7 (installation option (d)) indicates that installing the fishway with scaled walls drastically reduces the flows through the fishway but also greatly reduces the range of water depths achievable. Additionally, as the scale gets smaller, the V-notch elevation gets higher in this configuration, meaning the upstream pond elevation must be much higher for the fishway to be operationally similar to the full scale. After reviewing these installation options, it was decided to continue with testing using configuration (c). This layout allowed for the greatest reduction in flows while also allowing for testing at a wide range of flow rates.

The flow rates and EDF values were recalculated with full height walls to match installation option (c) and can be seen in Table 2.1. This caused two major shifts: the maximum expected flow rate increased significantly and the EDF values went from decreasing as the fishway scale got smaller to increasing as the scale decreased. The flow rate increased significantly because the cross-sectional flow area increased with the additional height. As for the EDF values, the increase in flow rate outpaced the increase in flow area, leading to an

increase in velocity, a main component in the EDF equation. The increase in height created higher turbulence estimates, especially as the scale was reduced, meaning the combination of higher walls and narrower slot widths trapped more water between the baffles and recirculated it into the main swimming channel (Towler et al. 2015)

### Laboratory Set Up and Testing

Den60 and Den75 were constructed out of marine-grade plywood and oriented strand board (OSB) and painted yellow to match the full scale fishways previously used for testing at the BFTC, and the color used in many Denil fishways installed in the Big Hole Watershed. Grooves were cut along each side and bottom panel at 12.7 cm on center to allow for baffle spacing adjustments during hydraulic testing. The baffles were also made from plywood and were cut using a Computer Numerical Control (CNC) machine to ensure uniformity. At 0.76 m intervals along the length, a baffle was permanently installed in the Denil to create rigidity in the structure. Additional bracing was added to help the fishways maintain structural integrity and reduce leakage as the trials progressed.



Figure 2.8: Photos of the prototype scaled Denil fishways in the MSU hydraulics laboratory set up for hydraulic testing. The left photo shows the grooves cut into the sides of each Denil to allow for baffle spacing analysis. The right photo shows Den75 full of water and provides an idea of flow conditions tested.

All hydraulic testing was completed at the Montana State University hydraulics lab. This testing was carried out to better understand the effects of baffle spacing in scaled Denil fishways and to verify the hydraulics of the scaled models were similar to the rating curve derived flow rates calculated previously. Each scaled Denil was tested separately. The Denil was placed between a permanent headwater tank and a temporary tailwater tank, with intermediate support between the tanks. The laboratory setup can be seen in Figures 2.8 and 2.9. Water was pumped into the headwater tank from an overhead pipe via a recirculating pump system and passed through a screen to reduce and homogenize turbulence and velocity before entering the Denil. The tailwater tank measured 1.22 meters wide and 2.44 meters long, with a sluice gate at the far end of the tank to control the tailwater depth.

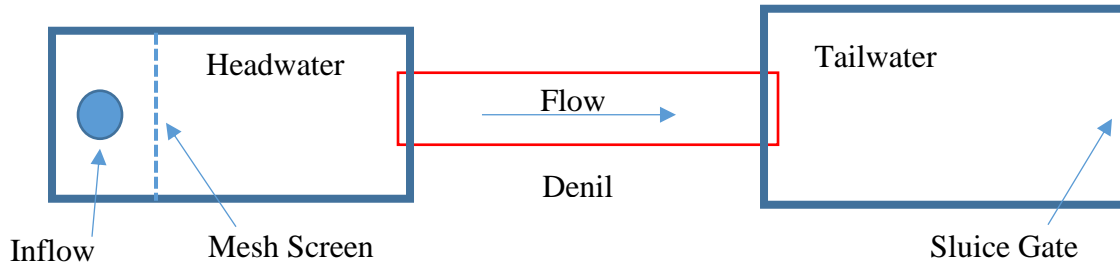


Figure 2.9: Montana State hydraulics lab layout for the baffle spacing analysis.

Each hydraulic trial conducted included a unique combination of headwater depth and baffle spacing. A total of 21 trials were conducted with Den60 and Den75. The tailwater depth was held constant at full depth (55.9 cm) throughout all trials and was measured vertically from the lowest point on the Denil floor at the downstream end. Baffle spacing options were either 12.7, 25.4, or 38.1 cm on center. The headwater depths tested varied by 5.1 cm increments between 20.3 and 40.6 cm. Headwater depths were measured from the Denil floor at the upstream end of the fishway. Headwater depths deeper than 40.6 cm could not be achieved due to pump system constraints. A list of trials conducted for each scale model can be seen in Table 2.2.

Table 2.2: Trial specifics for hydraulic testing of Den60 and Den75. Each trial was a unique combination of baffle spacing and headwater depth. Tailwater depth was held consistent at 55.9 cm for all trials.

Trial number	Denil scale	Baffle Spacing (cm)	Headwater Depth (cm)	Flow rate (m <sup>3</sup> /s)
1	0.6	38.1	30.5	0.0323
2	0.6	38.1	25.4	0.0222
3	0.6	38.1	20.3	0.0074
4	0.6	38.1	40.6	0.0631
5	0.6	38.1	35.6	0.0509
6	0.6	25.4	25.4	0.0225
7	0.6	25.4	30.5	0.0341
8	0.6	25.4	35.6	0.0483
9	0.6	25.4	40.6	0.0608
10	0.6	12.7	25.4	0.0244
11	0.6	12.7	30.5	0.0339
12	0.6	12.7	35.6	0.0506
13	0.6	12.7	40.6	0.0647
14	0.75	38.1	30.5	0.0396
15	0.75	38.1	25.4	0.0256
16	0.75	25.4	40.6	0.0715
17	0.75	25.4	30.5	0.0355
18	0.75	25.4	25.4	0.0256
19	0.75	12.7	40.6	0.0735
20	0.75	12.7	30.5	0.0421
21	0.75	12.7	25.4	0.0271

Headwater and tailwater depths were measured using a meter stick at the beginning and end of each trial. The flow rate entering the headwater tank was measured using a Portable Ultrasonic Flowmeter (Fuji Electric, Tokyo, Japan) attached to the supply pipe. Flow rates were recorded at the beginning and end of each trial. The height of the sluice gate opening was also recorded.

To start each trial, the pipe system was pressurized, the valve at the outlet pipe was opened and the system was allowed to reach equilibrium. The headwater and tailwater depths were measured and the flow rate and sluice opening were adjusted until the predetermined trial

headwater and tailwater depths were reached. Once the system was verified to be in equilibrium at the appropriate water levels, velocity and water surface elevations were measured.

Velocity Velocity was measured at either seven or nine points along the length of each of the two fishways, depending on the baffle spacing. If the spacing was 12.7 or 38.1 cm, nine measurements were taken (at every third baffle or each baffle, respectively). If the spacing was 25.4 cm, seven measurements were made, one at every other baffle. See Figure 2.10 for the measurement locations. Water velocity was measured along the centerline of the fishway using a Hach FH950 Portable Velocity Meter. The velocity probe was attached to a wading rod and the base of the wading rod was placed where the baffle met the fishway floor and held vertically in the water column. Velocity was measured at 20 percent and 80 percent of the water column above each designated baffle V-notch. The velocity was measured twice at each location. Each measurement consisted of a 40-second time-averaged reading. The velocity for each location was calculated as the average of the two measurements.

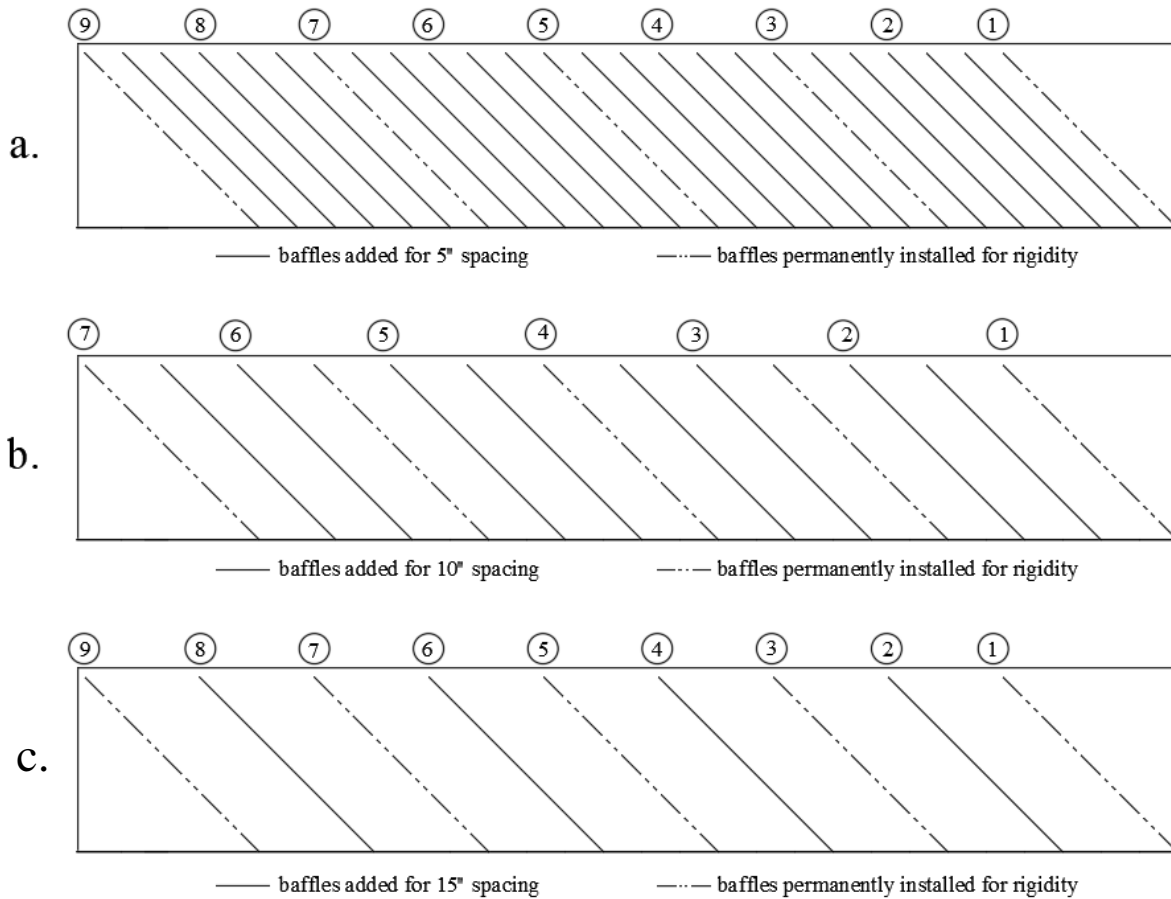


Figure 2.10: Velocity measurement locations for the laboratory study. Each measurement was taken at the v notch of the indicated baffle. The numbering above the baffles aligns with the measurement locations noted in Table 2.3 and Appendix B. (a) denotes the configuration for the 12.7 cm baffle spacing, with nine velocity measurement locations. (b) shows the configuration for the 25.4 cm baffle spacing, with seven velocity measurement locations. (c) shows the configuration for the 38.1 cm baffle spacing, with nine velocity measurement locations.

Water Surface Elevation Water surface elevations were measured at each baffle. A meter stick was placed vertically in the water column and used to measure the water depth from the Denil floor, behind the V-notch of each baffle. For the 38.1 cm baffle spacing, additional water surface elevations were taken where the downstream end of each baffle met the fishway floor. This additional set of water surface elevations were measured due to the 38.1 cm baffle spacing being larger than the other spacings, resulting in large gaps in the water surface profile if only

one measurement was made at each baffle. Water surface elevations were measured and recorded for each trial after velocity measurements were completed.

For each baffle spacing configuration, a trial was conducted using the maximum flow rate the laboratory pipe system could provide. For this set of trials, the tailwater was still constant at 55.9 cm but the headwater was allowed to rise as high as the pump system allowed. During this trial, velocity measurements were not taken along the length of the fishway, but water surface elevations, flow rates, and headwater and tailwater depths were recorded.

Table 2.3 presents an example of the velocity measurements taken during Trial 1. See Appendix A for the remaining velocity measurements taken during this analysis. Due to constraints of the lab's pump system, the highest headwater depth achieved was 40.6 cm, even though the full height of both Denils was 61.0 cm. Each baffle spacing configuration achieved a different series of water depths due to variability in the supply water pressure in the lab. Most treatments recorded at least three headwater depths. The 38.1 cm baffle spacing treatment on Den75 recorded the fewest with only two (trials 14 and 15).

Table 2.3. Velocity measurements for the 30.5 cm headwater depth and 38.1 cm baffle spacing trial for the 0.6 scale Denil. Notch depth is the water depth above the V notch at each measurement site. Depth 1 and depth 2 are the water depths of the velocity measurement, measured from the V-notch. V1 and V2 for each depth were 40 second time-averaged velocity measurements. The average flow rate for this trial was 0.032 cms and the sluice gate at the tailwater box was set at a 2.9 cm opening.

Baffle	Notch Depth (cm)	Depth 1 (cm)	V1 (cm/s)	V2 (cm/s)	Depth 2 (cm)	V1 (cm/s)	V2 (cm/s)
1 - Lower	49.53	34.80	14.33	13.41	9.14	26.82	28.65
2	43.82	34.29	15.24	13.72	8.64	34.75	34.44
3	43.18	34.29	16.46	16.76	8.26	35.36	33.22
4	39.37	31.50	20.42	17.68	8.13	33.53	36.88
5	38.1	30.48	14.02	8.84	7.62	40.84	39.32
6	34.29	27.18	-0.61	7.92	7.11	49.07	45.11
7	33.02	26.16	17.68	17.68	6.60	54.86	53.04
8	30.48	24.38	14.33	11.58	5.59	66.75	67.67
9 - Upper	29.21	23.37	34.75	33.22	5.84	55.78	56.08

### Baffle Spacing Analysis

After both scaled fishways were hydraulically tested at all designated headwater depth and baffle spacing combinations, a series of graphs were constructed to determine the optimum baffle spacing for the swimming trials. Figures 2.11 and 2.12 illustrated how all three spacings created a common trend in longitudinal velocity distribution for both Den60 and Den75, with the highest velocities occurring about one meter from the upstream end of the Denil and gradually reducing in the downstream direction with the lowest velocities occurring at the outlet to the tailwater box. Additionally, all baffle spacings created a vertical velocity gradient with a lower velocity zone along the notch of the baffles, as previously noted by Rajaratnum and Katopodis (1984). This can be seen in Figures 2.11 and 2.12 as well as in Table 2.1. Both Figures 2.7 and 2.8 showed the 12.7 cm baffle spacing had the highest velocity at nearly every measurement point and the 25.4 cm and 38.1 cm spacings had similar longitudinal and vertical velocity profiles.

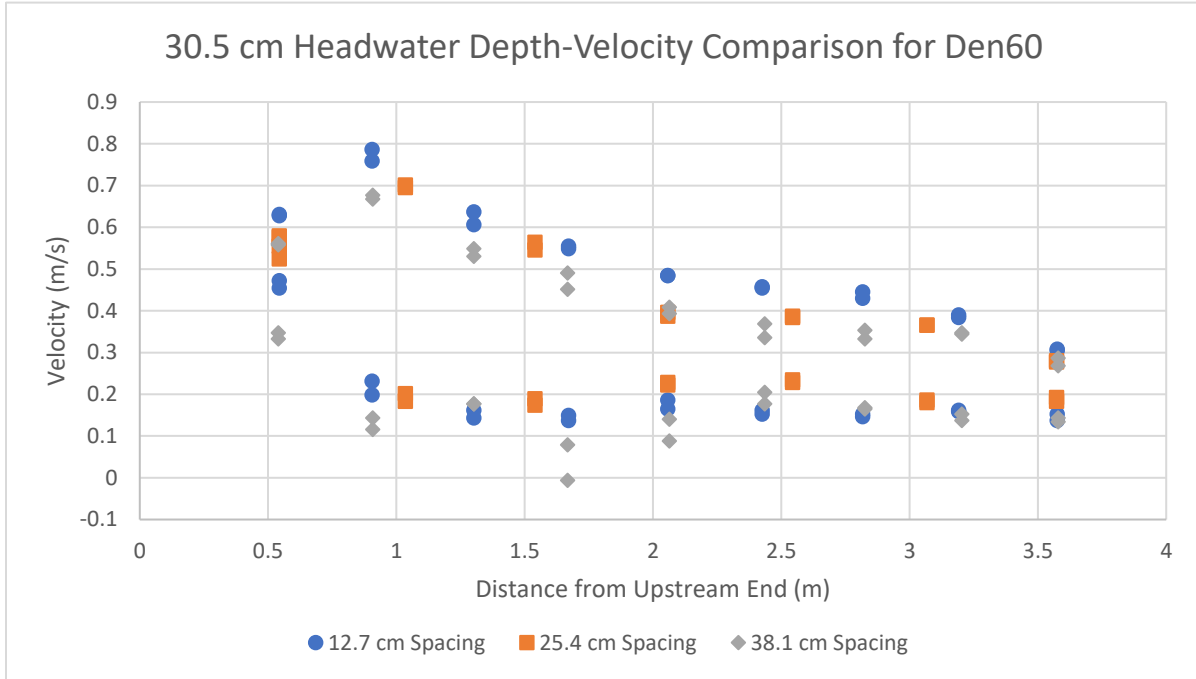


Figure 2.11: A graph representing velocity measurements along the length of Den60 for each baffle spacing that correspond to the 30.5 cm headwater depth. Four measurements were taken at each location, two at 20 percent of the water column and two at 80 percent.

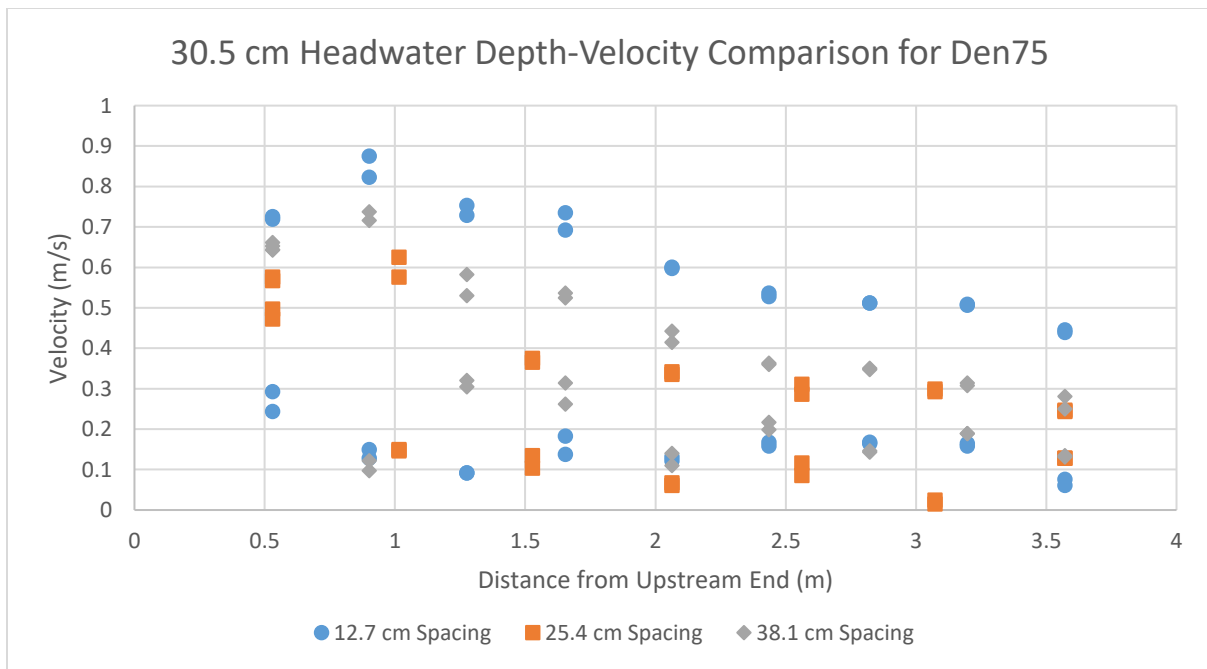


Figure 2.12: A graph representing velocity measurements along the length of Den75 for each baffle spacing that correspond to the 30.5 cm headwater depth. Four measurements were taken at each location, two at 20 percent of the water column and two at 80 percent.

Ultimately, the baffle spacing that resulted in the lowest velocities was preferred, as Arctic grayling prefer to ascend fish ladders and other obstructions through low velocity zones (Dockery et al. 2019). While turbulence was assessed when selecting the scaled Denil sizes, this parameter was not a consideration in baffle spacing selection. The fishways were narrow and the flow through them was complex, which created high levels of air entrainment. This would have limited the effectiveness of an ADV, as it has been shown that even small amounts of air entrainment can create large amounts of noise in the data (Plymesser 2014). As a result, the choice of a preferred baffle spacing was based on the velocity measurements taken along the fishway length.

As stated previously, the 12.7 cm spacing resulted in the highest velocities for all headwater depths and was removed from the analysis. The 25.4 cm and 38.1 cm spacing had very similar velocities. However, a major difference in flow profiles was observed between these two spacings. The 38.1 cm spacing created some minor plunging flows between each baffle and had slight fluctuations in the velocity measurements along the length. The 25.1 cm spacing created a more consistent water surface profile while also reducing the velocities along the fishway floor. Therefore, the 25.4 cm spacing was chosen for the swimming study for two reasons: (1) it created more consistent and lower velocities and (2) it is the same spacing as the standard Denil.

Conclusion

This chapter is a review of the processes used to select Denil fishway scaling factors and baffle spacings. All hydraulic tests were completed in the Hydraulics lab at Montana State University. The 0.6 and 0.75 scale Denil fishways were selected based on a comparison of calculations from three related rating equations created for Denil fishways and the expected turbulence (EDF) based on these flow rates. The baffle spacing portion of the study showed that both the 25.4 cm and the 38.1 cm spacing produced favorable results but the 25.4 cm spacing was ultimately chosen due to it being a field standard for Denil fishways.

CHAPTER 3

ARCTIC GRAYLING (THYMALLUS ARCTICUS) PASSAGE THROUGH A SCALED  
DENIL FISHWAY

Contribution of Authors and Co-Authors

Manuscript in Chapter 3

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

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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.

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

Manuscript Information

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### **Abstract**

Irrigation systems are essential for agriculture but can act as barriers to aquatic species. Small diversions are common in the Big Hole River watershed in Southwest Montana where Arctic grayling, (*Thymallus arcticus*) a state species of special concern, reside. Denil fishways have been installed at diversions throughout the Big Hole River watershed to provide grayling passage. The Denils are “simple” type and standard in size; notably the full-sized Denil is installed at several small tributaries with low flow rates where they can use most of the water. When water is in high demand by agriculture during the summer, these fishways may be partially or completely blocked to ensure sufficient water for irrigation. Conservation agencies have proposed developing smaller Denil fishways for low flow diversions and small streams. This study tested a smaller “scaled” Denil that required less water for operation. The size was selected by analyzing predicted flow rates and considering the swimming mechanics of adult grayling. The model results led to the selection and design of a 0.6 scaled Denil fishway. We used controlled laboratory-based experiments to quantify the effect of eight combinations of headwater and tailwater depths on grayling passage through the 0.6 scaled Denil. Depth treatments were replicated three times for a total of 24 trials with 192 fish tested. Grayling entrance rates ranged from 30-100% and the passage efficiency ranged from 50-100% across all trials. The lowest passage efficiencies occurred when the tailwater depth was three times lower than the headwater depth and the highest passage success occurred when headwater and tailwater depth were closer to equal. The 0.6 scale Denil fishway required less flow for full-flow conditions than the Denil fishways currently in operation and provided high passage efficiency suggesting it may achieve a compromise between fish passage and water allocation at small diversions.

### **Introduction**

The Big Hole River Valley in Southwest Montana, along with the nearby Red Rocks Lakes and Ennis Reservoir, are the last areas within the contiguous United States home to fluvial heritage Arctic grayling (*Thymallus arcticus*) (Peterson and Arden 2009). Private landowners have built irrigation diversions across the tributaries of the Big Hole River to irrigate their land; Montana provides landowners a water right to use water in a prescribed manner. The widespread use of

dams and diversion structures has created highly fragmented habitat throughout the river valley (MFWP and USFWS 2006). Additionally, these irrigation diversions may cause stream dewatering and reduce the available habitat for grayling and other aquatic species (DNRC 2014). Grayling have been shown to migrate long distances (upwards of 80 km) for spawning, feeding and refugia (Shepard and Oswald 1989; Northcote et al. 1995) and these irrigation diversions can impede migration and movement. This disruption may have inhibited the historic recovery of the species (Kaya 1991). In response to an effort to federally list Arctic grayling under the Endangered Species Act, a Candidate Conservation Agreement with Assurances (CCAA) was initiated in order to facilitate conservation and restoration of grayling in 2006 (MFWP and USFWS 2006). Under recommendations provided in the CCAA, Denil fishways have been added to many of the irrigation diversions in the Big Hole River Valley to assist habitat connectivity (Cayer and McCullough 2014). These additions, along with other widely implemented stream restoration techniques, are working toward rebuilding the stressed grayling population in the Big Hole River Valley.



Figure 1: Full scale simple Denil installed at an irrigation diversion and operating during a low flow condition in the Big Hole River Valley.

A Denil fishway is a flume with a rectangular cross-section and V-notched baffles spaced evenly throughout the length (Rajaratnam and Katopodis 1984), as shown in Figures 1 and 2.

The most common Denil fishway used in the Big Hole River Valley has “standard” dimensions, which measures:  $b = 0.56$  m,  $b_a = 0.36$  m,  $c_1 = 0.13$  m,  $c_2 = 0.26$  m and  $a = 0.25$  m (see Figure 2) (Rajaratnam and Katopodis 1984). The baffles in a Denil fishway create regions of reverse flow between baffles and along the side walls of the fishway, which mix with and dissipate the higher energy flows running through the center of the baffles (Rajaratnam and Katopodis 1984; FAO 2002; Odeh 2003). This dissipation creates lower velocity zones along the floor of the fishway, which assist weaker swimming fishes to pass upstream (Rajaratnam and Katopodis 1984; FAO 2002). When depths exceed three times the slot width ( $b_a$ ), the low velocity zone along the baffles is not created and a more linear vertical velocity gradient takes its place (Rajaratnam and Katopodis 1984). Fish passage is often less successful in this scenario, especially for smaller fish (FAO 2002). Understanding the characteristics and functions of a Denil fishway are important in the design of these fishways and scaling them for specific applications.

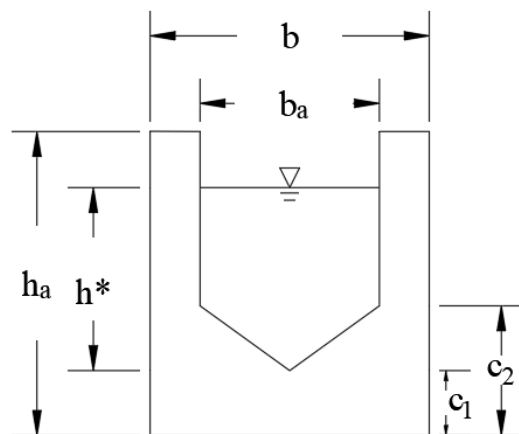


Figure 2. Denil fishway baffle dimensions with notation from Odeh (2003). The “standard” size has dimensions of:  $b = 0.56$  m,  $b_a = 0.36$  m, and  $c_1 = c_2 = 0.13$  m, along with  $h_a$  being fishway height, and  $h^*$  being water depth measured from the V-notch of the baffle. The distance between baffles along the Denil length,  $a$ , is not shown in this graphic.

Due to the snow driven hydrograph and irrigation demands (Lohr et al. 1996; Sladek 2013) low flow conditions are common during the summer months in the Big Hole River Valley. When the water level is low and agriculture demands are high, irrigators will sometimes fully or partially block the fishways so water can be diverted for irrigation instead of flowing through the Denil and continuing downstream (MFWP and USFW 2006). While this practice is not permanent, it can inhibit the natural movement of Arctic grayling and other aquatic species

(MFWP and USFW 2006). Conservation agencies have proposed developing a smaller Denil fishway for low water volume diversions and small streams.

Denil fishway passage efficiency studies have been completed with many species, including Arctic grayling; however, most were observational studies of fishways already installed at dams and diversions and hydrological variables that effect fish passage metrics could not be controlled or manipulated (for example: Fulton et al. 1953; Schwalme et al. 1985; Bunt et al. 1999; Schmetterling et al. 2002; Baumgartner 2006; Mallen-Cooper and Stuart 2007). Laboratory studies of Denil fishways that assess its hydraulics characteristics were also conducted, but these studies were on large fishways and did not test passage efficacy (for example: Rajaratnam and Katopodis 1984; Katopodis 1992; Rajaratnam and Katopodis 1997; Katopodis et al. 1997). Multiple studies conducted in the Big Hole River watershed and at the Bozeman Fish Technology Center (BFTC), strived to connect measured hydraulics and grayling passage in Denil fishways. The conclusions from these studies built an understanding of the grayling's ability to pass a full scale Denil based on flow rate, water depths and swimming speeds (Cahoon et al. 2018; Dockery et al. 2019; Blank et al. forthcoming; Plymesser et al. forthcoming). One of these studies, executed to address reducing flows through the Denils while maintaining passage, considered adding restrictor plates to the upstream end of a simple Denil to reduce the flows (Plymesser et al. forthcoming). The study found that while the Denil flow rates were reduced for some restrictor plate geometries, passage of grayling was diminished for all plates tested. The current study built on these results and reduced flows by building a smaller-scaled Denil instead of adding restrictor plates at the upstream entrance of the fishway.

The objective of this study was to develop and test a smaller-scaled Denil fishway that required less water for operation and could provide passage for Arctic grayling. Published rating curves were used to determine a range of size alternates and aided in the selection of a 0.6 scale Denil fishway. The scaled fishway was then hydraulically tested at the Montana State University hydraulic laboratory to confirm the hydraulic properties required for fish passage were present in the scaled model. Baffle spacing was also analyzed during this testing. The final prototype of the scaled Denil fishway was evaluated in the outdoor flume at the Bozeman Fish Technology Center; grayling were volitionally swum to test passage over a range of flow rates similar to flows measured during previous field studies in the Big Hole River tributaries. The scaled Denil

passage trials followed the standardized framework for fishway evaluation (set forth by Bunt et al. 2012 and 2016) with modifications appropriate to a laboratory-based study. This study was undertaken to develop and improve passage for Arctic grayling, a species of special concern, and to address the water demands of agriculture.

## **Methods**

### **Scaled model selection**

This study began with the design and selection of a scaled Denil fishway geometry that would significantly reduce the flow required to provide upstream passage while maintaining the width required for the full swimming motion of grayling. Established Denil fishway rating equations (Katopodis 1992; Rajaratnum et al. 1997; Katopodis et al. 1997) were used to estimate the ‘full’ flow for a range of scaled Denil fishway geometries. For all calculations, the length and slope of the fishway were held constant at 3.65 m and 8.3%, respectively. The length matched previously studied Denil fishways in the Big Hole River Valley (Triano et al. forthcoming). Scaled fishways were tested at a fixed slope of 8.3% to align with the current installation recommendations for Denil fishways in the Big Hole River Valley (Emily Cayer, former Montana Grayling Recovery Program coordinator, personal communication). Figure 3 provides a comparison of scale sizes and the calculated flow rates at a variety of water depths. The graph compares flows when each scaled Denil V-notch is installed at the same elevation, an important installation recommendation to achieve the desired flow reductions.

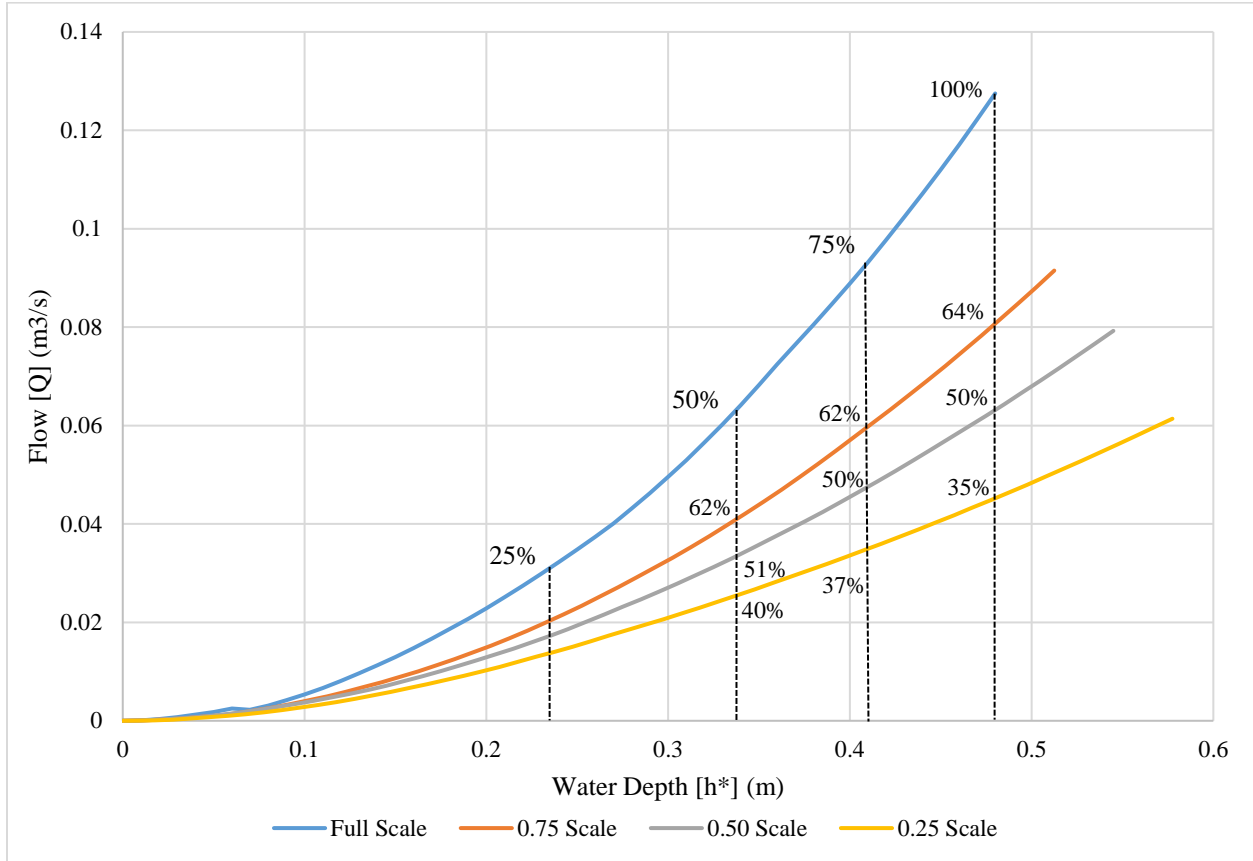


Figure 3. A comparison of the rating curves of the scaled Denil fishways. Each curve is the average of three discharge rating equations (Rajaratnam and Katopodis 1984; Katopodis 1992; Katopodis et al. 1997). The rating curves assume that all fishways would be installed with the same V-notch elevation. Each dashed line provides a comparison between the full scale Denil fishway flow rate at a given water depth and the scaled model flow rate. The percentages represent the flow rate expected through the scaled sizes when compared to the total amount in the full-scale.

The 0.6 scale (referenced as Den60) was selected for use in the swim trials. Den60 exhibited desirable flow characteristics and provided significantly reduced flows at most water depths when compared to the full-scale Denil fishway; while scaling less than 0.6 further reduced flow, there was concern narrower fishways might inhibit the swimming motion of adult grayling. Note, Den60 was built with full scale height walls to test a wide range of flows; this study was not designed to test the optimum height of scaled fishways, as that is a detail that should be left to the fishway designer.

A plywood construction of Den60 was assembled and tested to confirm its hydraulic characteristics and determine optimal baffle spacing. Hydraulic tests and analysis of Den60 were conducted at the hydraulics laboratory at Montana State University. The trials confirmed the Den60 exhibited the lower-velocity zone along the fishway floor necessary to improve fish passage (Rajaratnam and Katopodis 1984; FAO 2002). Baffle spacings of 12.7 cm, 25.4 cm and 38.1 cm were tested for a range of headwater depths ranging from 20.3 to 40.6 cm (see Figures 4, 5, and 6 for examples). Velocity measurements were taken along the centerline of the fishway, with two readings at each measurement location: one high in the water column and one near the V-notch. Figures 4, 5, and 6 provide velocity profiles for each of the baffle spacings tested for the specified headwater depth. These velocity profiles indicated there were no major factors that led us to deviate from the prescribed standard 25.4 cm spacing to create the desired passage conditions. This decision was made based on two factors: (1) the 25.4 cm spacing created consistent flow profiles while the other spacing created streaming and plunging flows through the fishway, and (2) the 25.4 cm spacing matched the standard Denil fishway baffle spacing.

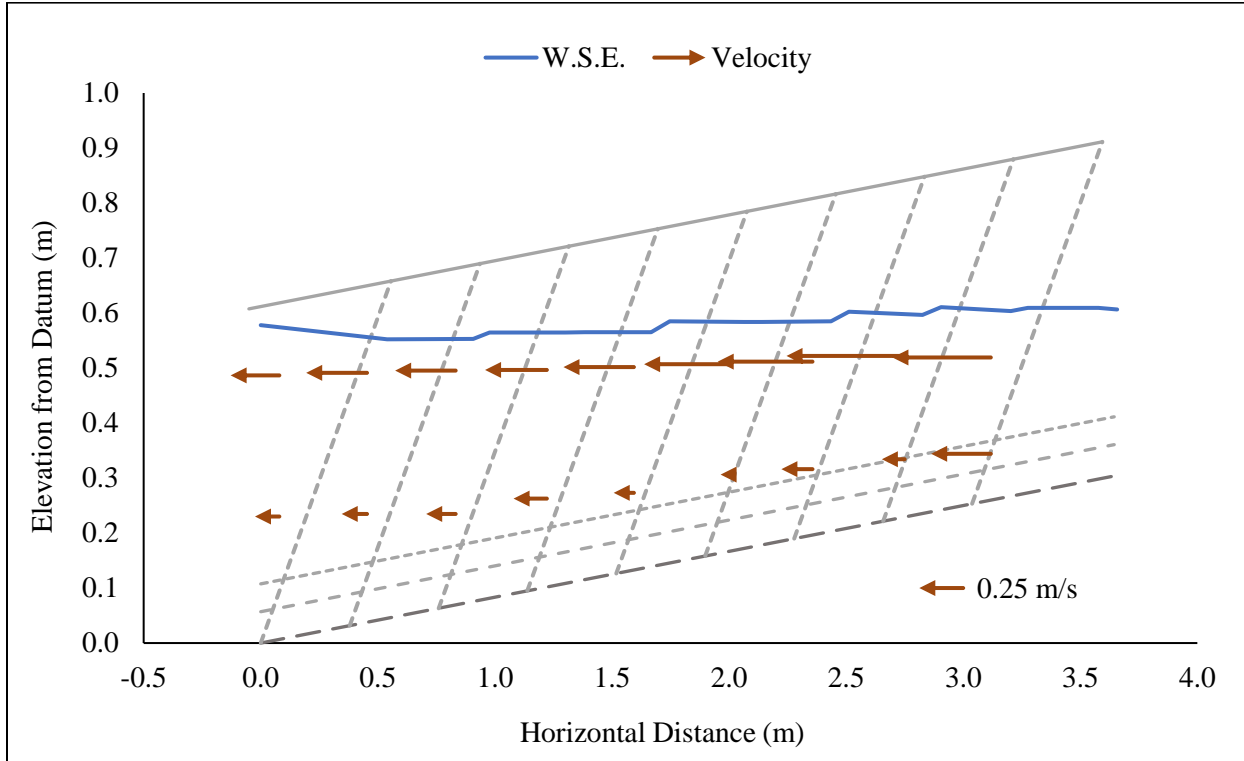


Figure 4. Water surface profile and velocity profile for the 38.1 cm baffle spacing for a 25.4 cm headwater depth. The velocity arrows are scaled by magnitude and are oriented to align with the measurement angle. Velocity measurements were taken along the centerline of the fishway, at 20% and 80% of the water depth, measured from the V-notch of each baffle.

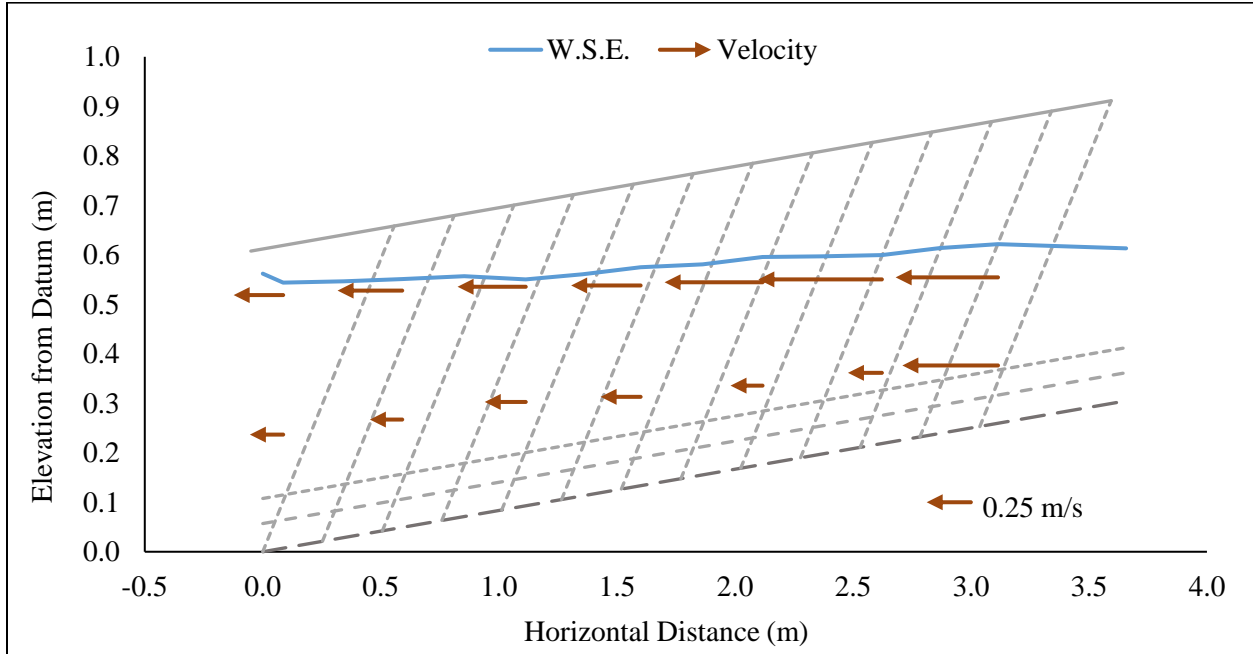


Figure 5. Water surface profile and velocity profile for the 25.4 cm baffle spacing for a 25.4 cm headwater depth. The velocity arrows are scaled by magnitude and are oriented to align with the measurement angle. Velocity measurements were taken along the centerline of the fishway, at 20% and 80% of the water depth, measured from the V-notch of every other baffle.

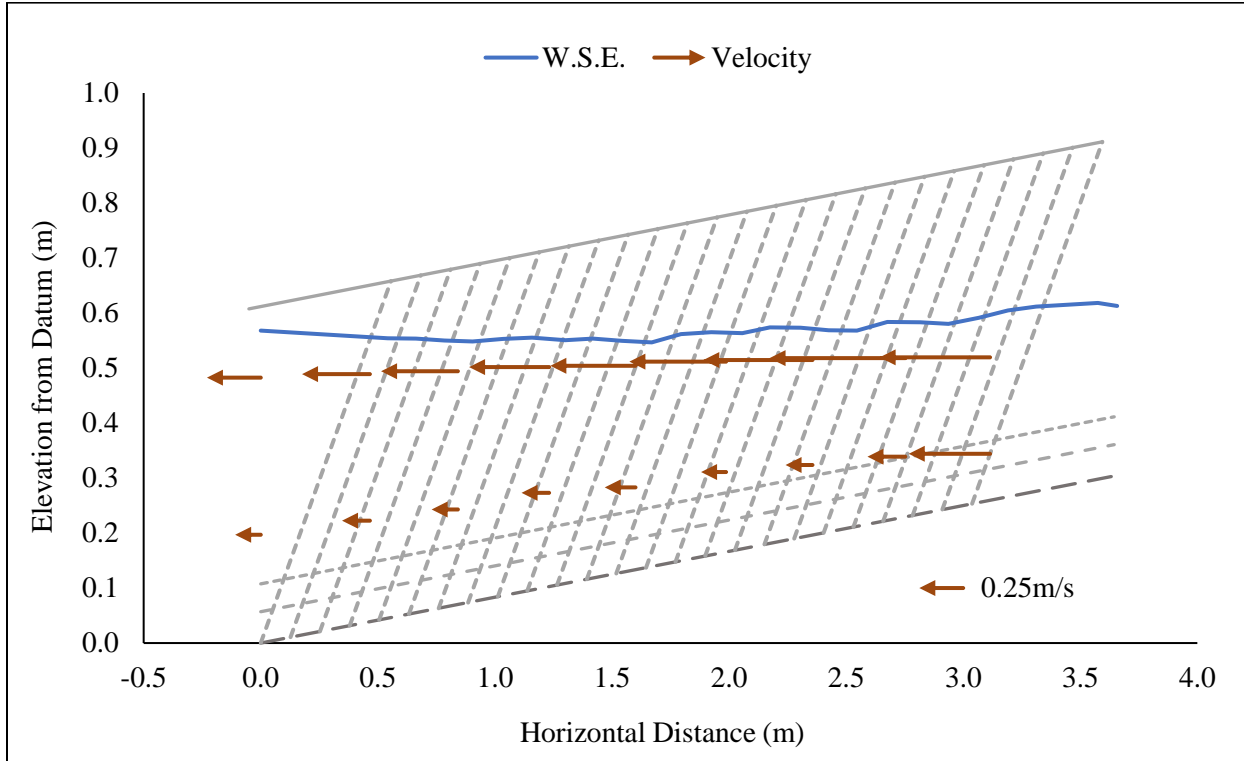


Figure 6. Water surface profile and velocity profile for the 12.7 cm baffle spacing for a 25.4 cm headwater depth. The velocity arrows are scaled by magnitude and are oriented to align with the measurement angle. Velocity measurements were taken along the centerline of the fishway, at 20% and 80% of the water depth, measured from the V-notch of every third baffle.

## Passage trials

### *Flume layout.*

The fish swimming trials were completed in an open channel flume during September and October of 2020 at the United States Fish and Wildlife (USFW) Bozeman Fish Technology Center (BTFC) in Bozeman, MT. The flume was 17.07 m long with windows along one side and a clear inside width of 1.22 m. See Figure 7 for the flume layout. The tailwater chamber contained areas for fish holding and the tailwater depth was regulated via the addition and removal of 0.15-m wooden weir boards along the back and side of the tank. Freshwater from a nearby spring was piped into the headwater and tailwater tanks and recirculated using a three-pump system to create the desired flow rate. Water temperature was regulated through the addition of warm and cool spring water using two separate valves at each of the inflow pipes and the water mixed prior to it entering the flume. During the trials, a tarp was used to cover the

windows of the flume and a UV screen was pulled over the top of the flume to minimize outside disturbance to test fish.

The prototype was placed in the flume with the upstream end 9.75 m from the upstream end of the flume. A headwall and support structure were built at the upstream side of the Denil to ensure an 8.3% slope, matching the discharge rating equation input and the recommendation for field installations in the Big Hole River Valley. Walls were added around the downstream end of the Denil to prevent fish from attempting to swim around the fishway during trials.

A Multi-Antenna HDX Reader (Oregon RFID, Portland OR, USA) passive integrated transponder (PIT) antenna system was used along with a video recording system to record passage through the Denil. A four-antenna array was used to track fish through each trial, similar to Hodge et al. (2017), with alterations to account for a laboratory setting. One antenna was placed 1.22 m downstream of the entrance to the Denil (antenna A) and measured participation, or fish that approached the Denil and became active participants in the trial. A second antenna was placed 0.61 m upstream of the entrance to the Denil (antenna B) and measured entrance, or fish that entered the mouth of the Denil. The third antenna was at the exit or upstream end of the Denil (antenna C) and the fourth sat approximately 4.75 m upstream from the upstream end of the Denil (antenna D). Both antenna C and D were used to measure passage success, or fish that fully ascended the Denil. Detection probability was tested for the antenna system similar to Triano et al. (forthcoming) and the system was calibrated until 100% detection was achieved for the single tag test. A video camera (HandicamHDR-XR-150, Sony, Tokyo, Japan) was placed at the downstream end of the Denil, facing in the upstream direction to visually check for passage attempts and help verify the PIT system readings.

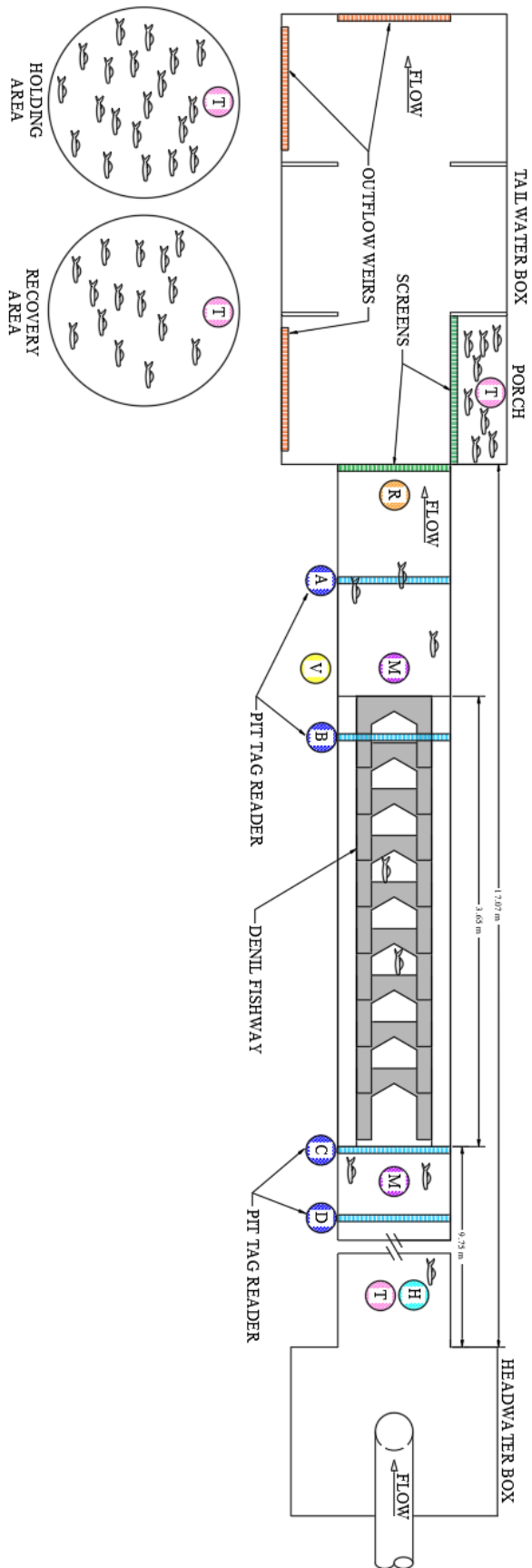


Figure 7: Schematic of the flume at the Bozeman Fish Technology Center. T denotes where temperature readings were taken. H indicates where flow rate was measured when using the USGS Midsection Method. M indicates where staff gages were installed to record water depths. V denotes the location of the video camera. A, B, C, and D correspond to PIT antenna locations. R indicates where fish were released at the start of each trial

*Fish handling.*

Grayling were raised from broodstock collected in 2019 at Axolotl Lake, a spawning tributary of Ennis Lake. The embryos were transported to the Yellowstone River Trout Hatchery in Big Timber, Montana, then moved to the BFTC where they were incubated and reared at 12 °C. Test fish were progressively moved to larger tanks to maintain a density below .023 kg/L. The final tank, a 3-m circumference outdoor tank, was outfitted with a small pump a few weeks before the trials and provided water velocities between 0.0 and 0.9 m/s to build fitness; exercised grayling have been tested and demonstrated abilities similar to their wild counter parts (Cahoon et al. 2018; Dockery et al. 2019). The tank also functioned as the holding tank for the trials. Fish were fed daily via a belt feeder with 3.5 mm feed (Classic Trout; Skretting, Tooele, UT). The water temperature and water velocities of the holding tank were held consistent throughout the study.

To identify individual grayling, 23 mm HDX passive integrated transponder (PIT) tags (OregonRFID, Portland, OR) were inserted into the peritoneal cavity through a small incision between the pelvic fins. Sutures were not required to close the incisions. MS 222 was used to lightly anesthetize the fish prior to tagging, and this was the only time the fish were handled before the start of the experiments. All fish were given at least one week to recover before being included in a trial.

*Experimental treatments.*

Twenty-four trials with eight grayling in each were completed; a summary of the trial conditions is provided in Table 1. The trials consisted of three replicates of eight treatments. The treatments were a combination of four different headwater depths (30.5 cm, 40.5 cm, 51.0 cm, and 61.0 cm) and three different tailwater depths (15.2 cm, 30.5 cm, and 61.0 cm). Trial order was grouped by tailwater depth and the order of headwater depth treatments was determined using a random number generator. There was no control used in this experiment due to a constraint on the number of fish available. Previous experiments at BTFC have also shown that grayling would volitionally swim a flume (Dockery et al., 2019, Blank et al, forthcoming). Each trial was conducted for 18 h, which included an overnight period, as it had been observed in previous field trials in the Big Hole River Valley, grayling preferred to pass fish ladders around dusk (Triano et al. forthcoming).

Table 1. A summary of hydraulic conditions for each swim trial at the BTFC where passage was assessed through a scaled Denil fishway at a variety of headwater and tailwater depths. Bulk velocity at the downstream entrance assumed all flow was channeled through the Denil, the exit cross section was the full width of the fishway, without the baffle constriction, and the tailwater depth was the water depth at this point. Bulk velocity in the swimming channel is from the upstream-most baffle and assumed all flow entered the Denil, the swimming channel was equivalent to the slot width, and the headwater depth was equal to the water depth at the first baffle.

Treatment	Trial	Nominal Headwater Depth (cm)	Nominal Tailwater Depth (cm)	Flowrate (m <sup>3</sup> /s)	Bulk Velocity at Downstream Entrance (m/s)	Bulk Velocity in Swimming Channel (m/s)	Water Temp (C)	Avg Fish Fork Length (mm)
T1	1	30.5	61.0	0.0379	0.185	0.933	13.00	205.5
	2	30.5	61.0	0.0316	0.154	0.778	12.85	212.5
	6	30.5	61.0	0.0229	0.112	0.564	13.30	217.5
T2	14	30.5	15.2	0.0346	0.677	0.852	12.96	207.5
	15	30.5	15.2	0.0332	0.65	0.818	12.52	219.0
	18	30.5	15.2	0.0337	0.66	0.83	12.22	235.0
T3	20	30.5	30.5	0.0349	0.341	0.859	11.68	208.5
	22	30.5	30.5	0.0338	0.33	0.832	12.48	214.0
	23	30.5	30.5	0.0336	0.328	0.827	12.53	201.0
T4	4	40.5	61.0	0.0521	0.254	0.838	13.20	207.0
	8	40.5	61.0	0.0435	0.212	0.699	13.55	214.0
	10	40.5	61.0	0.0367	0.179	0.59	13.91	215.5
T5	3	50.9	61.0	0.0748	0.365	0.883	13.20	233.0
	11	50.9	61.0	0.0794	0.387	0.938	13.90	229.5
	12	50.9	61.0	0.0797	0.389	0.941	13.47	197.0
T6	5	61.0	61.0	0.1121	0.547	1.053	13.55	232.0
	7	61.0	61.0	0.1104	0.539	1.037	13.25	203.5
	9	61.0	61.0	0.1024	0.5	0.962	13.67	199.5
T7	13	61.0	15.2	0.1241	2.43	1.165	13.04	217.5
	16	61.0	15.2	0.1218	2.385	1.144	12.14	218.5
	17	61.0	15.2	0.1199	2.348	1.126	12.02	216.0
T8	19	61.0	30.5	0.1247	1.217	1.171	12.20	208.0
	21	61.0	30.5	0.1246	1.216	1.17	11.82	219.5
	24	61.0	30.5	0.1143	1.115	1.073	11.77	201.0

### *Trial process.*

Twenty-four hours prior to the start of a trial, eight fish were moved from the circular holding tank to the porch area in the flume, which measured 2.44 m by 0.53 m (See Figure 7). The fish

were not fed during this period. Before being placed in the porch, each fish was scanned using a Destron Fearing 601 Handheld reader (Destron Fearing, DFW Airport, TX) or a HPR Lite (Biomark, Boise, ID) PIT tag reader to ensure the fish had a functioning PIT tag.

Before the start of each trial, the pump was turned on and the system equilibrated for approximately 20 minutes. Then, UV screens were pulled over the top of the flume to keep light levels consistent and reduce any external auditory or visual influence on the fish. The HD camcorder and the PIT system were turned on and calibrated using a spare 23 mm HDX tag attached to the end of a meter stick which was moved within the video camera view and within range of the B antenna in quick succession. This allowed the video footage to be synced with the PIT tag data at a later point if there were any discrepancies when analyzing the data.

At the trial start, fish were collected from the porch and released into the trial area, at the location noted in Figure 7, where they remained for 18 hours to volitionally pass the Denil without disturbance. At the end of the trial, screens were inserted at the upstream and downstream end of the Denil fishway to prevent any further fish movement. Fish were then individually caught, and fork lengths were recorded. The location of capture was also noted (above, below or within the Denil). Fish were then moved to a recovery tank for the remainder of the experiment. Each fish was only used in one trial for this study.

#### *Data collection.*

Once each hydraulic configuration achieved equilibrium, the water depth, temperature, and flow rate were measured in the flume, at the locations noted in Figure 7. Water depths were measured at the upstream and downstream end of the Denil, using staff gauges attached to the head and tail walls. Temperature was measured using an Ertco-Eutenchnics Model 4400 digital thermometer (Alpha Technics Oceanside, CA). Readings were taken in three locations: in the flume upstream of the Denil, in the tailwater tank, and in the fish holding tank. Additional temperature readings were also intermittently taken in the fish recovery tank to ensure consistency. Water depths and temperatures were also recorded at the end of each trial.

Flow rate was measured before each trial began using one of two methods: the USGS Midsection Method (Rantz 1982; Rantz & Peck 1982) or using a Signet 2540 Paddlewheel flow sensor (GF Piping Systems, Schlaffhausen, Switzerland) installed in the recirculation supply pipe. The cross section used for all Midsection Method measurements was 7.30 m upstream from

the Denil fishway, as noted in Figure 7. For the Midsection method, a Hach FH950 Portable Velocity Meter (Hach Corp., Loveland, CO) and a top-setting wading rod were used to obtain 40-s time-averaged velocities at vertical subsections across the flume width. The paddlewheel flowmeter took continuous 2-min time-averaged flow rates and provided updated readouts every two seconds. Five readouts from the flywheel flowmeter were recorded, and the average of these measurements was calculated to obtain the flow rate in the flume. For six of the 24 trials, both flow rate methods were used and the average difference between these methods was 6.8%.

#### *Data analysis.*

Data from the Multi-Antenna HDX Reader were downloaded onto a computer and Microsoft Excel was used to analyze fish passage success. The PIT antenna system recorded fish movement by creating an entry each time a fish moved within the range of an antenna. The data was reduced to look for the points where each fish became a participant in the trial (A), entered the Denil (B), and passed the Denil (C and/or D) for the first time. The clock times associated with these points were extracted from the data. There were several fish that moved up and down the length of the fishway multiple times during the trial period, but only the first passage was noted in this study. As a quality check, the data from each trial were reviewed to look for irregularities, which could include the same tag being read by two different antenna at the same time or a tag being recorded at antenna in a non-sequential order. The antenna entries near the irregularity were used to verify fish location and passage metrics, if these occurred. Video recordings were also used to verify entrance if the movement occurred during daylight hours.

The data were combined for each trial to create participation, entrance, and passage metrics. A fish was a participant if it was recorded by the downstream antenna (A). An entrance success was a fish that entered the Denil and was detected by the antennae inside the Denil (B). A successful passage was defined as a fish that swam upstream through the entire structure, exited the top of the Denil, and was recorded by the upstream antennae (C and D). A fish that did not become a participant in the trial would not be considered in the entrance success metric. A fish that failed to enter the Denil would not be considered in the passage success metric. Finally, overall passage success was also determined based on number of participant fish in the trial, no matter how far the fish moved up the fish ladder.

Bulk velocity was calculated for each trial based on the measured flow rate, water depth and cross-sectional area of the fishway. Entrance velocity, or the velocity at the downstream end of the fishway where fish entered the Denil, was based on the measured tailwater depth and the full width of the fishway. Swimming channel velocity, or the velocity felt by a fish while ascending the fishway, was based on the measured headwater depth and the slot width of a baffle. The calculated bulk velocities can be seen in Table 1.

## **Results**

### **Swim Trial Hydraulic Conditions**

The average flow rate over all trials was 0.0715 m<sup>3</sup>/s. The average flow rate for trials with a 30.5 cm headwater depth was 0.0329 m<sup>3</sup>/s, 0.0441 m<sup>3</sup>/s for trials with a 40.5 cm headwater depth, 0.078 m<sup>3</sup>/s for trials with a 50.9 cm headwater depth and 0.1172 m<sup>3</sup>/s for trials with a 61.0 cm headwater depth. The flows measured during the swimming study trials were used to develop a rating curve for Den60 (Figure 8). The average bulk velocity in the swimming channel with a 30.5 cm headwater depth was 0.810 m/s, 0.709 m/s for the 40.5 cm headwater depth, 0.921 m/s for the 50.9 cm headwater depth and 1.100 m/s for the 61.0 cm headwater depth. The headwater depth varied by ±0.53 cm for the 30.5 cm headwater trials, ±1.7 cm for the 40.6 cm headwater trials, ±2.1 cm for the 50.8 cm headwater depth trials, and ±1.9 cm for the 61.0 cm headwater trials. The tailwater depth varied by ±8.0 cm for the 61.0 cm tailwater depth trials, ±7.2 cm for the 30.5 cm tailwater depth trials, and ±7.8 cm for the 15.2 cm tailwater depth trials.

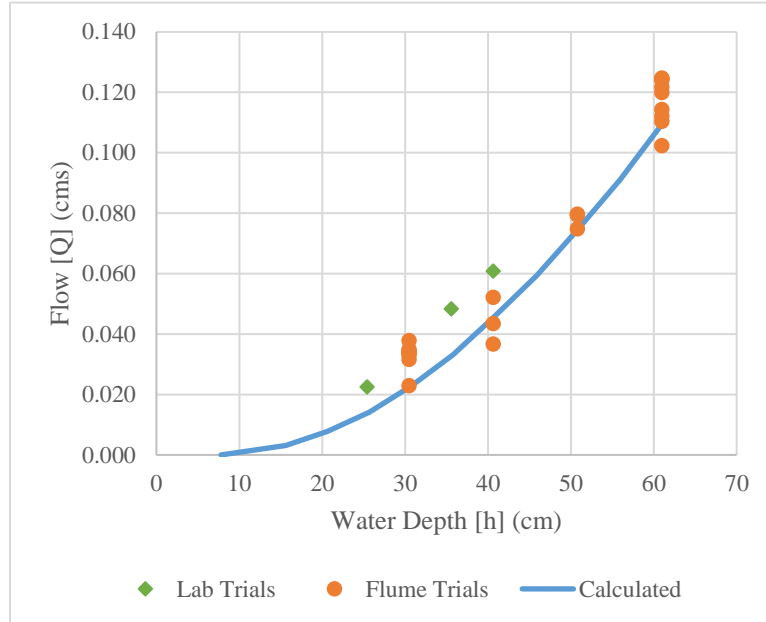


Figure 8. Rating curve for Den60 using flow rates and water depths collected during fish swimming trials (circular points) and hydraulic testing (diamond points). The calculated line is the average of the three discharge rating equations used during scaled model selection (Rajaratnam and Katopodis 1984; Katopodis 1992; Katopodis et al. 1997), with the Den60 dimensions used as inputs.

### Passage Efficiency

Of the 192 fish used for this study, two were removed from the trials after they began; one was removed for tail damage that occurred during the 24-hour holding period prior to the trial start and the second due to predation during the trial. The participation, entrance, and passage rates, as well as the overall passage rate, are shown in Table 2 along with the headwater and tailwater depths, flow rate, and bulk velocity for each trial. There was 100% participation among the remaining fish for all 24 trials. The entrance rate varied between 30.4% and 100%, with the lowest entrance occurring in the nominal 15.2 cm tailwater depth trials (T2 and T7). The overall passage, based on total participant fish, for all trials was 83.7%. The percent passage of fish that entered the fishway was 94.6%, with the lowest passage occurring in the nominal 15.2 cm trial. Of the 96 fish that were part of treatments with a 61.0 cm tailwater depth (T1, T4, T5 and T6), 99% successfully passed the Denil. For the treatments with a 30.5 cm tailwater depth (T3 and T8), 92.7% passed and for treatments with the 15.2 cm tailwater depth (T2 and T7) the passage

success was 64.3%. Figure 9 summarizes the passage percentages based on headwater and tailwater depths for each treatment.

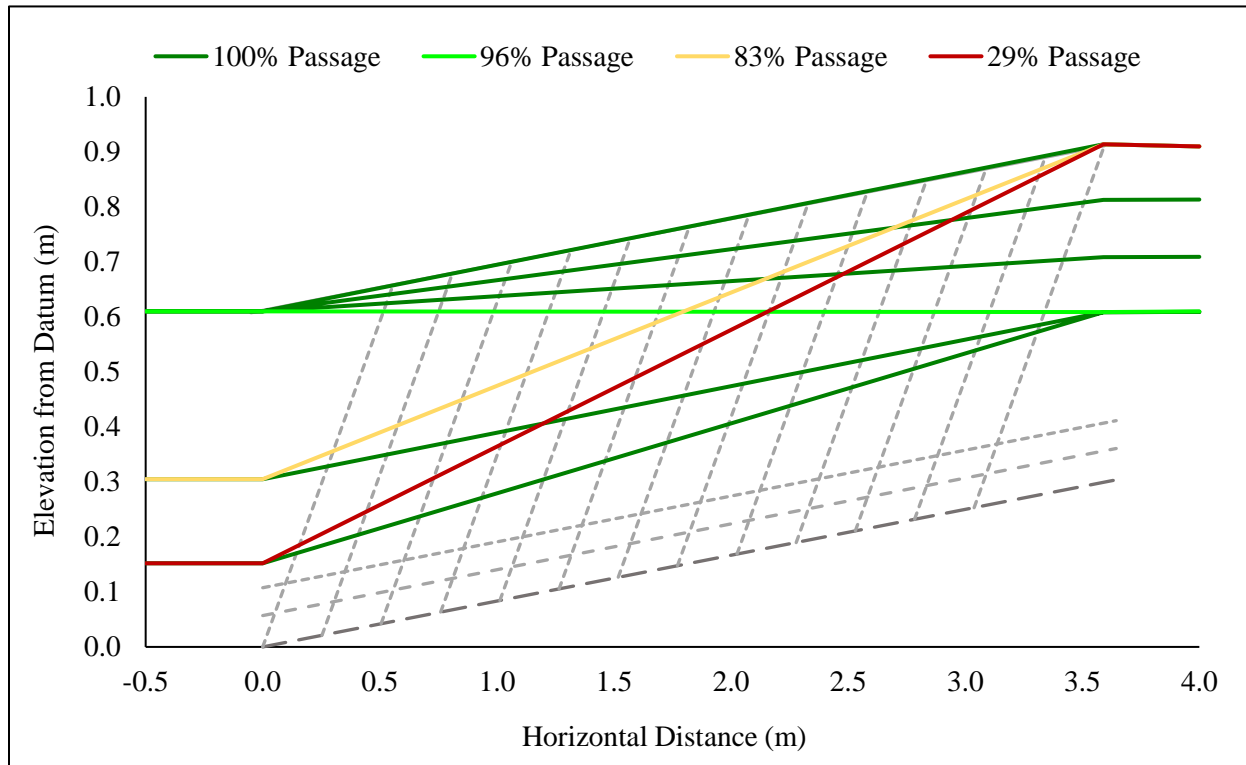


Figure 9. Passage results based on headwater and tailwater depths for each treatment. Each colored line represents a treatment detailed in Table 2. The dashed lines provide scale of treatment depths versus the prototype Den60. Each color represents the average passage for each treatment, with dark green being the highest passage and red being the lowest.

Table 2. A Summary of fishway efficiencies over all swimming trials. Trials are grouped into treatment type based on headwater and tailwater depth. Bulk velocity in the swimming channel is based on the water depth at the upstream end of the fishway and the slot width of a baffle. Participation rate is the number of fish that passed the (A) antenna divided by the fish released into the flume. Entrance rate is the fish that passed the (B) antenna divided by the fish that passed the (A) antenna. The passage rate is the fish that ascended the fishway and passed the (C) or (D) antenna divided by the fish that passed antenna (B). Overall success is the number of fish that ascended the fishway divided by the total number of fish in each trial.

Treatment name	Trial Number	Headwater Depth (cm)	Tailwater Depth (cm)	Flow rate (m <sup>3</sup> /s)	Bulk Velocity in Swimming Channel (m/s)	Participation Rate	Entrance Rate	Passage Rate	Overall Passage Rate
T1	1	30.5	53.0	0.0379	0.933	1.00	1.00	1.00	1.00
	2	30.4	53.0	0.0316	0.778	1.00	1.00	0.88	0.88
	6	30.4	53.6	0.0229	0.564	1.00	1.00	1.00	1.00
T2	14	31.0	15.2	0.0346	0.852	1.00	1.00	1.00	1.00
	15	31.0	15.8	0.0332	0.818	1.00	1.00	1.00	1.00
	18	30.4	15.8	0.0337	0.830	1.00	1.00	1.00	1.00
T3	20	30.4	28.6	0.0349	0.859	1.00	1.00	1.00	1.00
	22	30.4	28.6	0.0338	0.832	1.00	1.00	1.00	1.00
	23	30.4	29.2	0.0336	0.827	1.00	1.00	1.00	1.00
T4	4	38.9	56.0	0.0521	0.838	1.00	1.00	1.00	1.00
	8	40.2	58.8	0.0435	0.699	1.00	1.00	1.00	1.00
	10	39.5	56.6	0.0367	0.590	1.00	1.00	1.00	1.00
T5	3	48.7	57.8	0.0748	0.883	1.00	0.88	1.00	0.88
	11	49.9	59.7	0.0794	0.938	1.00	1.00	1.00	1.00
	12	49.3	59.7	0.0797	0.941	1.00	1.00	1.00	1.00
T6	5	60.0	63.3	0.1121	1.053	1.00	1.00	1.00	1.00
	7	60.9	63.3	0.1104	1.037	1.00	1.00	1.00	1.00
	9	60.6	63.3	0.1024	0.962	1.00	1.00	1.00	1.00
T7	13	59.1	19.4	0.1241	1.165	1.00	0.14	0.00	0.00
	16	59.1	23.1	0.1218	1.144	1.00	0.25	0.00	0.00
	17	59.1	22.5	0.1199	1.126	1.00	0.50	0.50	0.25
T8	19	59.4	37.7	0.1247	1.171	1.00	0.86	1.00	0.86
	21	61.0	37.7	0.1246	1.170	1.00	0.88	0.86	0.75
	24	60.3	37.7	0.1143	1.073	1.00	0.63	0.60	0.38

## Discussion

Through preliminary hydraulic analysis and further validation via laboratory testing, this study showed a 0.6 scale Denil fishway creates similar hydraulic conditions to a full-scale standard Denil fishway, while reducing flows by up to 44%. Installing scaled fishways in a way that

maintains the same V-notch elevation as a full scale Denil fishway is important to provide the flow reductions seen in this study. The baffle spacing analysis confirmed the standard 25.4 cm spacing provided the optimal hydraulic conditions when looking at centerline velocities and water surface elevations. The FAO (2002) noted this spacing as important to Denil hydraulics and deviating drastically changes the characteristics of the fishway, as the current study reiterated. While not described herein, an additional 0.75 scale prototype was also built and hydraulically tested, finding the same hydraulic conditions as the 0.6 scale fishway. The larger prototype was not used during swimming trials due to the high success of the 0.6 scale Denil fishway. This analysis and verification of hydraulic characteristics provides support to prototype additional scaled Denil fishways and confirms the discharge equations used to calculate flow through the fishways created an accurate representation of results for scaled Denil fishways.

### Scaled Denil Passage

The results of the swim study showed that Grayling volitionally pass Den60 when the tailwater depth was full (61.0 cm), with 99% of all grayling passing the Denil. It has previously been shown that Grayling pass Denil fishways with high levels of success when the tailwater is high in both laboratory studies (Blank et al. forthcoming) and in the field (Triano et al. forthcoming). This study echoed that trend, even as the width of the swimming channel was reduced to 60% of the standard width.

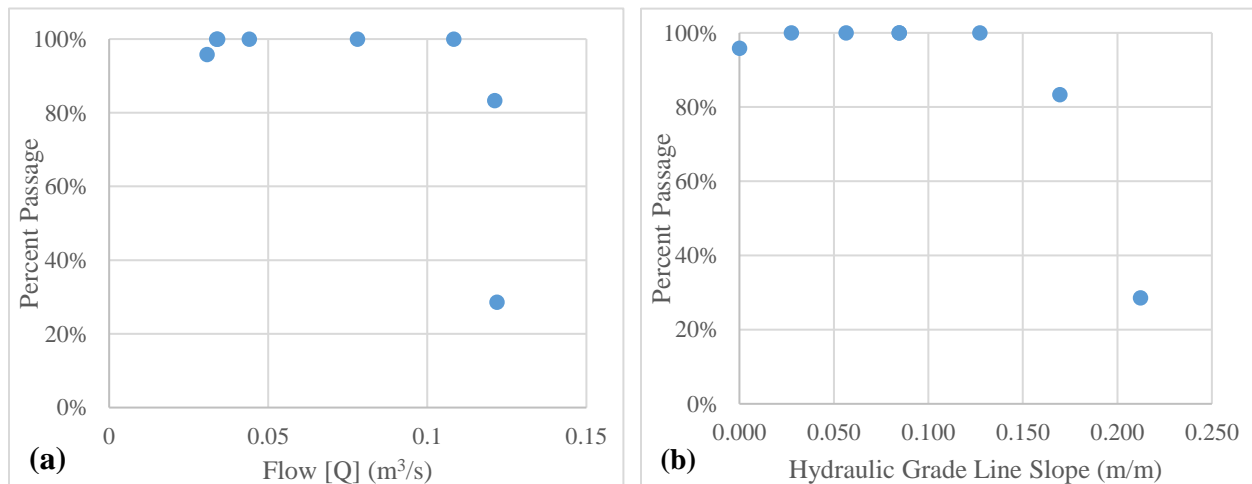


Figure 10: Two graphs showing (a) flow and (b) hydraulic grade line slope versus percent passage. These graphs show a near linear trend at 100% passage with two treatments showing lower passage percent as the flow and hydraulic grade line slope increased.

In contrast, as the tailwater decreased, the entrance and passage percentages also decreased, especially when the headwater was at least half full (31.5 cm and above). This scenario created the steepest hydraulic grade line (or water surface profile) slope for all treatments, meaning the slope of the water surface along the length of the fishway is an important factor in grayling passage (see Figure 9). This can easily equate to water depth ratios between the upstream and downstream pools, with passage decreasing as this ratio increases. Additionally, when the head difference was largest, plunging flows were noticed throughout the Denil, possibly creating unsuitable passage conditions. When plotting percent passage against hydraulic grade line slope, flow and other hydraulic characteristics, there were no statistical trends observed (Figure 10). The data points showed high passage until the flow rate and hydraulic grade line slope increased to the maximum seen in all trials. These results provide incentive to continue pursuing scaled fishways as a possible solution to balancing irrigation demands with aquatic species passage, especially during lower flows.

### **Future considerations**

We conducted 18-hour trials which showed 57.6% of initial successful passage occurred around dusk, a behavior that was noted in field trials with grayling (Triano et al. forthcoming) but laboratory-based swimming studies are often too short in duration to assess this metric. The current study was not designed to test the time of passage, but it was an interesting observation that will influence the design of further laboratory-based studies of grayling.

This study was limited in scope due to the onset of winter weather and fish availability. While this study found promising results, it did not consider multiple variables that may affect passage in a natural setting. These included fish age and size class, slope of fishway, and minimum possible size. We used age 1+ grayling with an average length of 21.4 cm for the study, which was expected for the age class but not the largest lengths seen in Montana, where grayling can be as large as 35.5 cm (Brown 1971). Additionally, it is common for the Big Hole population of grayling to live for up to five years (Liknes 1987). Ideally, a range of sizes and ages would be included in further testing to ensure a scaled Denil fishway provides passage for all life stages of grayling. Secondly, only one slope (8.3%) was used to maximize the number of flow conditions that could be tested, while Denil fishways installed in the Big Hole River Valley range in slope from 0.6% to 19.9% (Triano et al. forthcoming). Further studies on the scaled

Denil should include fishways with varied slopes to better replicate all conditions found in the Big Hole River Valley. Finally, while the Den60 created excellent passage conditions, the results also suggested that this was not the smallest scale that grayling would pass with high success. Additional studies to understand the smallest fishway that creates acceptable passage rates should be conducted if additional flow reduction is desired, noting concern that reducing the slot width further could deter entrance for larger fish. This, along with considerations of attraction flow and operating range, should be considered if a smaller scale fishway is tested.

This study was designed to answer questions about scaled Denil fishway efficiency for a specific location and species but a smaller Denil fishway could be used in agricultural valleys with salmonid populations and heavy irrigation impacts across the western United States. This preliminary study provided a possible solution to meet irrigation demands and improving habitat connectivity for grayling, a species of concern.

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## CONCLUSION

This study was undertaken to understand the hydraulics and passage efficacy of a small scale Denil fishway. The motivation for designing and studying smaller scale Denil fishways was to improve habitat connectivity for native fish species in southwest Montana while also maintaining sufficient water for irrigation. Using a small scale Denil in place of a standard Denil in irrigation diversions is one way to reduce the water required for the fishway to be operational, which would lead to more water being available for diversion. This study was the continuation of previous research at MSU and the BTFC to alter Denil fishways to reduce flows while still providing adequate fish passage. This study consisted of two parts: hydraulics testing of the scaled Denil models and a fish passage study using Arctic grayling.

The study began with an analysis of possible scale sizes and corresponding flow rates and was performed using three discharge rating equations. The goal was to find a Denil scale that would significantly reduce the flow rate while also not impeding grayling's natural swimming motion. The 0.6 and 0.75 scale were selected to be built and hydraulically tested.

Hydraulic testing of both scaled Denils took place at the MSU hydraulics lab. Flow rates, velocities and water surface elevations were measured for each Denil for combinations of headwater depths and baffle spacing. The results of these tests led to the selection of 25.4 cm baffle spacing for both Denil scales.

The fish passage portion of this study was completed at the Bozeman Fish Technology Center. The new fiberglass and concrete outdoor flume was used for the trials. Arctic grayling, a species of concern in Montana, was used for the studies. Twenty-four 18-hour trials were completed using eight different treatments. Each treatment consisted of a different combination

of headwater and tailwater depths. Flow rate, water depths and temperatures were taken prior to each trial. These trials provided insight into grayling's ability to pass smaller scaled Denil fishways.

This study concluded that grayling passed the scaled Denil with high success at all headwater and tailwater combinations tested except those where the hydraulic grade line slope was at its maximum. Additionally, most of the passage occur around dusk and the least amount occurred at night. This was similar to the findings of a field study of grayling that occurred in the Big Hole River Valley (Triano et al. forthcoming).

This study provided promising results that could both appease irrigators in the Big Hole River Valley and allow more passage days per year. Additionally, this study suggests the scaled Denil size selected for the fish swimming trials was not the smallest possible Denil that would provide adequate passage and further studies of even smaller scaled Denils should be considered. Finally, this study was performed using one fishway slope. The fishway slope varies greatly within the Big Hole Valley and should be considered in future work. Overall, this study indicated that smaller Denils are a viable option for grayling, but should be researched further before large-scale implementation occurs.

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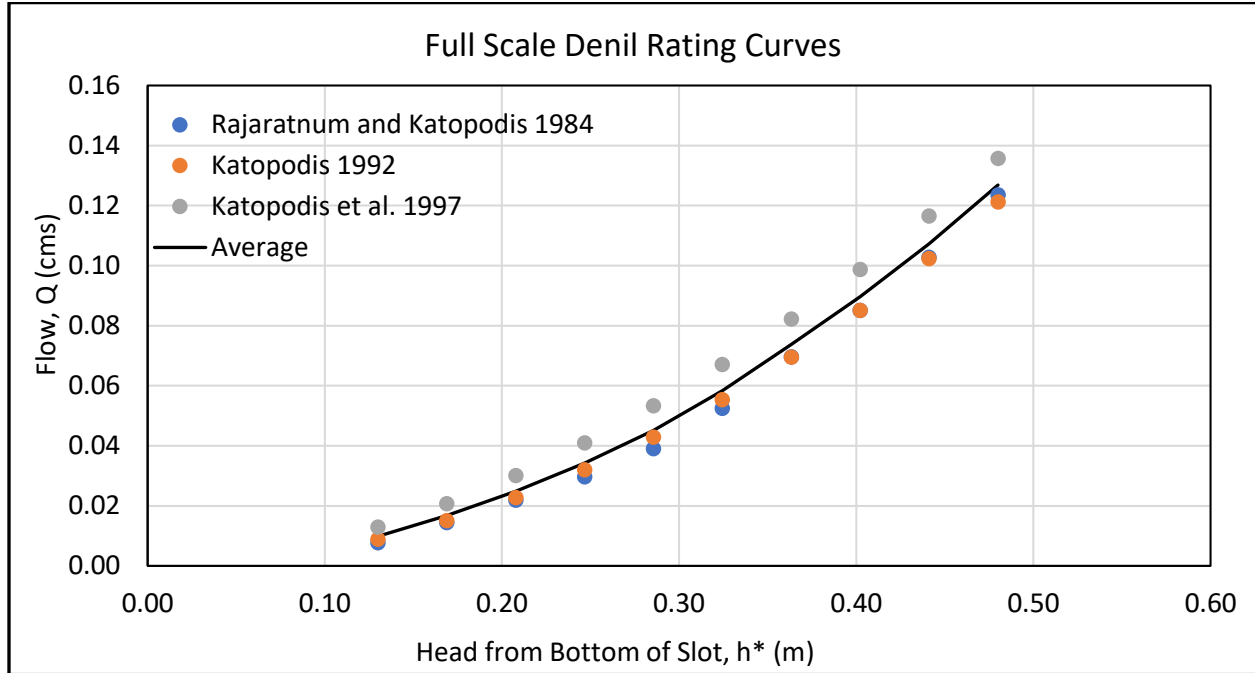
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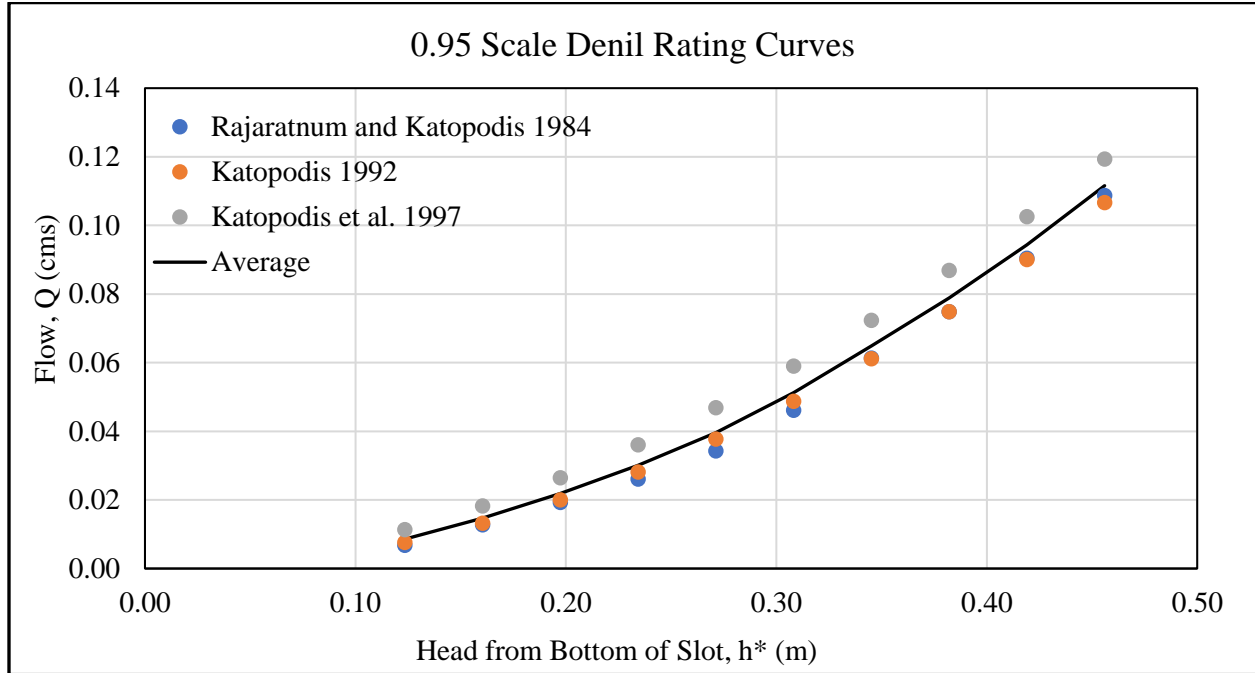
APPENDICES

APPENDIX A

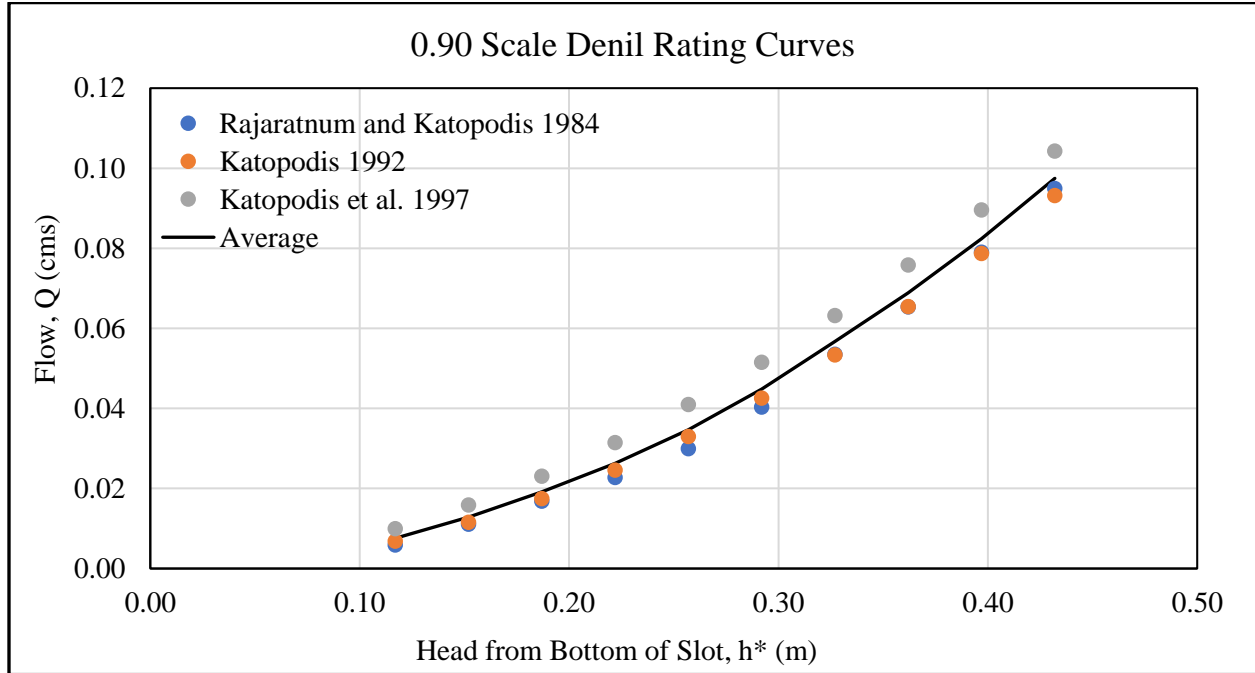
RATING CURVES FOR SCALED DENILS



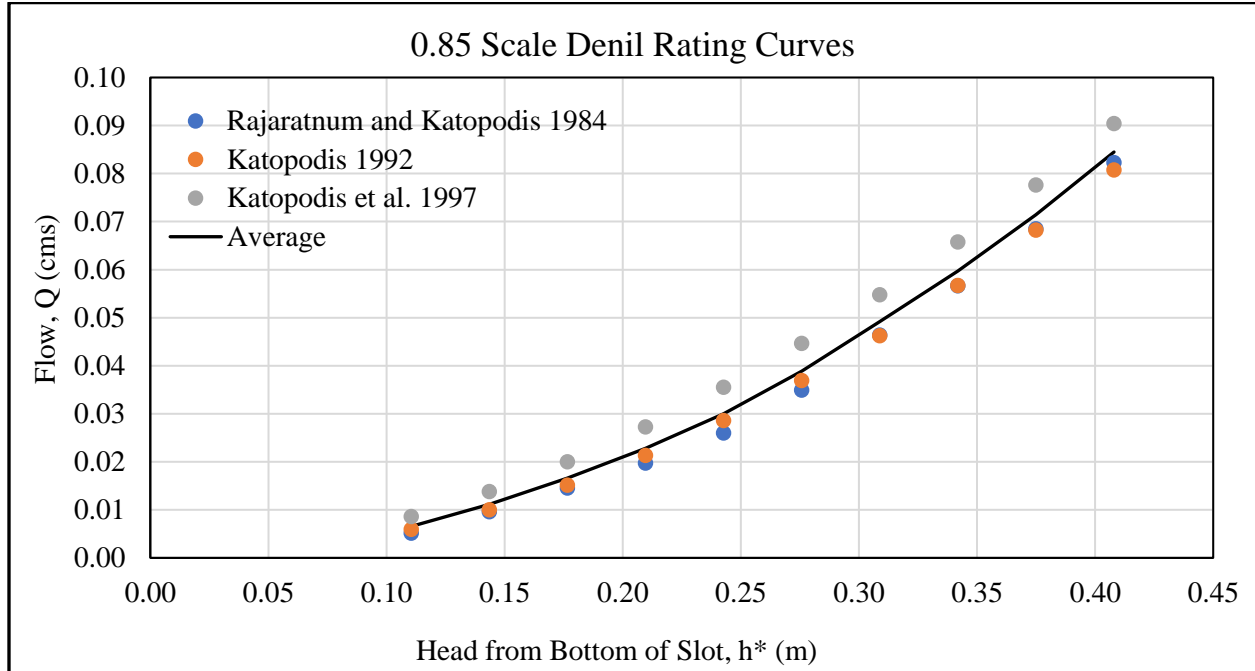
Rating curves for the full scale Denil using three discharge equations (Katopodis 1992; Rajaratnum et al. 1997; Katopodis et al. 1997). Each equation is plotted separately and an average line was added to the data. The farthest right point on the average line was taken as the maximum expected flow through the Denil fishway.



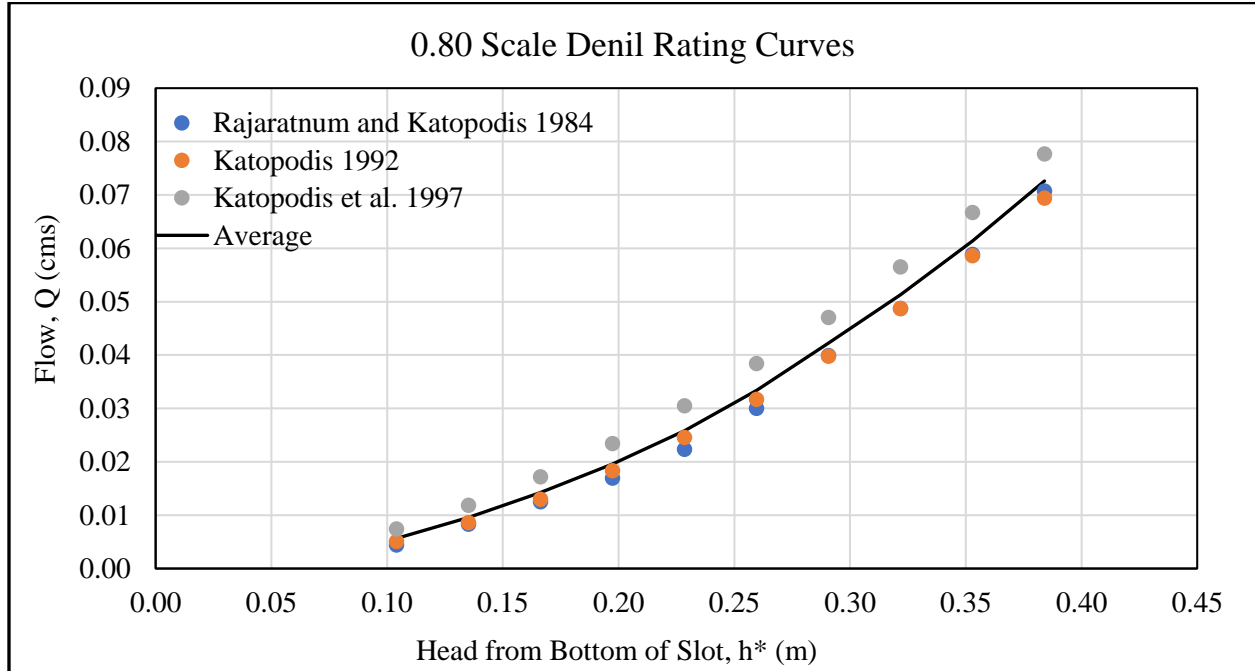
Rating curves for the 0.95 scale Denil using three discharge equations (Katopodis 1992; Rajaratnum et al. 1997; Katopodis et al. 1997). Each equation is plotted separately and an average line was added to the data. The farthest right point on the average line was taken as the maximum expected flow through the Denil fishway.



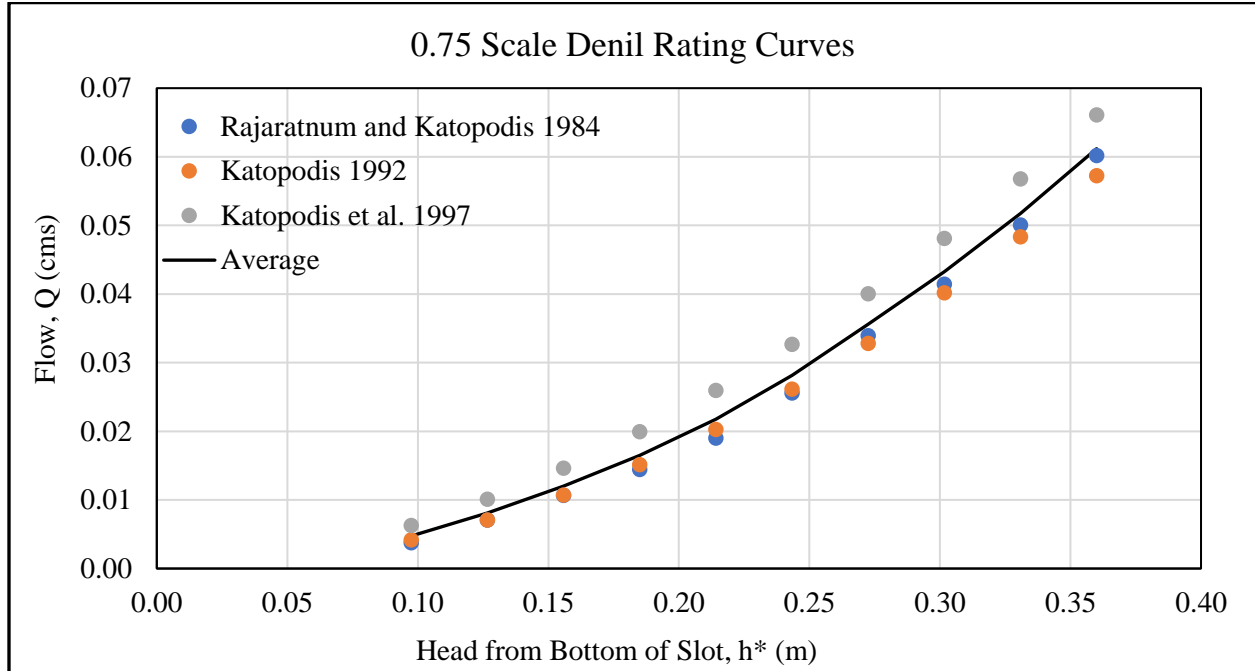
Rating curves for the 0.90 scale Denil using three discharge equations (Katopodis 1992; Rajaratnum et al. 1997; Katopodis et al. 1997). Each equation is plotted separately and an average line was added to the data. The farthest right point on the average line was taken as the maximum expected flow through the Denil fishway.



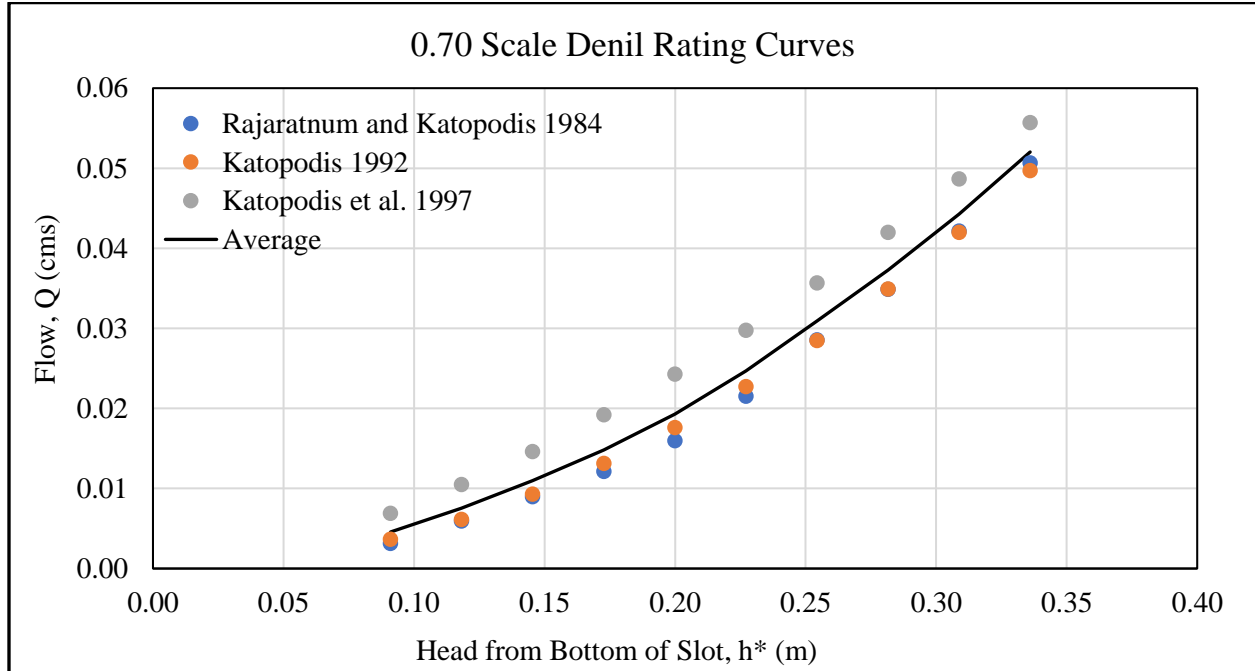
Rating curves for the 0.85 scale Denil using three discharge equations (Katopodis 1992; Rajaratnum et al. 1997; Katopodis et al. 1997). Each equation is plotted separately and an average line was added to the data. The farthest right point on the average line was taken as the maximum expected flow through the Denil fishway.



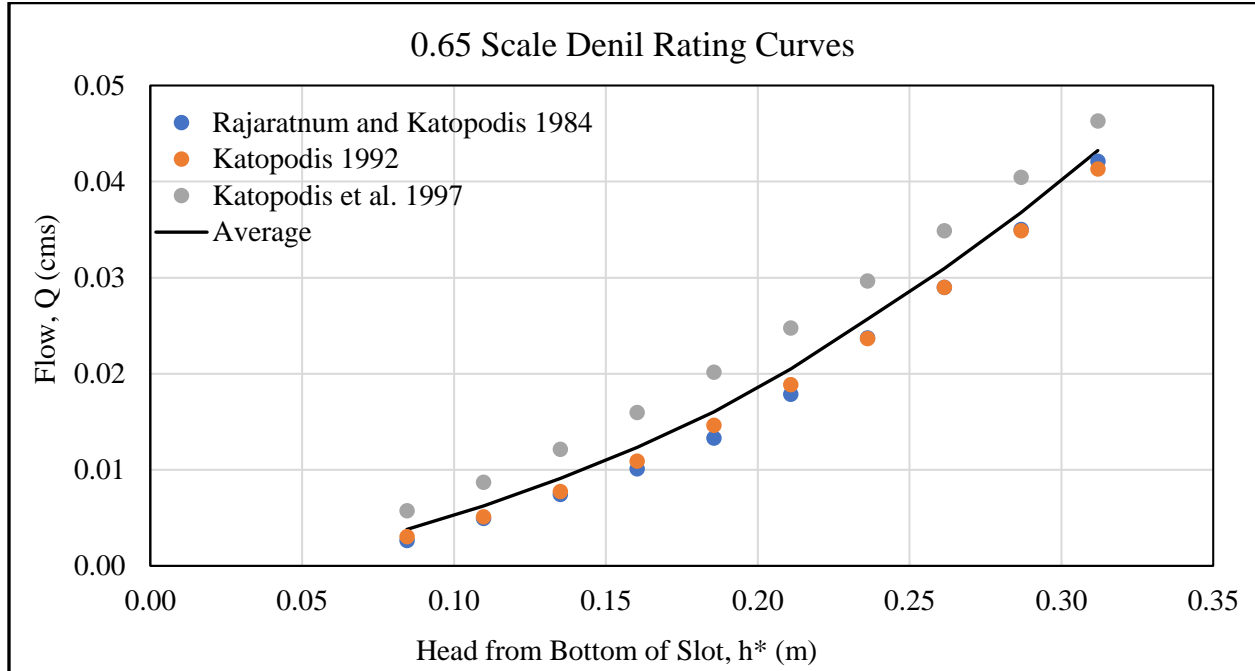
Rating curves for the 0.80 scale Denil using three discharge equations (Katopodis 1992; Rajaratnum et al. 1997; Katopodis et al. 1997). Each equation is plotted separately and an average line was added to the data. The farthest right point on the average line was taken as the maximum expected flow through the Denil fishway.



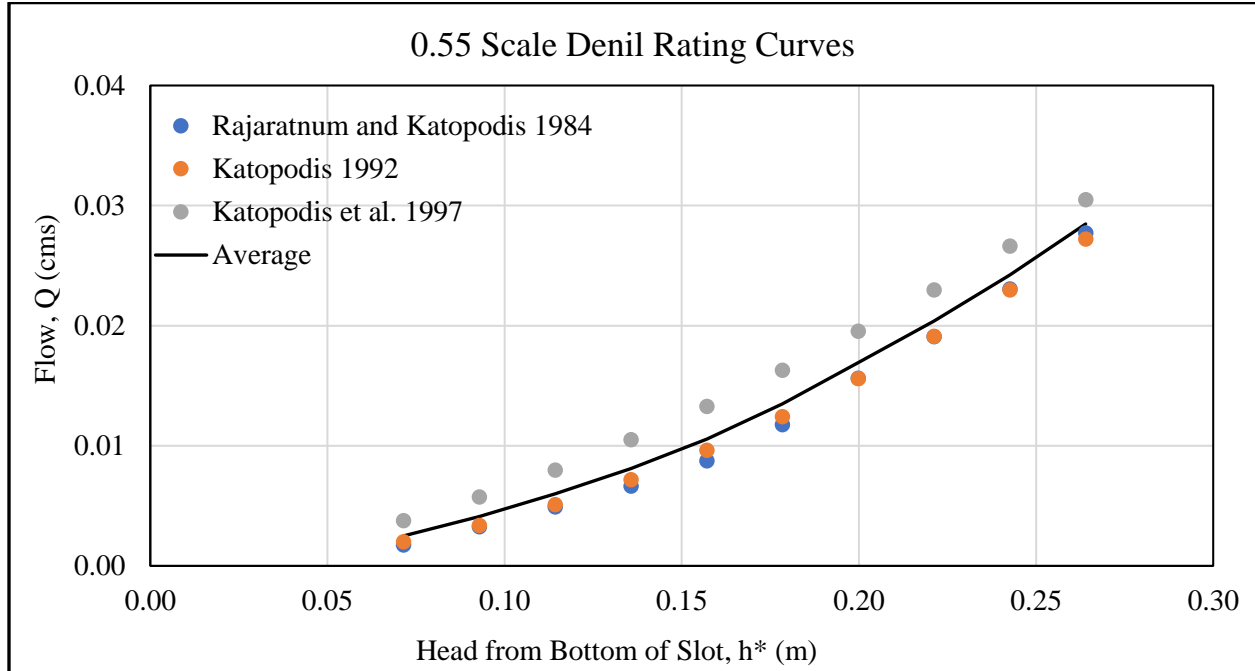
Rating curves for the 0.75 scale Denil using three discharge equations (Katopodis 1992; Rajaratnum et al. 1997; Katopodis et al. 1997). Each equation is plotted separately and an average line was added to the data. The farthest right point on the average line was taken as the maximum expected flow through the Denil fishway.



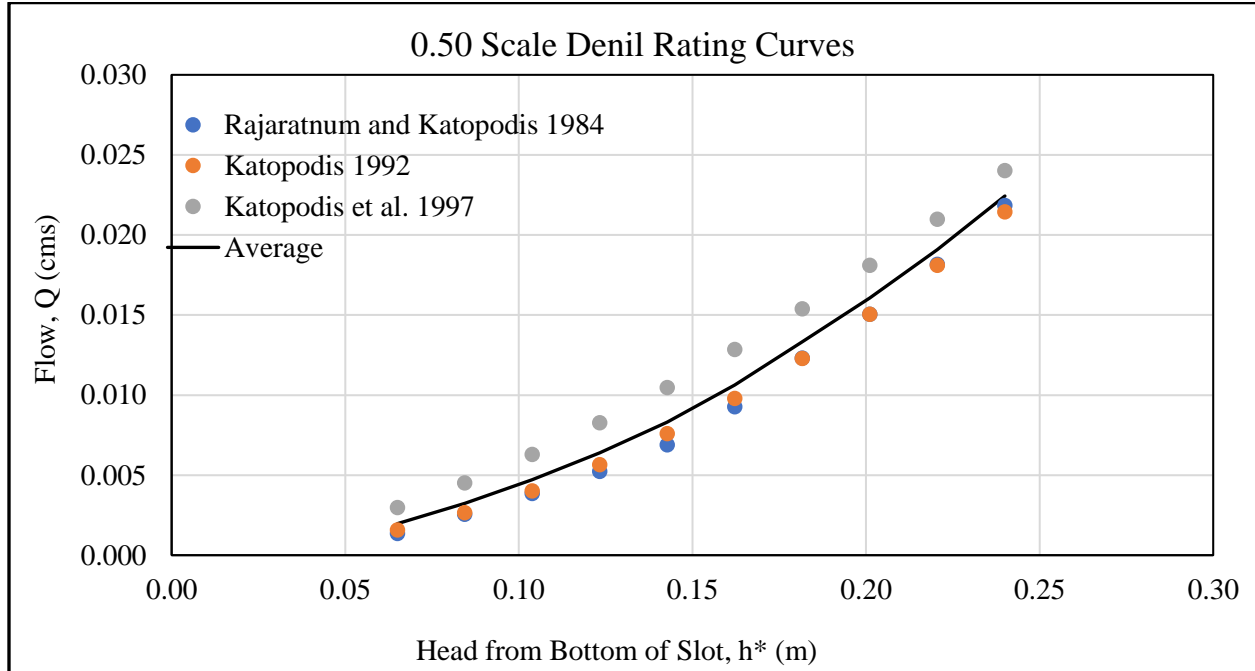
Rating curves for the 0.70 scale Denil using three discharge equations (Katopodis 1992; Rajaratnum et al. 1997; Katopodis et al. 1997). Each equation is plotted separately and an average line was added to the data. The farthest right point on the average line was taken as the maximum expected flow through the Denil fishway.



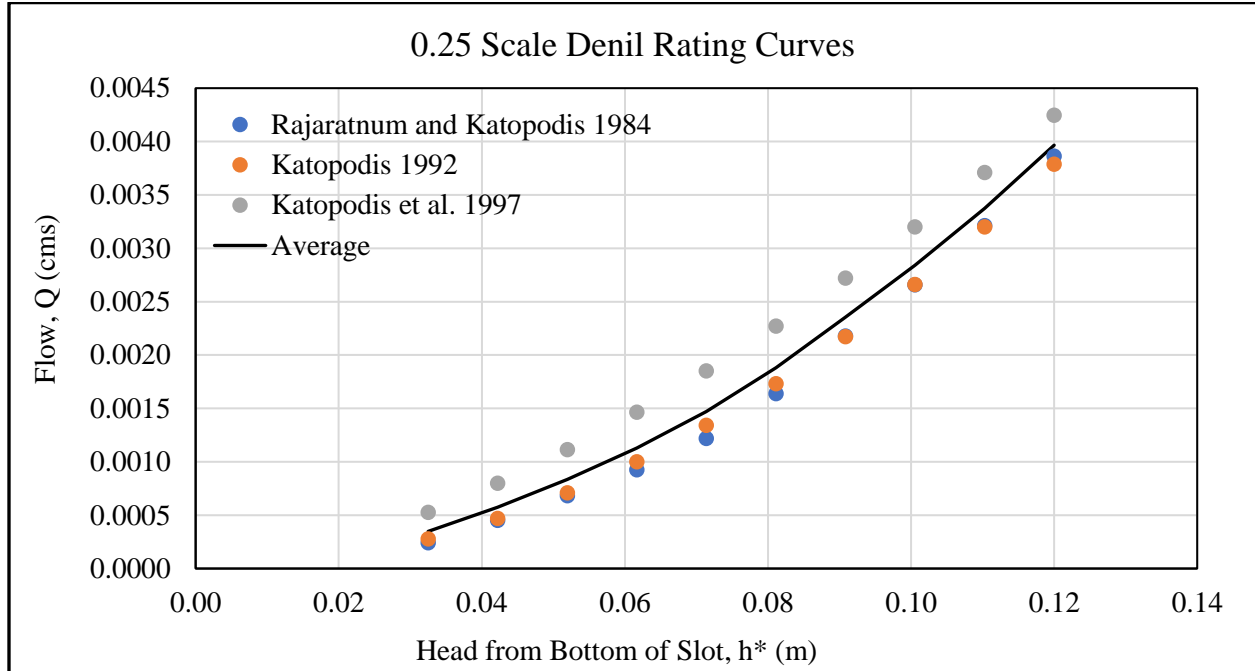
Rating curves for the 0.65 scale Denil using three discharge equations (Katopodis 1992; Rajaratnum et al. 1997; Katopodis et al. 1997). Each equation is plotted separately and an average line was added to the data. The farthest right point on the average line was taken as the maximum expected flow through the Denil fishway.



Rating curves for the 0.55 scale Denil using three discharge equations (Katopodis 1992; Rajaratnum et al. 1997; Katopodis et al. 1997). Each equation is plotted separately and an average line was added to the data. The farthest right point on the average line was taken as the maximum expected flow through the Denil fishway.



Rating curves for the 0.50 scale Denil using three discharge equations (Katopodis 1992; Rajaratnum et al. 1997; Katopodis et al. 1997). Each equation is plotted separately and an average line was added to the data. The farthest right point on the average line was taken as the maximum expected flow through the Denil fishway.



Rating curves for the 0.25 scale Denil using three discharge equations (Katopodis 1992; Rajaratnum et al. 1997; Katopodis et al. 1997). Each equation is plotted separately and an average line was added to the data. The farthest right point on the average line was taken as the maximum expected flow through the Denil fishway.

APPENDIX B

LABORATORY VELOCITY MEASUREMENTS

Trial 1– velocity measurements for the 0.6 scale with 30.5 cm headwater and 38.1 cm baffle spacing. Measurements were taken at every baffle along the Denil length. Two 40-second time averaged velocity measurements (V1 and V2) were taken at each depth using a Hach Velocimeter and a top setting wading rod for a total of four measurements at every baffle. The average flow rate for this trial was 0.032 cms and the tailwater sluice had a 2.9 cm opening.

Baffle	Notch Depth (cm)	Depth 1 (cm)	V1 (cm/s)	V2 (cm/s)	Depth 2 (cm)	V1 (cm/s)	V2 (cm/s)
1 - Lower	49.53	34.80	14.33	13.41	9.14	26.82	28.65
2	43.815	34.29	15.24	13.72	8.64	34.75	34.44
3	43.18	34.29	16.46	16.76	8.26	35.36	33.22
4	39.37	31.50	20.42	17.68	8.13	33.53	36.88
5	38.1	30.48	14.02	8.84	7.62	40.84	39.32
6	34.29	27.18	-0.61	7.92	7.11	49.07	45.11
7	33.02	26.16	17.68	17.68	6.60	54.86	53.04
8	30.48	24.38	14.33	11.58	5.59	66.75	67.67
9 - Upper	29.21	23.37	34.75	33.22	5.84	55.78	56.08

Trial 2 – velocity measurements for the 0.6 scale with 25.4 cm headwater and 38.1 cm baffle spacing. Measurements were taken at every baffle along the Denil length. Two 40-second time averaged velocity measurements (V1 and V2) were taken at each depth using a Hach Velocimeter and a top setting wading rod for a total of four measurements at every baffle. The average flow rate for this trial was 0.022 cms and the tailwater sluice had a 1.6 cm opening.

Baffle	Notch Depth (cm)	Depth 1 (cm)	V1 (cm/s)	V2 (cm/s)	Depth 2 (cm)	V1 (cm/s)	V2 (cm/s)
1 - Lower	46.99	37.47	7.32	4.88	9.40	16.46	18.59
2	44.13	35.31	4.57	4.27	8.89	19.81	20.42
3	41.91	33.53	7.62	4.88	8.38	19.51	19.20
4	37.15	29.59	5.79	5.49	7.37	22.56	21.95
5	36.51	29.46	7.92	0.30	7.11	24.38	21.34
6	32.39	26.42	11.58	10.67	6.35	28.35	26.82
7	31.12	24.89	1.22	0.00	6.35	39.01	35.66
8	26.99	21.84	8.23	3.96	5.46	53.04	52.12
9 - Upper	25.40	20.57	26.21	25.60	5.08	43.59	43.28

Trial 3 – velocity measurements for the 0.6 scale with 20.3 cm headwater and 38.1 cm baffle spacing. Measurements were taken at every baffle along the Denil length. Two 40-second time averaged velocity measurements (V1 and V2) were taken at each depth using a Hach Velocimeter and a top setting wading rod for a total of four measurements at every baffle. The average flow rate for this trial was 0.007 cms and the tailwater sluice had a 0.6 cm opening.

Baffle	Notch Depth (cm)	Depth 1 (cm)	V1 (cm/s)	V2 (cm/s)	Depth 2 (cm)	V1 (cm/s)	V2 (cm/s)
1 - Lower	46.67	37.34	2.44	2.13	9.40	5.49	5.18
2	44.45	35.56	0.61	0.91	8.89	6.40	6.10
3	41.91	33.78	0.30	1.22	8.26	7.01	7.01
4	39.05	31.88	1.52	1.52	7.87	6.40	7.62
5	35.56	28.58	2.13	3.66	7.11	8.53	7.32
6	31.75	25.65	0.30	1.52	6.35	8.84	10.06
7	29.53	23.62	6.71	5.79	5.97	8.23	10.97
8	25.08	19.94	5.49	6.10	5.08	15.24	14.02
9 - Upper	22.86	18.29	11.58	12.50	5.08	14.63	15.24

Trial 4 – velocity measurements for the 0.6 scale with 40.6 cm headwater and 38.1 cm baffle spacing. Measurements were taken at every baffle along the Denil length. Two 40-second time averaged velocity measurements (V1 and V2) were taken at each depth using a Hach Velocimeter and a top setting wading rod for a total of four measurements at every baffle. The average flow rate for this trial was 0.063 cms and the tailwater sluice opened into a weir configuration.

Baffle	Notch Depth (cm)	Depth 1 (cm)	V1 (cm/s)	V2 (cm/s)	Depth 2 (cm)	V1 (cm/s)	V2 (cm/s)
1 - Lower	45.72	36.58	24.08	20.73	9.14	60.66	58.83
2	45.09	36.32	32.31	27.43	8.38	66.45	65.84
3	44.45	35.56	30.18	27.43	8.64	68.58	66.45
4	40.64	32.51	2.13	2.13	8.13	79.86	76.50
5	40.64	32.00	33.83	30.18	8.13	68.58	65.23
6	39.37	31.75	28.35	21.03	8.13	80.47	81.08
7	38.10	31.12	21.34	12.80	7.62	96.62	90.22
8	36.83	29.72	12.80	18.29	7.37	94.18	93.57
9 - Upper	36.20	28.96	65.23	65.23	7.11	84.12	85.95

Trial 5 – velocity measurements for the 0.6 scale with 35.6 cm headwater and 38.1 cm baffle spacing. Measurements were taken at every baffle along the Denil length. Two 40-second time averaged velocity measurements (V1 and V2) were taken at each depth using a Hach Velocimeter and a top setting wading rod for a total of four measurements at every baffle. The average flow rate for this trial was 0.051 cms and the tailwater sluice had a 6.4 cm opening.

Baffle	Notch Depth (cm)	Depth 1 (cm)	V1 (cm/s)	V2 (cm/s)	Depth 2 (cm)	V1 (cm/s)	V2 (cm/s)
1 - Lower	45.72	36.58	22.25	23.16	9.14	45.11	44.20
2	45.09	36.07	31.39	29.57	9.14	47.24	48.16
3	42.55	34.29	28.35	28.04	8.38	52.73	50.29
4	38.10	30.48	21.03	21.95	7.37	61.57	61.26
5	38.74	30.73	27.13	25.60	8.13	60.35	58.52
6	35.56	28.45	10.97	18.29	7.37	79.25	81.99
7	34.93	27.69	39.01	39.93	6.86	85.95	88.39
8	32.39	26.16	27.43	24.38	6.10	89.61	89.31
9 - Upper	32.39	25.65	55.78	57.00	6.60	71.32	72.85

Trial 6 – velocity measurements for the 0.6 scale with 25.4 cm headwater and 25.4 cm baffle spacing. Measurements were taken at every other baffle along the Denil length. Two 40-second time averaged velocity measurements (V1 and V2) were taken at each depth using a Hach Velocimeter and a top setting wading rod for a total of four measurements at every other baffle. The average flow rate for this trial was 0.022 cms and the tailwater sluice had a 2.2 cm opening.

Baffle	Notch Depth (cm)	Depth 1 (cm)	V1 (cm/s)	V2 (cm/s)	Depth 2 (cm)	V1 (cm/s)	V2 (cm/s)
1 - Lower	45.09	36.07	12.80	13.11	9.02	17.98	18.90
2	41.28	33.02	9.75	11.89	8.26	23.77	22.86
3	36.20	29.08	14.02	12.50	7.24	25.91	27.43
4	34.29	27.69	11.28	10.36	6.86	24.99	25.30
5	29.85	23.88	17.68	17.07	5.97	28.65	28.65
6	27.31	21.84	8.53	10.36	5.46	39.32	36.27
7 - Upper	24.77	19.81	35.36	41.45	4.95	47.24	44.81

Trial 7 – velocity measurements for the 0.6 scale with 30.5 cm headwater and 25.4 cm baffle spacing. Measurements were taken at every other baffle along the Denil length. Two 40-second time averaged velocity measurements (V1 and V2) were taken at each depth using a Hach Velocimeter and a top setting wading rod for a total of four measurements at every other baffle. The average flow rate for this trial was 0.034 cms and the tailwater sluice had a 3.2 cm opening.

Baffle	Notch Depth (cm)	Depth 1 (cm)	V1 (cm/s)	V2 (cm/s)	Depth 2 (cm)	V1 (cm/s)	V2 (cm/s)
1 - Lower	46.99	37.59	19.20	18.29	9.40	27.74	28.04
2	43.18	34.54	18.59	17.98	8.51	36.58	36.58
3	38.74	30.99	23.47	22.86	7.75	38.71	38.40
4	37.47	29.97	22.86	22.25	7.49	38.71	39.62
5	34.61	27.69	18.90	17.37	6.86	56.39	54.56
6	31.12	25.15	20.12	18.29	6.22	69.49	70.10
7 - Upper	29.53	23.62	55.47	52.43	5.84	57.61	57.91

Trial 8 – velocity measurements for the 0.6 scale with 35.6 cm headwater and 25.4 cm baffle spacing. Measurements were taken at every other baffle along the Denil length. Two 40-second time averaged velocity measurements (V1 and V2) were taken at each depth using a Hach Velocimeter and a top setting wading rod for a total of four measurements at every other baffle. The average flow rate for this trial was 0.048 cms and the tailwater sluice had a 5.7 cm opening.

Baffle	Notch Depth (cm)	Depth 1 (cm)	V1 (cm/s)	V2 (cm/s)	Depth 2 (cm)	V1 (cm/s)	V2 (cm/s)
1 - Lower	45.72	36.58	24.69	25.60	8.89	38.71	38.40
2	42.23	33.78	13.11	11.58	8.38	51.21	52.73
3	39.37	31.50	22.86	23.47	7.87	53.64	52.12
4	39.05	31.24	16.76	16.46	7.87	49.07	49.99
5	35.56	28.45	21.03	25.30	7.11	52.43	54.25
6	33.66	26.92	22.56	26.21	6.86	82.91	84.12
7 - Upper	33.02	26.42	62.18	63.09	6.60	74.37	74.98

Trial 9 – velocity measurements for the 0.6 scale with 40.6 cm headwater and 25.4 cm baffle spacing. Measurements were taken at every other baffle along the Denil length. Two 40-second time averaged velocity measurements (V1 and V2) were taken at each depth using a Hach Velocimeter and a top setting wading rod for a total of four measurements at every other baffle. The average flow rate for this trial was 0.061 cms and the tailwater sluice was opened into a weir configuration.

<b>Baffle</b>	<b>Notch Depth (cm)</b>	<b>Depth 1 (cm)</b>	<b>V1 (cm/s)</b>	<b>V2 (cm/s)</b>	<b>Depth 2 (cm)</b>	<b>V1 (cm/s)</b>	<b>V2 (cm/s)</b>
1 - Lower	45.72	36.58	27.74	31.09	9.40	50.60	50.90
2	42.23	33.78	29.26	30.18	8.38	70.10	70.10
3	39.69	31.75	34.14	35.97	7.87	74.07	73.76
4	39.37	31.50	19.51	17.37	7.87	76.81	78.64
5	37.47	29.97	11.28	9.14	7.49	99.97	100.28
6	36.20	28.96	52.12	53.34	7.24	99.97	100.28
7 - Upper	35.56	28.45	73.15	73.76	7.11	93.27	93.27

Trial 10 – velocity measurements for the 0.6 scale with 25.4 cm headwater and 12.7 cm baffle spacing. Measurements were taken at every third baffle along the Denil length. Two 40-second time averaged velocity measurements (V1 and V2) were taken at each depth using a Hach Velocimeter and a top setting wading rod for a total of four measurements at every third baffle. The average flow rate for this trial was 0.024 cms and the tailwater sluice had a 2.2 cm opening.

<b>Baffle</b>	<b>Notch Depth (cm)</b>	<b>Depth 1 (cm)</b>	<b>V1 (cm/s)</b>	<b>V2 (cm/s)</b>	<b>Depth 2 (cm)</b>	<b>V1 (cm/s)</b>	<b>V2 (cm/s)</b>
1 - Lower	45.72	36.58	10.97	10.36	9.14	24.38	24.08
2	41.28	34.04	10.97	10.97	8.51	29.87	30.18
3	40.64	32.51	12.80	13.11	8.13	34.44	33.83
4	36.20	28.96	13.72	13.72	7.24	36.27	35.97
5	34.93	27.94	13.11	12.80	6.99	38.71	37.80
6	30.48	24.38	14.02	14.63	6.10	42.98	42.98
7	29.53	23.50	9.14	8.23	5.84	51.51	51.82
8	26.04	20.83	14.63	11.89	5.21	66.75	66.14
9 - Upper	25.40	20.32	38.40	39.01	5.08	53.04	53.04

Trial 11 – velocity measurements for the 0.6 scale with 30.5 cm headwater and 12.7 cm baffle spacing. Measurements were taken at every third baffle along the Denil length. Two 40-second time averaged velocity measurements (V1 and V2) were taken at each depth using a Hach Velocimeter and a top setting wading rod for a total of four measurements at every third baffle. The average flow rate for this trial was 0.034 cms and the tailwater sluice had a 3.2 cm opening.

Baffle	Notch Depth (cm)	Depth 1 (cm)	V1 (cm/s)	V2 (cm/s)	Depth 2 (cm)	V1 (cm/s)	V2 (cm/s)
1 - Lower	47.63	38.10	13.72	15.24	9.53	30.78	30.48
2	44.45	35.56	16.15	15.85	8.89	39.01	38.40
3	42.23	33.53	14.63	15.24	8.38	42.98	44.50
4	38.10	30.48	16.15	15.24	7.62	45.72	45.42
5	36.83	29.46	18.59	16.46	7.37	48.46	48.46
6	33.34	26.67	14.94	13.72	6.60	55.47	54.86
7	31.75	25.40	14.33	16.15	6.35	60.66	63.70
8	29.85	23.88	19.81	23.16	5.97	75.90	78.64
9 - Upper	29.21	23.37	47.24	45.42	5.84	62.79	63.09

Trial 12 – velocity measurements for the 0.6 scale with 35.6 cm headwater and 12.7 cm baffle spacing. Measurements were taken at every third baffle along the Denil length. Two 40-second time averaged velocity measurements (V1 and V2) were taken at each depth using a Hach Velocimeter and a top setting wading rod for a total of four measurements at every third baffle. The average flow rate for this trial was 0.051 cms and the tailwater sluice had a 6.4 cm opening.

Baffle	Notch Depth (cm)	Depth 1 (cm)	V1 (cm/s)	V2 (cm/s)	Depth 2 (cm)	V1 (cm/s)	V2 (cm/s)
1 - Lower	46.99	37.34	18.90	17.07	9.14	49.07	49.68
2	43.18	34.54	24.99	22.56	8.64	62.18	61.57
3	40.64	32.51	26.21	25.91	8.13	70.10	70.10
4	37.47	29.97	28.65	27.74	7.49	75.90	76.50
5	37.47	29.97	28.35	28.04	7.49	78.64	77.72
6	34.29	27.43	34.75	33.83	6.86	88.39	87.48
7	34.29	27.43	32.92	33.22	6.86	98.45	99.06
8	32.07	25.65	39.62	41.76	6.35	104.24	104.85
9 - Upper	32.39	25.91	70.10	72.54	6.48	81.38	81.99

Trial 13 – velocity measurements for the 0.6 scale with 40.6 cm headwater and 12.7 cm baffle spacing. Measurements were taken at every third baffle along the Denil length. Two 40-second time averaged velocity measurements (V1 and V2) were taken at each depth using a Hach Velocimeter and a top setting wading rod for a total of four measurements at every third baffle. The average flow rate for this trial was 0.65 cms and the tailwater sluice opened into a weir configuration.

Baffle	Notch Depth (cm)	Depth 1 (cm)	V1 (cm/s)	V2 (cm/s)	Depth 2 (cm)	V1 (cm/s)	V2 (cm/s)
1 - Lower	45.09	36.07	14.33	11.89	9.02	63.40	63.40
2	42.86	34.29	28.96	26.82	8.38	81.08	82.30
3	41.91	33.53	32.31	32.00	8.38	90.22	88.39
4	38.10	30.48	29.57	32.00	7.62	93.57	96.01
5	38.10	30.48	35.05	36.27	7.62	97.23	94.18
6	36.83	29.46	35.97	33.22	7.37	96.32	102.72
7	36.20	28.96	42.06	36.88	7.24	104.24	112.17
8	34.93	27.94	46.63	46.33	6.99	117.96	119.48
9 - Upper	36.83	29.46	88.39	88.39	7.37	101.80	103.02

Trial 14 – velocity measurements for the 0.75 scale with 30.5 cm headwater and 38.1 cm baffle spacing. Measurements were taken at every baffle along the Denil length. Two 40-second time averaged velocity measurements (V1 and V2) were taken at each depth using a Hach Velocimeter and a top setting wading rod for a total of four measurements at every baffle. The average flow rate for this trial was 0.040 cms and the tailwater sluice had a 4.1 cm opening.

Baffle	Notch Depth (cm)	Depth 1 (cm)	V1 (cm/s)	V2 (cm/s)	Depth 2 (cm)	V1 (cm/s)	V2 (cm/s)
1 - Lower	45.09	36.07	13.41	13.11	9.02	28.04	24.99
2	41.91	33.53	18.90	18.90	8.13	30.78	31.39
3	39.37	31.50	14.63	14.33	7.87	34.75	35.05
4	36.83	29.46	21.64	19.81	7.37	35.97	36.27
5	33.66	26.92	14.02	10.97	6.73	44.20	41.45
6	28.58	23.88	31.39	26.21	5.97	52.43	53.64
7	27.94	22.35	32.00	30.48	5.59	58.22	53.04
8	26.67	21.34	9.75	12.19	5.33	71.63	73.76
9 - Upper	25.72	16.51	64.31	66.14	5.08	65.23	64.31

Trial 15 – velocity measurements for the 0.75 scale with 25.4 cm headwater and 38.1 cm baffle spacing. Measurements were taken at every baffle along the Denil length. Two 40-second time averaged velocity measurements (V1 and V2) were taken at each depth using a Hach Velocimeter and a top setting wading rod for a total of four measurements at every baffle. The average flow rate for this trial was 0.026 cms and the tailwater sluice had a 2.2 cm opening.

Baffle	Notch Depth (cm)	Depth 1 (cm)	V1 (cm/s)	V2 (cm/s)	Depth 2 (cm)	V1 (cm/s)	V2 (cm/s)
1 - Lower	45.72	36.45	6.10	7.01	9.14	15.24	14.33
2	43.18	34.54	10.06	8.53	8.64	17.98	17.68
3	40.01	32.00	10.36	10.67	7.75	22.25	21.95
4	36.83	29.46	17.68	12.50	7.37	25.30	24.69
5	33.66	26.92	12.50	17.98	6.73	24.69	25.60
6	30.48	24.38	18.29	20.73	5.84	26.21	29.57
7	27.31	21.84	20.12	17.07	5.46	33.53	33.22
8	25.40	20.32	5.79	5.49	5.08	42.37	43.59
9 - Upper	23.50	18.80	41.15	42.98	4.70	46.94	46.02

Trial 16 – velocity measurements for the 0.75 scale with 40.6 cm headwater and 25.4 cm baffle spacing. Measurements were taken at every other baffle along the Denil length. Two 40-second time averaged velocity measurements (V1 and V2) were taken at each depth using a Hach Velocimeter and a top setting wading rod for a total of four measurements at every other baffle. The average flow rate for this trial was 0.071 cms and the tailwater sluice opened in to a weir configuration.

Baffle	Notch Depth (cm)	Depth 1 (cm)	V1 (cm/s)	V2 (cm/s)	Depth 2 (cm)	V1 (cm/s)	V2 (cm/s)
1 - Lower	53.34	41.91	15.54	14.94	11.18	42.37	45.72
2	51.44	41.15	2.13	6.40	10.16	49.07	50.60
3	48.90	39.12	1.83	1.22	9.91	53.34	52.12
4	47.63	38.10	1.83	1.83	9.65	52.43	50.60
5	46.36	37.59	-7.32	-10.67	9.40	74.37	75.90
6	43.18	34.29	14.63	13.72	8.89	103.94	98.15
7 - Upper	43.18	34.54	14.33	13.41	8.89	92.05	92.35

Trial 17 – velocity measurements for the 0.75 scale with 30.5 cm headwater and 25.4 cm baffle spacing. Measurements were taken at every other baffle along the Denil length. Two 40-second time averaged velocity measurements (V1 and V2) were taken at each depth using a Hach Velocimeter and a top setting wading rod for a total of four measurements at every other baffle. The average flow rate for this trial was 0.035 cms and the tailwater sluice had a 3.5 cm opening.

Baffle	Notch Depth (cm)	Depth 1 (cm)	V1 (cm/s)	V2 (cm/s)	Depth 2 (cm)	V1 (cm/s)	V2 (cm/s)
1 - Lower	45.09	36.07	12.80	12.80	9.02	24.38	24.69
2	40.64	32.51	1.52	2.44	8.38	29.26	29.87
3	36.83	29.46	11.58	8.53	7.37	28.65	31.09
4	34.29	27.43	6.10	6.71	6.86	33.53	34.14
5	30.48	23.88	13.41	10.36	6.60	36.58	37.49
6	27.94	22.10	14.94	14.63	5.84	62.48	57.61
7 - Upper	26.67	21.84	47.24	49.68	5.33	56.69	57.61

Trial 18 – velocity measurements for the 0.75 scale with 25.4 cm headwater and 25.4 cm baffle spacing. Measurements were taken at every other baffle along the Denil length. Two 40-second time averaged velocity measurements (V1 and V2) were taken at each depth using a Hach Velocimeter and a top setting wading rod for a total of four measurements at every other baffle. The average flow rate for this trial was 0.026 cms and the tailwater sluice had a 2.54 cm opening.

Baffle	Notch Depth (cm)	Depth 1 (cm)	V1 (cm/s)	V2 (cm/s)	Depth 2 (cm)	V1 (cm/s)	V2 (cm/s)
1 - Lower	43.18	34.54	8.23	10.67	8.64	14.94	16.46
2	38.74	30.99	12.50	12.50	7.62	21.95	21.95
3	35.56	28.45	11.89	14.63	7.11	22.25	20.12
4	31.75	25.40	12.19	10.06	6.35	26.21	27.74
5	27.94	22.61	9.14	6.40	5.59	32.00	30.78
6	24.77	20.07	5.18	8.23	5.08	42.06	42.06
7 - Upper	22.86	17.78	36.88	44.50	4.57	50.60	50.60

Trial 19 – velocity measurements for the 0.75 scale with 40.6 cm headwater and 12.7 cm baffle spacing. Measurements were taken at every third baffle along the Denil length. Two 40-second time averaged velocity measurements (V1 and V2) were taken at each depth using a Hach Velocimeter and a top setting wading rod for a total of four measurements at every third baffle. The average flow rate for this trial was 0.0735 cms and the tailwater sluice was opened to a weir configuration.

Baffle	Notch Depth (cm)	Depth 1 (cm)	V1 (cm/s)	V2 (cm/s)	Depth 2 (cm)	V1 (cm/s)	V2 (cm/s)
1 - Lower	44.45	34.80	11.28	8.84	8.89	69.49	70.41
2	40.64	33.02	23.77	24.08	8.13	81.38	81.69
3	40.01	32.00	16.46	17.37	7.87	80.77	82.30
4	39.37	31.50	5.79	7.01	7.87	80.47	81.69
5	36.20	28.96	12.19	14.02	7.62	80.77	81.99
6	35.56	28.19	12.19	13.41	7.62	86.56	84.43
7	34.29	27.43	12.19	11.58	6.86	96.32	95.71
8	34.29	27.43	22.25	21.64	6.60	114.00	113.39
9 - Upper	33.02	26.42	69.49	67.36	6.35	92.66	93.27

Trial 20 – velocity measurements for the 0.75 scale with 30.5 cm headwater and 12.7 cm baffle spacing. Measurements were taken at every third baffle along the Denil length. Two 40-second time averaged velocity measurements (V1 and V2) were taken at each depth using a Hach Velocimeter and a top setting wading rod for a total of four measurements at every third baffle. The average flow rate for this trial was 0.042 cms and the tailwater sluice had a 4.45 cm opening.

Baffle	Notch Depth (cm)	Depth 1 (cm)	V1 (cm/s)	V2 (cm/s)	Depth 2 (cm)	V1 (cm/s)	V2 (cm/s)
1 - Lower	45.72	36.58	6.10	7.62	9.40	43.89	44.50
2	41.91	33.53	15.85	16.46	8.38	50.60	50.90
3	40.01	32.00	16.76	16.46	8.13	51.21	51.21
4	36.20	28.96	15.85	16.76	7.11	53.64	52.73
5	33.66	26.92	13.11	12.19	6.60	60.05	59.74
6	31.12	25.15	18.29	13.72	6.35	73.46	69.19
7	29.85	23.11	9.14	9.14	6.10	75.29	72.85
8	26.67	21.34	14.94	12.80	5.59	82.30	87.48
9 - Upper	27.94	22.35	24.38	29.26	5.84	71.93	72.54

Trial 21 – velocity measurements for the 0.75 scale with 25.4 cm headwater and 12.7 cm baffle spacing. Measurements were taken at every third baffle along the Denil length. Two 40-second time averaged velocity measurements (V1 and V2) were taken at each depth using a Hach Velocimeter and a top setting wading rod for a total of four measurements at every third baffle. The average flow rate for this trial was 0.027 cms and the tailwater sluice had a 2.22 cm opening.

<b>Baffle</b>	<b>Notch Depth (cm)</b>	<b>Depth 1 (cm)</b>	<b>V1 (cm/s)</b>	<b>V2 (cm/s)</b>	<b>Depth 2 (cm)</b>	<b>V1 (cm/s)</b>	<b>V2 (cm/s)</b>
1 - Lower	45.72	36.58	5.79	6.40	9.14	29.26	29.57
2	42.55	34.04	10.67	9.75	8.64	30.78	31.70
3	39.37	31.24	10.36	10.36	8.13	31.39	31.39
4	36.20	28.96	10.06	9.75	7.11	32.61	31.70
5	33.02	26.42	7.32	6.71	6.60	36.58	37.49
6	29.85	23.88	7.62	7.62	5.59	37.49	40.54
7	27.31	22.10	6.71	7.32	5.33	46.02	51.21
8	24.13	19.30	7.92	7.32	4.83	64.31	60.96
9 - Upper	22.86	18.03	30.78	35.66	4.57	55.47	55.47