Ecohydraulics of Nature-Like Fishways and Applications in Arctic Aquatic Ecosystem Connectivity

By

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Abstract

Northern Canada is currently undergoing rapid mineral extraction development. As part of this development there is a need to perform fish habitat compensation projects and build effective fish passage facilities. There is currently limited information available on the hydraulics of nature-like fishways, as well as the behaviour of fish within these structures. Two studies were conducted: one laboratory study and one field study to improve the understanding of ecohydraulics and fish behaviour in nature-like fishways.

In the laboratory study a pool-weir style fishway was constructed using both natural rocks and concrete spheres. Weirs were constructed in a flume with one of three geometries: v-facing upstream, v-facing downstream, and horizontal. For the v-shaped weirs an angle of 140 degrees was used on the inside of the v. The aim of this experiment was to examine the influences of slope, discharge, and weir geometry on horizontal velocity, vertical velocity, turbulent kinetic energy, turbulence intensity, Reynolds stresses, and volumetric power dissipation in rock-weir fishways. An acoustic Doppler velocimeter (ADV) and point gauge were used to measure velocity and water surface profiles, respectively, for discharges between 30 and 150 l/s at bed slopes between 1.5% and 5.0%.

An effective operating range was identified for the proposed fishway design and a diagram was developed to aid designers in selecting appropriate discharge and bed slopes based on volumetric power dissipation. Two flow regimes were observed: plunging and transitional. A stage-discharge relationship was also developed to provide an improved estimate of discharge when compared with existing equations. Finally, a new method of

weir construction was proposed that allows rock-weirs to be constructed off site, reducing installation time and resulting in a more flexible final design.

In the field study the performance of a habitat connectivity project in the Canadian Barrenlands was evaluated where a stream was modified through the construction of nature-like fishway structures to increase habitat connectivity for Arctic Grayling (*Thymallus arcticus*). Under this project the total length of West Island Stream (WIS) was increased from 430 to 470 m and the slope of a steep cascade section deemed a barrier to fish passage was reduced. Five pools were selected in the steep lower-reach of WIS to evaluate for resting suitability for Arctic Grayling.

A diesel pump was used to manipulate the flow in WIS (1.0, 9.9, and 21.9 l/s) and an acoustic Doppler velocimeter to measure point velocities within each study pool. Adult Arctic Grayling were placed in the pools and their resting behaviour was observed under each flow condition using visual fish surveys and video recordings. This study showed that stream-scale flow manipulation can be an effective tool in evaluating habitat compensation projects. The results indicated that only one of the study pools would provide acceptable resting habitat during all flow conditions expected during spawning. Based on the observations of the use of pools by fish, it is recommended that future resting pools for Artic Grayling have a minimum surface area of 1.4 m^2, a minimum depth of 0.6 m, horizontal velocity magnitudes less than 0.2 m/s, and near-zero vertical velocities.

Preface

This thesis is an original work by Cody Kupferschmidt. Chapter 3 of this thesis is under review for publication as Kupferschmidt, C., Noddin, D., Zhu, D.Z., and Tonn, W.M., "Use of Resting Pools by Arctic Grayling (Thymallus arcticus) in a Nature-Like Fishway: Ecohydraulic Analysis and Implications for Fishway Design," in River Research and Applications.

Dedication

"But in every walk with Nature one

receives far more than he seeks."

- *John Muir*

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CHAPTER 1. Background

During our short existence on Earth, humans have had a profound impact on the planet's ecosystems. Freshwater ecosystems are among the most significantly impacted by human activity and as a result tend to have the highest number of species threatened with extinction (MEA, 2005). In North America alone, 46% of the almost 1200 species of freshwater and anadromous fish are recognized as imperiled or have at least one population of subspecies that is imperiled (Jelks et al., 2008).

From a freshwater fisheries perspective, the impact from humans has been widespread, including loss or fragmentation of habitat, blockage or delays during migration, environmental changes in temperature, flow, and water quality, and the introduction of invasive species (Dudgeon et al., 2006; Katopodis and Aadland, 2006). River basin development has resulted in the construction of millions of dams globally (Katopodis and Aadland, 2006), and has caused fragmentation and flow augmentation on over half of the world's large river systems (virgin mean annual discharge > 350 m^3/s) (Nilsson et al., 2005).

To mitigate the effects of human development and habitat fragmentation for fish, we can provide fish passage facilities that allow fish to overcome barriers to migration. Also known as fishpasses, fishways, or fish ladders, these structures can be installed at the location of both manmade and natural features to provide upstream and/or downstream passage. The need for fish passage facilities at manmade structures was realized long ago, with early structures constructed in Europe in the 17th century (Clay, 1995). However, despite these early efforts, a scientific approach to fish passage was not really adopted until the 20th century (Clay, 1995) and largely concentrated on anadromous fish of high commercial and recreational significance such as Salmon (*Salmonidae)* and to a lesser extent Shad (*Clupeidae)* (Katopodis and Williams, 2012).

Since the early 20th century, fishway design has progressed significantly, and conventional fishway designs can now largely be classified as four types: pool and weir, vertical slot, Denil, and culvert (Katopodis et al., 2001). These structures are typically built using construction materials such as concrete, metal, wood, and fiberglass and have been heavily researched and field tested (Katopodis et al. 2005). Fishway design is largely based on three factors: ichthyomechanics or swimming performance, bio-navigational features, and hydrotechnical issues (Katopodis et al., 2001). The basic hydraulics of conventional fishways have been well-studied through model testing and dimensional analysis (e.g. Rajaratnam and Katopodis, 1984; Katopodis et al., 1997; Rajaratnam et al., 1986; Rajaratnam and Katopodis, 1988; Ead et al., 2002), however, despite these efforts fish responses to the hydraulic characteristics of fishways are still poorly understood (Katopodis, 2005). As a result, the vast majority of fishway structures are not effective in mitigating the effects of barriers to upstream passage (Bunt et al., 2012).

In the late 1970s, a new type of fishway was proposed that was designed to mimic the width and cross-sectional area of a natural stream, and incorporate natural materials in its construction (Katopodis et al., 2001). Known as nature-like fishways, these structures are usually constructed using locally available material such as rocks, gravel, sand and wood and are designed to mimic natural streams (Katopodis et al., 2001). Nature-like fishways have shown some promise in improving fishway performance, as they typically have higher passage rates and pass more fish of more species than conventional technical fishways (Bunt et al., 2012). Over the past decades this has resulting in an increasing trend towards the use of nature-like fishways (Lucas and Baras, 2001). However, most nature-like fishway designs to date have been based on ad-hoc information, and there is an identified need to develop design guidelines for different species of fish in nature-like fishways based on hydraulic studies, controlled experiments with fish, and detailed field studies (Katopodis et al., 2001).

A number of laboratory studies have recently been conducted on the hydrotechnical characteristics of rock-ramp (Breton et al., 2013; Baki et al., 2014; Cassan et al., 2014; Baki et al., 2015) and pool style nature-like fishways (Wang and Hartlieb, 2011). Despite these studies, there is still limited data available on the hydraulics of nature-like fishways. In particular, there is very little species-specific data available and very few experiments have been conducted with fish.

Based on the available information, we identified the need to conduct experiments studying the hydrotechnical aspects of pool-weir fishways as well as collect species-specific data on fish use in these structures.

Research Motivation

Northern Canada is currently undergoing going rapid development in the resource extraction industry due to the presence of large mineral deposits that include diamonds, metals, and oil and gas (Government of Canada, 2013). Between 2011 and 2020 it is estimated that output of metallic and non-metallic minerals in northern Canada will grow 91 percent (The Conference Board of Canada, 2013) and the Government of Canada estimates that total investment in Canadian resource development will be approximately $650 billion over the next decade (Government of Canada, 2014).

Along with this development, there will be a resultant need to provide environmental protection and remediation services. An increasing trend of lake and stream destruction in northern Canada since the 1950s (Birtwell et al., 2005) has triggered a growing number of habitat compensation projects at sites that are protected under the Canadian Fisheries Act (2012). Despite recent changes to the Fisheries Act that have reduced the scope of protection to include only fisheries of commercial, recreational, or aboriginal importance (2012), there will nevertheless be a future need to provide habitat compensation projects for fisheries in northern Canada.

Fish habitat compensation projects are typically based on the principle of achieving no net loss (NNL) of productive capacity of the ecosystem for fish (DFO, 1986). This often includes requirements that are a combination of creating a certain number of habitat units, as well as ensuring habitat connectivity. To ensure that habitat compensation projects are successful, it is important to understand the biological characteristics of the target fish species. However, despite having poor species richness and little to no endemism (Abell et al., 2008), many of the native fish species in northern Canada are poorly studied, with limited information available on their swimming capabilities or hydraulic preferences. This lack of knowledge can make it difficult to provide effective structures for fish passage and to meet hydraulic requirements for a target fish species.

The Arctic Grayling (*Thymallus arcticus*) is a fish species that is common in northern Canada, but has experienced significant range reductions and extirpations in the southern part of its range (ASRD, 2005). Although slow growth rate and ease of capture through angling make grayling particularly susceptible to local extirpation (MacPhail and Lindsey, 1970), habitat fragmentation from the construction of road culverts and increased water temperatures from land use practices have also played a major role in range reductions of this species (ASRD, 2005). In Alberta, Arctic Grayling are listed as "Sensitive" and occupy a number of regions that include important areas of energy development, including the Hay River, Peace River, and Athabasca River watersheds (ASRD, 2005). Arctic Grayling are also present in many regions undergoing resource extraction development in the Northwest Territories and other regions of Canada.

There are only a few papers available on the swimming abilities and hydraulic preferences of Arctic Grayling (Hughes and Dill, 1990l Hughes, 1992a; Hughes, 1992b; Den Beste and McCart, 1984, Jones et al., 1974) which can result in limitations the ability to design effective fish passage structures.

In fall 2012 Diavik Diamond Mines Inc (DDMI) completed a habitat compensation project in the Barrenlands region of northern Canada with the goal of enhancing fish spawning habitat and providing improved habitat connectivity for a number of fish species including Arctic Grayling (Dillon, 2004; Courtice, 2014; Courtice et al., 2014). This completion of this project presented an excellent opportunity to study the hydrotechnical aspects of a nature-like fishway constructed as part of a habitat compensation project. By also gathering fish usage data for the same site, it was possible to perform an ecohydraulic analysis of the fishway Arctic Grayling and to develop guidelines for future fishway projects.

At the same time, a complementary laboratory study to the project would yield an improved understanding of the fishway hydraulics including information that could not be gathered in the field. In the past decades, it has been noted the intensity, periodicity, orientation and scale of turbulence can also affect fish passage (Lacey et al., 2011), in addition to the historically evaluated characteristics such as velocity and flow depth.

Advances in technology over the last several decades such as the use of high-frequency acoustic sampling methods to evaluate water velocity have made it easier to gather information on turbulence. Combined with the identified need to study flow patterns and turbulence in nature-like fishways (Katopodis et al., 2001), there project presented an excellent opportunity to use an acoustic Doppler velocimeter (ADV) to study the hydraulic characteristics within a nature-like fishway.

Research Objectives

This research for this thesis was split into two components: a laboratory study on the hydraulics of pool-weir nature-like fishways, and a field study evaluating resting habitat for Arctic Grayling in a nature-like fishway located in the Canadian Barrenlands.

Laboratory Experiment

The objective of the laboratory experiment is to yield an improved understanding of the influence of slope, discharge, weir shape, and weir orientation on rock-weir fishway design. Studies in a flume will evaluate a series of v-shaped weirs by measuring the surface water profile and taking high frequency (100 Hz) point velocity readings using a Nortek Vectrino acoustic Doppler velocimeter (ADV). This experiment will have a particular focus on mapping vertical velocity, horizontal velocity magnitude, Reynold's shear stresses, and turbulent kinetic energy zones within the fishway pools, as well as looking at how different designs affect the rate of volumetric power dissipation.

The goal of this research is to gain an improved understanding of the hydraulics of rock-weir fishways and to develop design tools to aid engineers and biologists in designing effective fishways. This research also aims to determine the relationship between weir shape, depth over the weir, and discharge so that discharge equations can be developed.

Field Experiment

The field experiment aims to evaluate an existing fishway in the Canadian Barrenlands. This experiment will be performed by releasing Arctic Grayling into the nature-like fishway at the West Island Stream (WIS) habitat compensation project, as well as studying several pools within the fishway using the SonTek FlowTracker ADV. The objective of this research is to determine if the existing pools in WIS provide sufficient resting habitat for Arctic Grayling and to examine their behaviour. The objective of this study is to develop hydraulic guidelines that can be used as design aids for future resting pools. The experiment will also provide the opportunity to examine the potential of using large pumps to perform stream-scale flow manipulation and determine if this technique could be a useful method for future stream evaluations.

Significance of Research

Both the laboratory and field component of this research will help improve our technical understanding of the hydraulics of nature-like fishways. These findings will aid designers in determining appropriate slope, rock size, weir configuration, and design flow rates to create effective fishways. This may also aid in creating fishways that are appropriate for not only the target species, but also entire fish communities. Although applicable on a global scale, these findings may be particularly useful in Canada during the next decade as resource extraction growth creates a need for effective fish passage designs.

The field experiment is also a valuable proof-of-concept experiment to determine if in-stream flow manipulations are an effective tool that can potentially be used to evaluate structures under a range of flow conditions during a single site visit. This has the potential to result in both time and money savings when evaluating fishways. An improved understanding of the behaviour of Arctic Grayling in pool-style fishways has the potential to help prevent range reduction of this species in Canada and to help ensure habitat compensation projects for this species are successful. The development of design guidelines for this species will be a valuable aid for designers to help ensure that future fishway and habitat compensation projects are more successful.

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CHAPTER 2. Flow Characteristics of Pool-Weir Fishways with Rock-Weir Construction[1]

Introduction

Fishpasses or fishways are structures that allow fish to overcome barriers to migration. The main objectives of fishpasses are to regulate water depth, water velocity, and drop height to provide conditions that allow for the upstream or downstream passage of fish. Fishways can be constructed in a nature-like fashion by incorporating natural materials such as cobble, boulders, logs, or branches into their design.

Weirs are structures that are designed to regulate rivers for hydrotechnical objectives and have widespread use around the globe. In many cases weirs are constructed to increase water depth, provide erosion prevention or energy dissipation, or to regulate discharge. Weirs can also be constructed in a nature-like fashion using rocks and timber. These types of weirs are often used to stabilize river channel boundaries and are referred to as river restoration structures when used for this purpose (Rosgen, 2001). A pragmatic approach can be used when designing weirs, aiming to satisfy both hydrotechnical and ecological considerations with a single design.

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[1] Presented in part at the 10th International Symposium on Ecohydraulics – Trondheim, Norway, June 2014. Contributing authors: M-È. Jean, D.Z. Zhu, and A.B. Baki.

Pool-weir fishways are the most common type of fishway installed in Canada (Hatry et al., 2013). They make use of an alternating pattern of weirs and pools to allow fish ascend a series of small drops, rather than ascending a large single drop. Pool-weir fishways can operate in both a streaming and plunging flow regime, with the streaming flow regime offering the advantage of allowing both jumping and non-jumping fish species to ascend (Clay, 1995).

An understanding of the hydraulics of pool-weir fishways is important to ensure that they perform satisfactorily for fish passage. Basic velocity requirements must be met, such as the maximum velocity across the weir being less than the burst velocity of the fish, and the average velocity in the pool being less than the cruising velocity of the target species to allow the fish to rest (Clay, 1995). More recently it has been recognized that other hydraulic parameters such as volumetric energy dissipation, turbulent kinetic energy, and Reynold's shear stresses are also important and can have significant impacts on the success of fish passage (Lacey et al., 2012).

The use of natural materials to construct the weirs in pool-weir fishways can offer several advantages. In addition to being visually appealing, this type of installation may create habitat for rheophilic species, and can pass small fish, fry, and benthic invertebrates through the gaps between rocks (FAO/DVWK, 2002). It has also been shown that nature-like fishways tend to pass more species of fish than technical fishways (Bunt et al., 2012). The installation of in-stream rock weirs can help create regions of hyporheic exchange flow (Gordon et al, 2013; Crispell and Endreney, 2009) which can regulate water temperature, enhance nutrient uptake, and oxygenate fish eggs (Crispell and Endreney, 2009).

However, natural materials can provide hydraulic challenges when designing these structures as they have irregularly sizes and geometries and can vary from site to site. The flow over rock weirs is complex as water passes not only over the top of the weir in either a streaming or plunging flow regime, but also through the gaps between the rocks. As a result, there is a need to study the flow patterns and turbulence in nature-like fishways (Katopodis et al., 2001). Recent hydraulic analyses of nature-like fishpasses have been performed that looked at rock ramp (Baki et al., 2014) and notched pool-weir structures (Wang and Hartlieb, 2011), including examining turbulence within the fishway.

The objectives of this research were to evaluate the influence of discharge and bed slope on the hydraulics of a rock-weir constructed out of concrete spheres with a v-shape facing in the upstream direction (VUS). The design of the weir used in this experiment is similar to that of cross-vane or rock vortex structures, commonly used for river-restoration (Rosgen, 2001). The experiment also examined the influence of weir geometry on the hydraulics of the structure. This was done by comparing the results with the weir when installed backwards with the v-shape facing in the downstream direction (VDS) and with a horizontal (HOR) rock weir. Finally, the use of natural rocks was compared with ideal concrete spheres to determine the extent of the impact of natural materials on fishway hydraulics.

Background

Basic Hydraulics of Rock Weirs

The simplest form of the weir equation for a horizontal rectangular channel is shown below where Q is the discharge, b is the length of the weir crest, g is the acceleration due to gravity, h_w is the approach flow depth above the weir crest h_w and C_d is the discharge co-efficient.

$$Q = C_d \frac{2}{3} \sqrt{2g} b H^{3/2} \qquad \textit{Equation 2.1}$$

The discharge co-efficient for weirs can vary with a number of factors including the height, thickness and shape of the weir. For linear weirs with a quarter-rounded crest on the approach side C_d typically ranges from about 0.5 to 0.75, while for triangular shaped labyrinth weirs C_d decreases as the weir angle decreases from linear (Tullis et al., 1995). The stage-discharge relationship of weirs with irregular geometries can be complicated. For example, labyrinth weirs operate as regular weirs with an increased crest length at low heads, however when water level is increased their discharge efficiency decreases as nappe collision occurs and local submergence regions are formed (Crookston and Tullis, 2012).

In cases where there is an orifice located in a weir or the weir is constructed using a porous material there will be an additional flow component caused by the flow below the weir crest. For pool-weir fishways containing an orifice the total discharge is typically calculated as the sum of the orifice and the weir flow (Katopodis, 1992). For gabion weirs, it is possible to apply the standard weir equation using a modified C_d to account for the additional discharge through the weir (Mohamed, 2010).

For boulder sills it has been recommended that discharge be calculated using a modified form of weir equation known as the Poleni formula (FAO/DVWK, 2002) where μ is the spillway coefficient (0.5-0.6 for sharp edged rocks, 0.6-0.8 for rounded stones), σ is the drowned-flow reduction factor, $\sum b_s$ is the sum of the unobstructed flow widths, and h_w is the water depth over the weir.

$$Q = \frac{2}{3}\mu\sigma\sqrt{2g}h_w{}^{3/2}\sum b_s \qquad \text{Equation 2.2}$$

Because weirs are located close together in pool-weir style fishways, multiple flow regimes can occur and the need for multiple equations can arise. Rajaratnam et al. (1988) identified this need for technical pool-weir fishways and developed specialized stage-discharge relationships for streaming, and transitional flow. Rajaratnam et al. (1988) also developed a number of dimensionless discharge parameters to identify the transition between flow plunging, transitional, and streaming flow.

The work of Rajaratnam et al. (1988) was expanded by Ead et al. (2004) to identify five different flow sub-regimes within the transitional flow regime and a supercritical jet flow regime. Ead et al. (2004) developed a diagram to predict the flow regime based on two dimensionless parameters: Q_{t*} and *L/P*, where S_0 is the bed slope, B is the flume width, *L* is the pool length, and *P* is the height of the weir above the bed.

$$Q_{t*} = \frac{Q}{\sqrt{g}S_0BL^{3/2}} \qquad \text{Equation 2.3}$$

Ecological Considerations

There are many ecological considerations for designing rock-weir nature-like fishway structures, with the most basic being the velocity of the water in the fishway. Fish swimming movement can be classified into three different types of activity: cruising speed which can be maintained for hours using aerobic muscle activity, burst speed which can usually be maintained for only a few seconds, and a sustained speed which can be maintained for several minutes but eventually tires the fish (Larinier, 2002a).

For fishways, the burst speed and cruising speed are the most important velocities to consider. The velocity across a weir or through an orifice must be less than the maximum burst speed of the target fish species to allow them to pass upstream, while the velocity in a pool must be slower than the cruising speed to allow the fish to rest. The burst and cruising velocities of many fish species and body types have been relatively well studied (e.g. Jones et al., 1974; Beach, 1984) and summarized by Katopodis and Gervais (2012).

In addition to mean velocity, turbulence must also be considered. High turbulence in flow has also been shown to impact fish swimming patterns and decreases the range of flows at which fish are able to perform rheoreaction (Lupandin, 2005). Currently, volumetric power dissipation is widely used to approximate turublence by using the mean rate of energy dissipation in fishways to regulate pool size. Guidelines for this metric are widely available, with Larinier (2002b) suggesting 200 W/m^3 as an upper limit for salmon and sea trout and 150 W/m^3 for small fishways designed to pass shad and riverine species. FAO/DVWK (2002) recommends 150 W/m^3 as an upper limit within pools for most types of fishways.

In reality, volumetric power dissipation is not necessarily a good indicator, as it represents a pool-averaged value of energy dissipation, rather than accurately representing local turbulence conditions. In reality, fish behaviour and locomotion within turbulent flow is controlled by the intensity, periodicity, orientation, and scale of the turbulence (Lacey et al., 2011). The size of eddies is extremely important to fish. Small eddies affect the stability of fish, while larger eddies affect their position (Webb, 2005). Small eddies cannot be resolved with acoustic methods and require techniques such as

PIV (Webb, 2005), so this study focused on mean turbulence characteristics would affect fish position rather than stability.

Turbulent kinetic energy ($TKE = \frac{1}{2}(\overline{u'^2} + \overline{v'^2} + \overline{w'^2})$ and turbulence intensity ($TI = \sqrt{TKE}/\overline{u_{local}}$) are both commonly used metrics to evaluate turbulence for fish where u', v', and w' are the fluctuating longitudinal, transverse and vertical velocity components and $\overline{u_{local}}$ is the mean longitudinal velocity at the specific measurement location. There are limited guidelines available on the acceptable level of TKE within a fishway, however, Breton et al. (2013) defined high turbulence zones as regions exceeding 0.15 m^2/s^2. Cotel et al. (2006) found that Brown Trout (*Salmo trutta*) in a natural stream selected for lower TI and observed fish occupying areas with TI values between 0.03 and 0.53.

The Reynolds shear stress components of the flow may also have major impacts on fish passage. Silva et al. (2011) found that the horizontal plane component ($-\rho\overline{u'v'}$) of Reynolds shear stress was the hydraulic parameter that affected fish behaviour most within their fishway. Stress rates over 1600 Pa are required to cause injuries to juvenile Chinook Salmon (*Oncorhynchus tshawytscha*) (Čada et al., 2006), however, shear stresses several orders of magnitude lower can have impacts on fish position and locomotion. Silva et al. (2011) observed Barbel (*Luciobarbus bocagei*) occupying positions with shear stresses of up to 60 Pa, but noted that fish spent less time in higher stress regions where absolute values ranged from 20 to 60 Pa. When designing fishways, resting areas provided must be large enough for the target fish species while meeting velocity, volumetric power dissipation, turbulence, and shear stress preferences or limitations of the fish.

In addition to hydraulic considerations, rock-weir fishways also have geometry-based impacts on fish passage. Small gaps at the bottom of rocks may allow for smaller or bottom-dwelling species of fish or benthic fauna to pass upstream that would not otherwise be able to pass over top of the weir. The use of rock-weirs has already shown to be an effective method of restoring habitat connectivity for small salmonids in at least one case (Martens and Connolly, 2010).

Experimental Setup

A series of eight weirs (or boulder sills) were constructed in a rectangular flume with a length of 8.89 m, width of 0.92 m, and a wall height of 0.60 m. Weir geometry differed between experiments, but the longitudinal spacing between weirs remained constant at 0.9 m. Weir spacing was selected to be equal to approximately one channel width, which is within the range of the pool length to channel width ratio for natural step-pool features in streams observed by Chin (1989; 1999). The proposed fishway was designed so that if constructed on a 3.0% bed slope it could be scaled up by as much as factor of 4, which would result in an elevation difference of 0.1 m and a pool length of 3.6 m.

For the experiments the three weir geometries in Figure 2.1 were used: a V facing in the upstream direction (VUS), a V facing in the downstream direction (VDS), and a straight horizontal weir (HOR) perpendicular to the flume wall. For the v-shaped weirs, an angle of 140 degrees was used on the inside of the V. For the V-shaped weirs, experiments were run using both natural rocks with a nominal diameter of 0.14 m and cast concrete spheres with a diameter of 0.14 m. The HOR weir was only evaluated using the cast concrete spheres. For the VDS and VUS geometries, each weir was constructed using seven rocks, while six rocks were used per weir for the HOR geometry and were spaced evenly across the channel.

The natural rocks were attached to the bed of the flume using caulking. This method was not effective for attaching concrete spheres, so concrete anchors were installed in their bases and sphere were then bolted to thin stainless steel plates in the weir arrangement (Figure 2.2). These steel plates were then bolted to the bed of the flume. Concrete spheres were constructed with a flat bottom to allow easy attachment and had an installed height of 0.13 m above the bed.

For all experiments flow was controlled using a pump connected to a variable frequency drive (VFD) and flow measurements were taken using a Foxboro IMT25 magnetic flow transmitter. Water surface profile measurements were taken to examine the impacts of slope, discharge, and weir geometry on flow depth. Measurements of the minimum and maximum observed water depth were taken along the centerline of the channel at 0.10 m intervals using a point gauge for a minimum of three pool lengths. The upstream-most and downstream-most two weirs were excluded from measurements due to backwater and tailwater effects. Water surface profile elevation was determined by averaging the minimum and maximum observed value for each location.

Measurements were taken at bed slopes of 1.5%, 3.0% and 5.0% for flowrates ranging from 30 to 150 l/s. The VUS, VDS, and HOR weir geometries were evaluated using concrete spheres while only VUS and VDS were evaluated for natural rocks. A complete list of experiment configurations can be found in Table 2.1.

To study the flow characteristics, measurements were also taken using a Nortek Vectrino acoustic Doppler velocimeter (ADV). To compare the impacts of weir geometry, VUS, VDS, and HOR were compared at 60 l/s and 3.0% bed slope. To compare the impacts of bed slope the VUS weir was evaluated at 60 l/s and 1.5%, 3.0% and 5.0% bed slope. To compare the impacts of discharge, the VUS weir was evaluated at 30 l/s, 60 l/s, and 120 l/s at 3.0% bed slope. To examine the impact of natural materials, the VDS and VUS weirs with natural rock construction were evaluated at 120 l/s and 3.0% bed slope. In total, nine cases were evaluated (Table 2.1).

The ADV was used to measure the longitudinal, transverse and vertical velocity components on a horizontal plane for one pool length (0.9 m) starting one-half of a pool length upstream of the fourth weir and running one-half of a pool length downstream of the fourth weir. This was done in order to study the mean flow, turbulence, and Reynolds shear stresses within the pool. Sampling points were spacing at 0.07 m intervals in the direction of flow and at 0.10 m intervals across the width of the flume. The weir configurations used in the experiment and the ADV sampling grid are shown in Figure 2.1. For the natural rock experiments, measurements using the ADV were taken 0.013 m or 0.08 m above the bed, while in all other cases measurements were taken 0.08 m above the bed. In addition to the horizontal plane measurements, a vertical slice along the channel centreline was also measured for the VUS and VDS cases with natural rock at 3.0% bed slope and 120 l/s, as well as the VUS with concrete spheres at 3.0% bed slope and 60 l/s. A complete list of cases sampled with the ADV is shown in Table 2.1.

For each ADV sampling location, data was collected at a rate of 100 Hz using a sampling volume of 5.5 mm. Data was collected for three minutes at each location, resulting in 18,000 data points per sampling location. Some points were not sampled due to insufficient water depth or were sampled using a side-mounted Sontek FlowTracker ADV at a lower sampling frequency to provide mean velocity measurements only.

After sampling, data was filtered using WinADV software. In highly turbulent or aerated flows it can be difficult to obtain high correlation values. Although correlation values greater than 70% are recommended for most applications, in difficult sampling conditions correlations as low as 30% can be used for mean velocity measurements (SonTek, 1997). Martin et al. (2002) found that correlation values as low as 40% could be used to calculate Reynolds stresses provided 70% of the data was retained or sufficient sampling time was used to reduce the Doppler noise. For this study a minimum correlation value of 40% and an average signal-to-noise ratio (SNR) of 15 were used to filter the data and the Goring and Nikora (2002) despiking method as modified by Wahl (2002) was used. To generate contour plots of ADV results, the MATLAB Biharmonic (v4) interpolation method was used.

Most plots were presented with lengths in a non-dimensional form by dividing by the rock diameter d = 0.14 m. TKE and Reynolds stresses were plotted in a dimensional form as recommended by Lacey et al. (2012).

Results and Discussion

A total of nine combinations of weir geometry, slope, discharge, and weir material were evaluated using the ADV. The complete list of experiments is shown in Table 2.1.

Images of the fishway operating at a variety of slopes and discharges are shown in Figure 2.3. To determine the filtering criteria, a sensitivity analysis was performed for the base weir case of VUS at 60 l/s and 3.0% bed slope. The preferred filtering criteria were determined to be a 40% correlation cutoff threshold with an average SNR threshold of 15 and the Goring and Nikora (2002) despiking method as modified by Wahl (2002). This method was selected because it allowed a greater percentage of data points to be retained to help avoid underestimating turbulence while having relatively consistent velocity and fluctuating velocity values compared with more strict filtering criteria (Figure 2.4).

Water Surface Profile and Discharge

Water surface profiles for all of the evaluated cases are shown in Figure 2.5. At 5.0% bed slope the fishway was operating in the plunging flow regime for all cases evaluated. At 3.0% bed slope, the fishway was operating in the plunging flow regime for all of the concrete sphere cases and for the VUS geometry with rock construction. For the VDS geometry with rock construction, the fishway appeared to enter a transitional flow regime at discharges of 120 and 150 l/s. At the lowest slope of 1.5%, discharges of 60 l/s or larger resulted in a transitional flow regime for all evaluated geometries. The streaming flow regime was not observed in this set of experiments.

The mean water depth was the largest for the VDS geometry and the smallest for the HOR geometry (Figure 2.6). Mean water depth increased with discharge and decreased with increasing slope. The maximum water depth was slightly higher for the VDS than the VUS, with the HOR having the lowest maximum depth. Maximum depth increased with discharge and decreased with increasing slope. The minimum water depth was the lowest for the VUS geometry, with the VDS having the largest minimum depth. The minimum depth for the VUS geometry was lower than other geometries due to the presence of a concentrated hydraulic jump region formed immediately downstream of the weir along the channel centerline. Minimum depth decreased for the VUS geometry with increasing bed slope and increased with increasing discharge.

The relationship between dimensionless discharge Q_{t*} and *L/P* was evaluated Figure 2.7. The results were similar to those presented by Ead et al. (2004), however, the transition from the plunging to streaming flow regime occurred at a greater value of Q_{t*}. Flow was observed in the plunging flow regime for Q_{t*} values between 0.24 and 2.03 and in the transitional flow regime for Q_{t*} values between 1.63 and 2.77.

A stage-discharge analysis was performed for the fishway based on the standard weir equation. Power-regression was used to determine C_d values for the proposed weir design as a function of the total head divided by the weir height (Figure 2.7). Three unique flow regimes were identified, with the transitions between regimes occurring at H_t/P values of 0.325 and 0.650. For each of the three regimes the resultant discharge coefficient equations are shown below.

$C_d = 0.21(H_t/P)^{-1.47}$ *for* $H_t/P < 0.325$ *Equation 2.4*

$C_d = 0.44(H_t/P)^{-1.38}$ *for* $0.325 < H_t/P < 0.650$ *Equation 2.5*

$C_d = 0.90(H_t/P)^{-0.80}$ *for* $0.650 < H_t/P$ *Equation 2.6*

The application of the proposed C_d values resulted in a mean error or 5.4% (SD = 3.8%) with a maximum error of 14.8% and a median error of 4.6% (Figure 2.8). The greatest error occurred when $Q_{t*}$was equal to 3.25 and flow was in the transitional flow regime. The C_d values obtained in this study are much larger than those for conventional weirs because the account for flow through the base of the weir in addition to flow over the weir crest.

It is possible to estimate the amount of flow passing through the weir as orifice flow (Q_O) by using the orifice equation shown below where A is the cross-sectional area not blocked by rocks, h_{max} is the maximum water depth and h_{min}.is the minimum water depth

$$Q_O = C_d A\sqrt{2g(h_{max} - h_{min})} \qquad \textit{Equation 2.7}$$

For all of the evaluated cases, an orifice discharge co-efficient of 0.6 was used to provide an estimate of the flow moving through the rocks as orifice flow. It was estimated that the orifice discharge ranged from 8 to 29 l/s and accounted for between 6% (at high slopes and low discharges) and 75% (at low slopes and high discharges) of the total flow in the fishway. Despite being able to estimate the amount of orifice flow, the most accurate stage-discharge relationship was obtained by varying $\mathrm{C_d}$ and applying the standard weir equation.

In the flow regime with the lowest H_t/P values, the flow has a large component of orifice flow, with minimal discharge occurring over the weir. In the lower portion of this range of H_t/P the effects of surface tension also affect the flow. From the developed equation, as H_t/P approaches zero the discharge co-efficient will approach infinity, and the equation will be invalid for H_t/P less than zero. The lowest flow regime should be applied carefully, and avoided for low values of H_t/P. In the intermediate and highest flow regime the flow is likely dominated by weir flow over the top of the weir, with orifice flow only playing a small component. It was not possible to determine what caused the abrupt jumps in C_d.

To develop the stage-discharge relationship three different water measurements were evaluated: maximum water depth, mean water depth (average of all measurements along the pool centerline), and minimum water depth. As shown in Figure 2.6, the mean depth was the most robust value when compared with minimum and maximum flow depth, as it showed much less scatter and clearer trends, particularly when natural materials were used for weir construction. Despite this, the best relationship for determining a discharge co-efficient was found to occur when the maximum flow depth was used and resulted in a stage-discharge relationship that did not appear to be very sensitive to weir geometry or weir material.

Flow Patterns and Velocity

By examining the flow patterns for the concrete spheres (Figure 2.9) it was observed that for the VUS weir geometry, streamlines converged towards the centre of the channel as flow approached the upstream side of the weir and diverged towards the flume walls on the downstream side of the weir. This pattern on the downstream side of the weir is more apparent at low discharges. Towards the centre of the pool the streamlines were largely parallel and facing directly downstream.

For the VDS geometry, the pattern upstream of the weir was opposite of the VUS weir with flow diverging towards the channel walls. On the downstream side of the weir flow near the channel walls continued to diverge towards the walls, while flow farther from the edge converged towards the centre of the channel. For the HOR weir geometry the streamlines were largely parallel, with some minor convergences and divergences occurring immediately downstream of the weir.

For both the VUS and VDS geometries, flow patterns mirrored along the channel centerline were similar to those observed for oblique weirs. Although flow separation is often observed on the downstream side of oblique weirs (Kabiri-Samani et al., 2010) it was not observed for the current experimental setup, likely due to the short pool length.

The impacts of weir geometry, bed slope, and discharge on the velocity within the fishway were evaluated (Figure 2.10). The mean streamwise velocity was the greatest for the VUS geometry, followed by the HOR and then the VDS geometry. Mean streamwise velocity increased with both increasing bed slope and discharge. The maximum streamwise velocity was also the largest for the VUS geometry and increased with both bed slope and discharge. The maximum vertical and transverse velocity magnitudes were the largest for the VDS geometry, followed by VUS and HOR geometries. Increasing bed slope and discharge resulted in an increase in velocity magnitude in both the vertical and transverse directions.

For the VUS geometry with concrete spheres (Figure 2.9) the region with the highest horizontal velocity was located along the centerline of the channel. While increasing the discharge in the fishway increased both the width and length of the high velocity region, increases in slope increased the width only and caused no noticeable impact on the length of the high velocity region.

For the VDS configuration the regions with the highest horizontal velocity were located along the edge of the channel, with a smaller region located immediately downstream of the weir. For the HOR weir configuration, the region with the highest velocity was located immediately downstream of the weir and maintained an approximately equal magnitude across the entire channel width.

From the velocity results for the VUS weir configuration, orifice flow can be seen flowing through the base of the rocks and is shown as an upwelling of vertical velocity for slopes of 3.0% or less and discharges of 60 l/s or less. At 120 l/s and 150 l/s this upwelling of water seems to disappear. For fishways designed to pass small bottom-dwelling fish, the structure should be designed to operate in a range where orifice flow occurs through the base of the rocks. This will serve to work as an attraction flow for small species of fish attempting to migrate upstream as well as helping to prevent the creation of recirculation zones on the downstream side of the weir that could trap debris. This flow pattern can also help to promote hyporheic exchange flow that can oxygenate the water and reduce water temperatures (Crispell and Endreney, 2009).

When examining vertical velocity (Figure 2.12) for the VUS geometry with concrete spheres it was observed that discharge had a major impact on the vertical flow patterns. For a discharge of 30 l/s, flow fell over top of the weir towards the edge of the channel with a negative velocity, but flow towards the centre of the channel had a positive vertical velocity, dominated by an upwelling of water that has moved through the rocks as orifice flow. When the discharge was increased to 60 l/s downward velocity regions were found at both the edges and in the centre of the channel, with some upwelling still occurring at the midpoints between the channel centre and the walls. At the discharge of 120 l/s the upwelling of water almost completely disappeared with water moving predominantly as downward flow over the weir.

The impact of slope on vertical velocity seemed to be largely magnitude related (Figure 2.10, Figure 2.12), with the maximum vertical velocity on the downstream side of the weir in both the centre of channel and towards the walls increasing drastically as slope increased. Slope also seemed to have an impact on upwelling, with limited upwelling regions occurring at the highest slope of 5.0%. When comparing weir geometry, HOR weirs had a lower maximum magnitude of downward flow when compared with the VUS and VDS geometries, which had similar maximum values. The orifice flow under the base of the rocks appeared to be much lower for the VDS and HOR geometries when compared with the VUS.

Vertical velocity was also evaluated as a vertical slice along the channel centerline for three weir configurations (Figure 2.13). Detailed measurements were taken for the VUS geometry with concrete spheres at 3.0% bed slope and 60 l/s, while less detailed measurements were taken for VUS and VDS geometries with natural rocks at 3.0% bed slope and 120 l/s. For the 60 l/s VUS weir, flow streamlines remained relatively parallel throughout the entire pool length, with the exception of small region of upward flow immediately upstream of the weir and small region of downward flow immediately downstream of the weir.

Although scour was not a major focus of this study, the VUS weir was effective in decreasing horizontal velocity magnitude along the banks and directing scour away from the banks towards the centre of the channel when compared with the VDS and HOR configurations. Based on this feature, the VUS geometry is well-suited for areas where scour is an issue, while the HOR and VDS geometries should only be considered for locations with less-erodible beds and banks. Although the VUS geometry did have some negative vertical velocity regions near the channel wall on the downstream side of the weir, these were likely exacerbated by flow concentration at the walls caused by the channel geometry and would cause less of an issue in a non-rectangular channel.

The maximum overall velocity magnitudes observed in the fishway were larger than predicted by the equation $V = \sqrt{2gLS_0}$ indicating that the weirs are not effective at dissipating all of the energy and that the upstream velocity head is an important component of the maximum velocity on the downstream side of the weir (Figure 2.11).

Turbulence, Shear Stress, and Power Dissipation

When looking at TKE for the concrete spheres (Figure 2.14) we can see that for VUS the high TKE zones were located on the downstream side of the weir close to each of the channel walls. As discharge increased, both the size and the intensity of the high TKE zones increased. While at 30 l/s the TKE was highly concentrated on the downstream side of the weir, by the time discharge was increased to 120 l/s there were regions where TKE exceeded 0.05 m^2/s^2 found throughout the pool. Changes to the slope of the fishway seemed to have less impact on TKE than changes in discharge. In general, increases in slope caused small increases in the size and magnitude of the high TKE regions. When examining the impacts of weir geometry on TKE, we can see that the magnitude of the maximum turbulence is much lower for the HOR configuration. For the HOR geometry the maximum TKE zone occurred approximately two boulder diameters downstream of the weir, rather than immediately on the downstream side. VUS and VDS both had similar TKE magnitudes, with the highest TKE regions occurring in roughly the same locations.

For the VUS geometry with concrete spheres, TI patterns (Figure 2.15) were relatively similar to those for TKE, with the highest TI regions occurring on the downstream side of the weir near the channel walls. Changes in discharge seemed to have little to no impact on TI, while increasing slope caused a decrease in the size of high TI zones, as well as decreasing the maximum values observed. Increases in slope also caused the high TI zone to progress further downstream in the pool, moving away from the weir. When comparing weir geometries, the maximum TI for the VUS geometry was slightly higher than either the HOR or VDS geometry. For the HOR geometry the maximum TI zone occurred approximately two rock diameters downstream of the weir and ran across the entire channel width. For the VDS geometry the maximum TI zone was located towards the centre of the channel and formed a downstream facing v-shape. For the VDS weir there was a noticeable low TI zone immediately downstream of the weir in the centre of the channel.

Reynolds stresses were evaluated in the XY plane only (Figure 2.16). For the VUS geometry with concrete spheres, the regions with the highest plane Reynolds stresses were located on the downstream side of the weir near the channel walls, in a similar location to the regions with the highest TKE and TI. Increasing the discharge resulted in an increase in the maximum magnitude of Reynolds stresses, as well as the size of the regions with high Reynolds stresses. At a discharge of 120 l/s Reynolds stresses exceeding 80 Pa were observed occurring towards the centre of the pool on the upstream side of the weir. Increasing the bed slope from 1.5% to 3.0% increased the magnitude of the maximum Reynolds stresses, but there was no major change in magnitude that occurred when slope was increased from 3.0% to 5.0%. Comparing the weir geometries, the VDS geometry had regions of similar size and magnitude to the VUS while the maximum Reynolds stresses for the HOR geometry occurred approximately two boulder diameters downstream of the weir.

The water surface profile data was used to calculate the volumetric power dissipation. The equation used for volumetric power dissipation E is shown below where V_{Water} is the volume of water in a single pool. The average water depth was used to calculate the pool volume and was averaged over three pools.

$$E = \frac{\rho g Q S_0 L}{V_{Water}} \quad \text{Equation 2.8}$$

The results for volumetric power dissipation (Figure 2.20) show that the VDS weir with rock construction had the lower power dissipation rates than any other weir geometry or construction material. The HOR weir geometry had the highest volumetric power dissipation rate of any of the concrete weir constructions. Similar power dissipation rates were observed for all other weir geometries. For each bed slope, volumetric power dissipation appeared to follow a power function of the discharge to the exponent of 2/3. At 1.5% bed slope, all of the evaluated discharges were below the upper limits for volumetric power dissipation in fishways. At 3.0% bed slope only discharges of 120 l/s or less were at or below the upper limit, while at 5.0% bed slope only discharges of 30 l/s were at or below the upper limit.

Impacts of Natural Materials

When natural rocks were used for the weir construction the flow patterns were also much more irregular, in particular for the VUS geometry (Figure 2.17). When the horizontal velocity of the concrete spheres was compared with that of the natural rock construction

(Figure 2.17), the maximum velocity magnitudes were similar despite having different sampling planes. The high velocity region was still located in the same location along the channel centerline. For the VDS with rock construction at 120 l/s, which was not evaluated with concrete spheres, high velocity regions were observed forming along the channel walls, with a low velocity region located along the channel centerline.

When natural rock construction was used, the vertical velocity became highly irregular, with most of the negative velocities concentrated towards a single side of the channel (Figure 2.17). When comparing the 120 l/s VDS rock weir with the 60 l/s VDS concrete weir it was observed that at higher discharges the downward flow was concentrated towards the channel walls, with no region of downward flow along the channel centerline.

For the VUS with natural rocks operating at 120 l/s the streamlines in the vertical direction (Figure 2.13) showed a similar pattern to the VUS at 60 l/s, with relatively parallel streamlines and the weir operating in the plunging flow regime. In contrast, the VDS weir at 120 l/s showed backwards flow indicating the presence of a recirculation zone on the downstream side of the weir and water surface profile shows the fishway operating in the oscillating flow regime.

For the natural rock construction, the VUS weir had relatively low levels of TKE (Figure 2.18) when compared with the concrete construction. The location of the regions with the highest turbulence was similar for both construction materials. The VDS weir with rock construction had the highest TKE values observed out of any weir evaluated. The position of these high TKE zones was similar to that of the VDS weir with concrete construction evaluated at 60 l/s.

Comparing the TI for natural rocks (Figure 2.18) with the concrete spheres, the patterns and magnitudes were similar. For the VUS weir configuration the regions of high TI were concentrated along the channel walls and for the VDS configuration they were located in the regions of high TKE on the downstream side of the weir near the channel wall and along the centerline of the channel.

For the natural rock construction, lower Reynolds stresses were observed on the downstream side of the weir for the VUS geometry, while the VDS geometry had the highest Reynolds stresses out of any weir configuration evaluated (Figure 2.19). No impact of natural materials was observed on volumetric power dissipation (Figure 2.20).

Although there were some differences between experiments run with concrete spheres and natural rocks, flow patterns and mean flow characteristics were largely similar. This suggests that the findings of this study can be practically applied to rock-weirs constructed with natural materials.

Implications for Fish Passage

When designing this style of fishway, an installation location should be selected cautiously. During low flow periods there may not be enough flow to pass over the top of the rocks which could cause some fish could become stranded. In comparison with sharp crested weirs, this type of structure will continue to allow for the passage of small fish through the base of the rocks during these low flow conditions.

With respect to resting area for fish, it is necessary to provide a region that is at least the size of the fish targeted by the fishway, with the zone preferably being multiple times the length, height, and width of the fish. From a velocity perspective for the VUS weir it appears that fish would rest near the channel walls on the downstream side of the weir, and for the VDS configuration fish would rest near the centre of the channel. For the HOR configuration fish would be forced to rest 2 to 3 weir diameters downstream of the weir in the lower velocity zone. The VUS has an advantage over the HOR by having regions with lower minimum velocities than the HOR geometry.

It may also be necessary to determine the velocity through the base of the rocks for burst speed requirements. This problem was not addressed in this study, so we recommend using the maximum velocity observed in the fishway to produce a conservative design.

When velocity requirements for resting zones are combined with TKE and TI, the regions near the channel walls immediately downstream of the weir become undesirable for fish due to high levels of TKE. This appears to be largely in part to the presence of the submerged hydraulic jump at this location. Weak-swimming fish would likely rest just downstream of these high TKE regions in the low-velocity zone near the channel wall, while stronger fish may choose to rest in the centre of the channel towards the downstream end of the pool. Although the TI in these resting zones is relatively high (0.4 to 0.6) there would likely be minimal impact on fish as the mean velocity is low. Because TI is relative to the mean local velocity, it can be difficult to use with some high TI zones offering excellent habitat for fish due to having extremely low mean velocities. Since small changes in TKE can have major impacts on fish when the mean velocity is low, we recommend developing a minimum threshold for mean velocity and TKE, below which TI values become an unimportant habitat parameter.

Examining the Reynolds stresses in the XY plane, the regions with the highest stresses occurred in roughly the same location as the regions with high TKE. Although potentially uncomfortable for fish, even the highest values observed in this study were orders of magnitude below the threshold required to injure small salmonids (Čada et al., 2006). The Reynolds stresses findings suggest that weak-swimming fish would rest downstream of the weir near the channel wall, with stronger fish resting in the centre of the channel towards the downstream end of the pool. It should be noted that Reynolds stresses decrease when there are large roughness elements present on the bed (Martin et al., 2002), so the stresses in a fishway with a rough bed would likely be lower than those observed during the experiments.

If the resting zones within the pool are too small for the target species, the pool length could be increased for all cases where the weir was observed to be operating in a plunging flow regime. This would increase the length of the low-velocity zone downstream of the highly turbulent region on the downstream side of the weir. Increasing the pool length would also reduce the volumetric power dissipation rate for the pool.

Comparing the results of the volumetric power dissipation analysis with the velocity and turbulence results, it seems that at least for the current weir there is good agreement between acceptable designs from both analyses. For example, the VUS weir at 60 l/s and 5.0% slope and the VUS weir at 120 l/s and 3.0% are both meet or exceed the limit for acceptable volumetric power dissipation in fishways. An examination of the velocity and turbulence characteristics leads to the same conclusion. Because the relationship between discharge, bed slope, and volumetric power dissipation is very clear for the evaluated weirs, Figure 2.20 could serve as a valuable design tool for designing rock-weir fishways. This finding also suggests that using the average water depth to calculate volumetric power dissipation may be a good way to perform an in-situ evaluation of effectiveness for existing rock-weir fishways if more detailed measurements are not possible.

Potential Applications

The results of this experiment have a number of limitations, largely the use of a rectangular channel cross-section and a smooth bed. Applying this research to practical applications should be done so carefully so that field verification of laboratory results can be performed.

We recommend that a field test of the propose fishway design take place. For a test installation of this style of rock-weir fishway, we suggest that installation take place in a box culvert or canal to mimic the rectangular cross-section used in this experiment. For small structures this could even allow the fishway to be installed on a 1:1 scale, eliminating any scaling issues. On a 1:1 scale, this project could also be installed in small streams, where the simplicity of the structure and ability to use local materials may reduce costs when compared with conventional technical fishpasses.

The method of attaching the concrete spheres to the bed used for this experiment (Figure 2.2) also has potential real-world applications. By using concrete anchors to attach natural rocks to steel plates in the desired weir configuration, weirs can be preassembled off-site and reduce the required installation time. The use of concrete anchors also increases the strength of the attachment, reducing the risk that rocks will be lost during high flows or when impacted by ice. The ability to bolt the entire weir in place allows for quick addition or removal of weirs if required and the position of weirs can be quickly adjusted. This method of attachment also makes it easy to repair or replace a single rock when compared with rock-weir structures that are cast-in-place. This method of installation also makes it easy to improve fishways that are not functioning satisfactorily, as weirs can easily be moved, modified, or increased in number.

Conclusions

We examined the flow characteristics of series of rock-weir fishways with different weir geometries. We found that the VUS weir geometry offered acceptable resting zone with respect to turbulence and velocity for slopes of 1.5% at discharges below 150 l/s and slopes of 3.0% at discharges at or below 120 l/s. Resting zones were identified on the downstream of the hydraulic jump and near the channel walls. At slopes below 3% with discharges of 60 l/s or less there was significant orifice flow through the base of the weir.

At a discharge of 120 l/s we identified the formation of a recirculation zone on the downstream side of the VDS weir, but this was not observed at the same discharge for the VUS configuration. Although the VUS weir configuration had similar volumetric power dissipation rates to the HOR and VDS weir configurations, it offered the advantage of directing scour toward the centre of the channel and reducing the velocity along the banks. The volumetric power dissipation rate was found to be related to the discharge through a power function, and a figure was created to aid engineers in designing VUS rock-weir fishways that are within the acceptable limits for volumetric power dissipation.

We found that none of the existing stage-discharge relationships provided an accurate estimate of discharge for the design fishway so a new relationship was proposed that provided a mean error of 5.3% (SD = 3.8%) and represented a significant improvement over the existing equations. From the water surface profile we identified plunging and transitional flow regimes but did not observe streaming flow.

Finally, we proposed a new method of rock-weir construction to reduce installation time, cost, and improve design flexibility.

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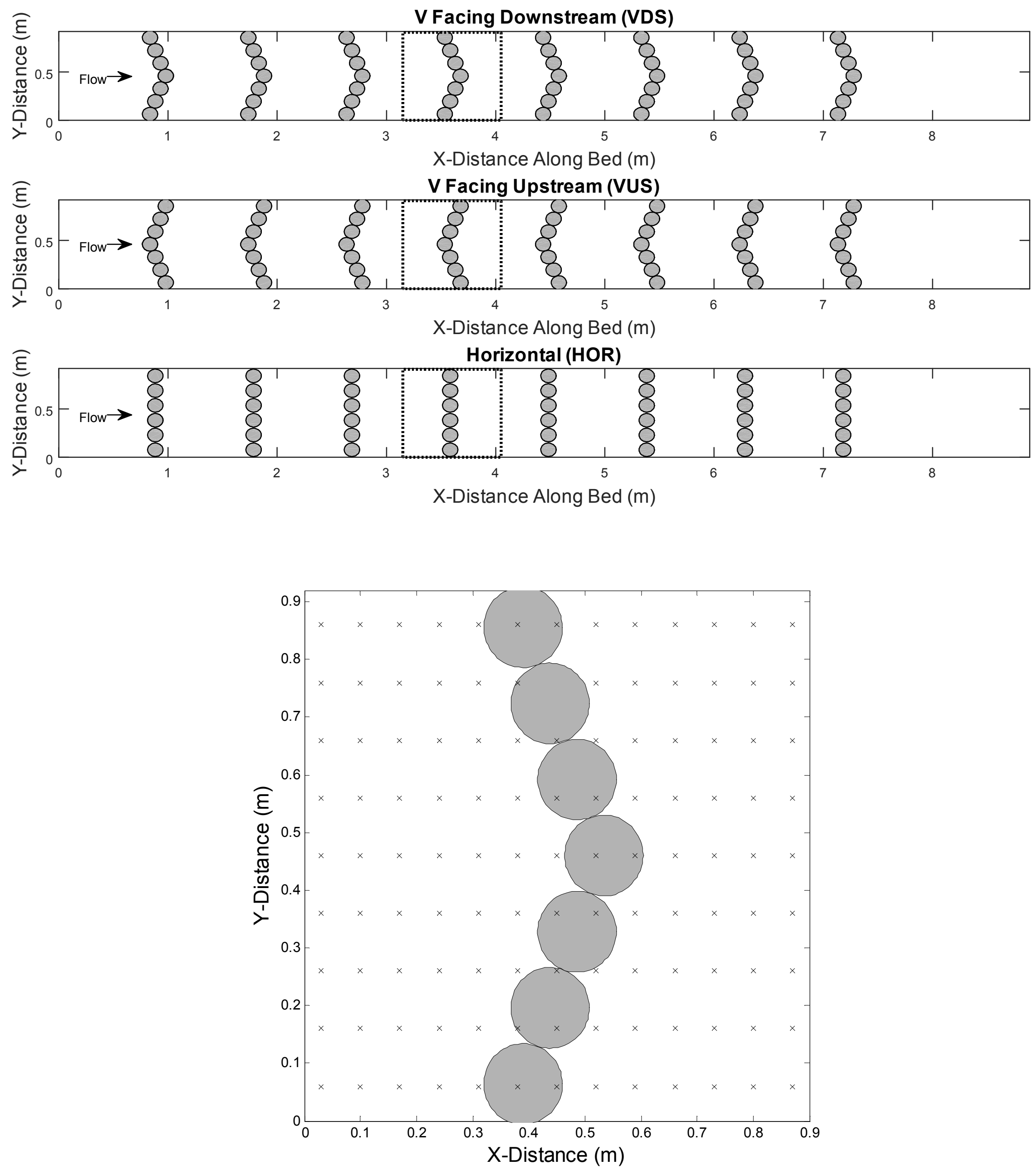

Figure 2.1. The three weir configurations used in this study are shown (top). The detailed measurement pool is shown as a dashed box. ADV sampling locations in the detailed measurement pool are shown with an 'x' (bottom). ADV sampling locations were spaced 0.07 m in the direction of flow and 0.10 m across the width of the flume. Some locations were not sampled with the ADV due to the presence of rocks or insufficient water depth.

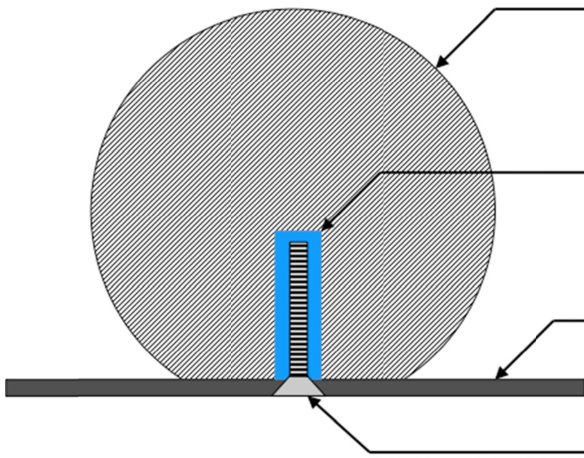

Figure 2.2. Flat-bottom concrete sphere attachment method for weir construction. Stainless steel plates were bolted to the flume bed.

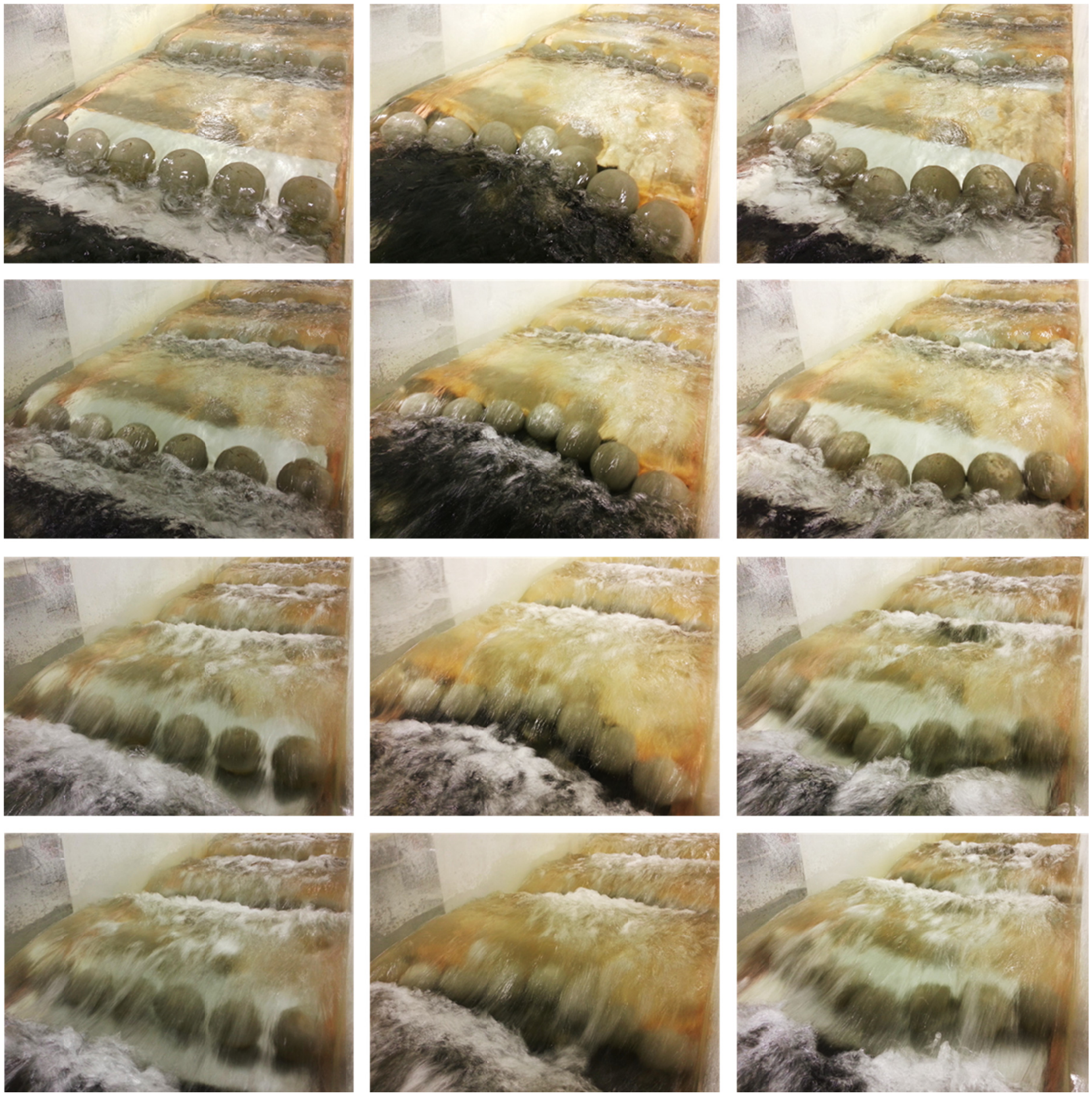

Figure 2.3. Fishway operating during laboratory studies at 30 l/s (top row), 60 l/s (second row), 120 l/s (third row), and 150 l/s (bottom row) for 3.0% bed slope using concrete spheres for HOR (left), VUS (centre), and VDS (right) weir geometries.

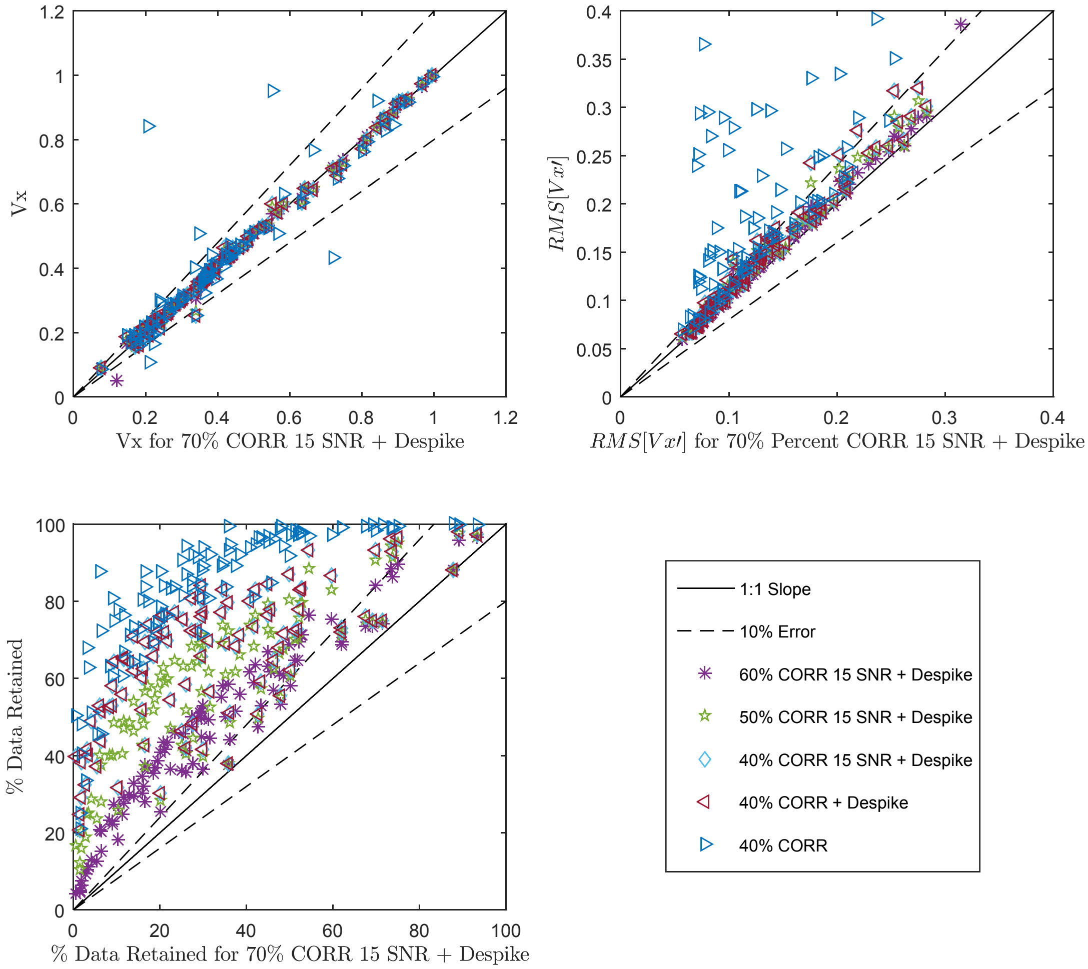

Figure 2.4. Impact of ADV filtering criteria on x-direction mean velocity (top-left), x-direction fluctuating velocity component (top-right), and percent of data retained (bottom-left) for the VUS weir operating at 3.0% bed slope and 60 l/s. For despiking Goring and Nikora (2002) as modified by Wahl (2002) was used. For correlation filtering a minimum threshold was used, while for SNR filtering an average value was used.

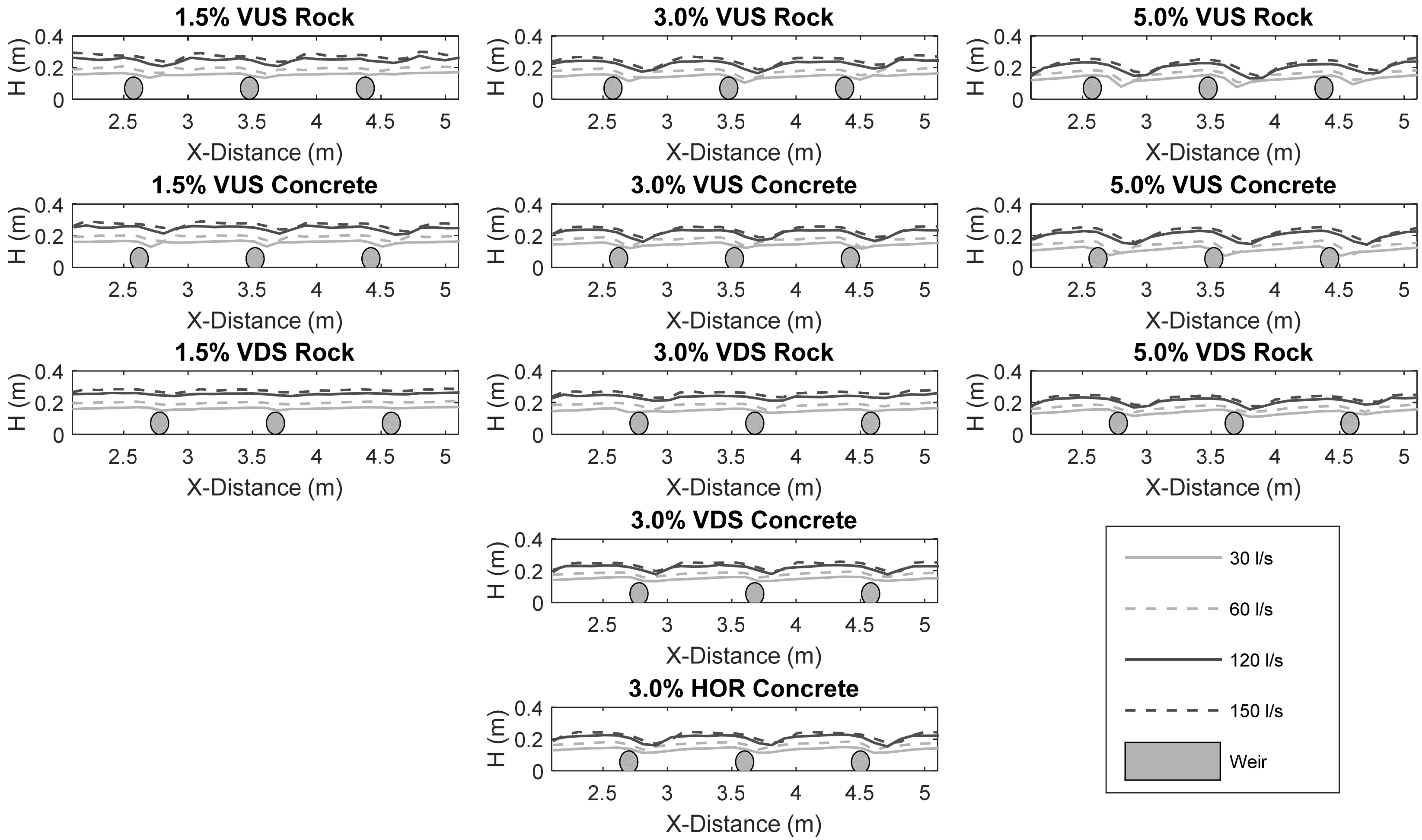

Figure 2.5. Water surface profile plots for the fishway under a variety of operating conditions. Two flow regimes were observed: plunging (weir), and transitional.

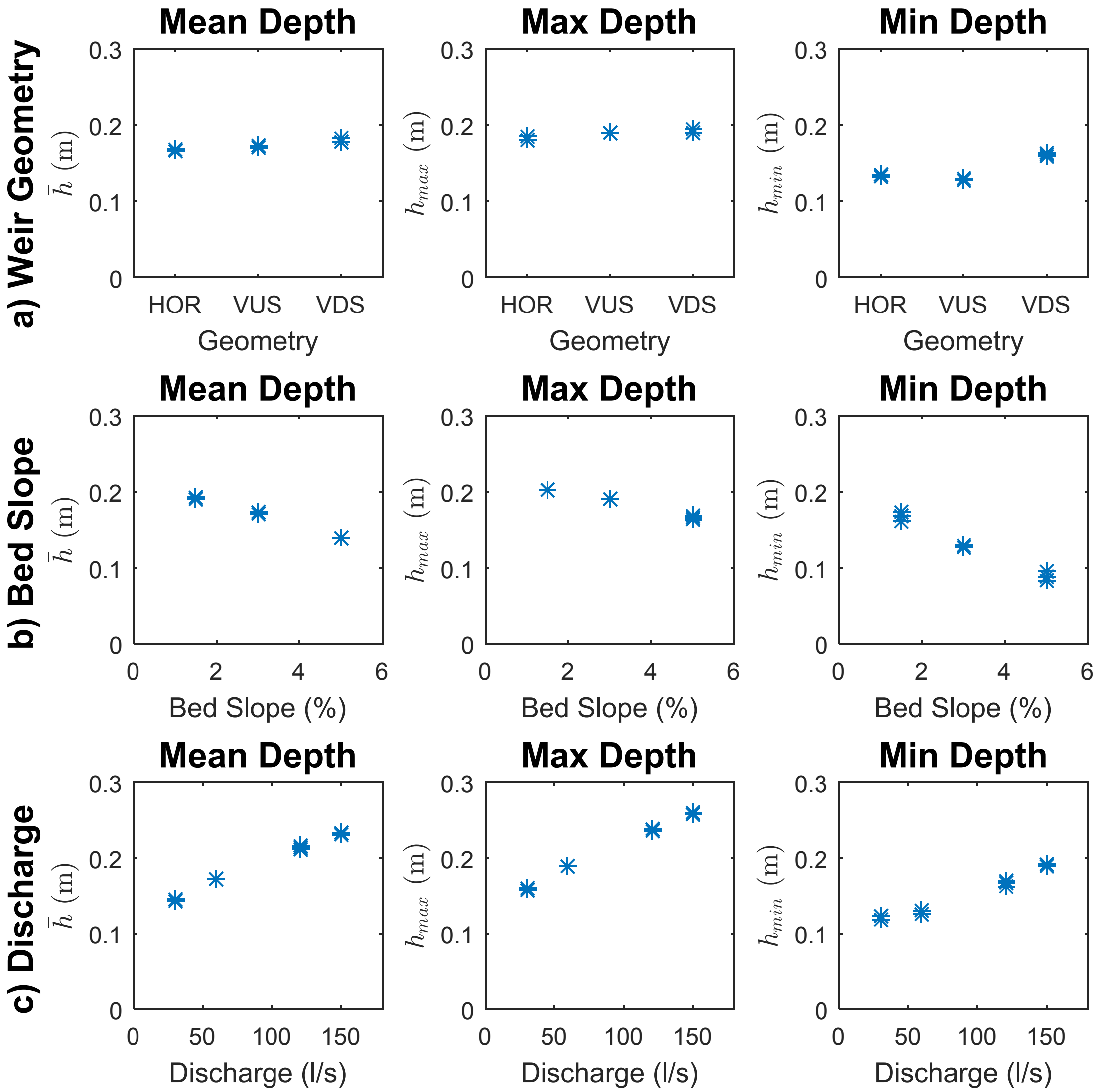

Figure 2.6. Impact of discharge, slope, and weir geometry on water depth. Row a) was run at 60 l/s and 3.0% bed slope, row b) at 60 l/s with VUS, and row c) at 3.0% bed slope with VUS. All results shown are for concrete spheres. Three pools were evaluated individually for each case.

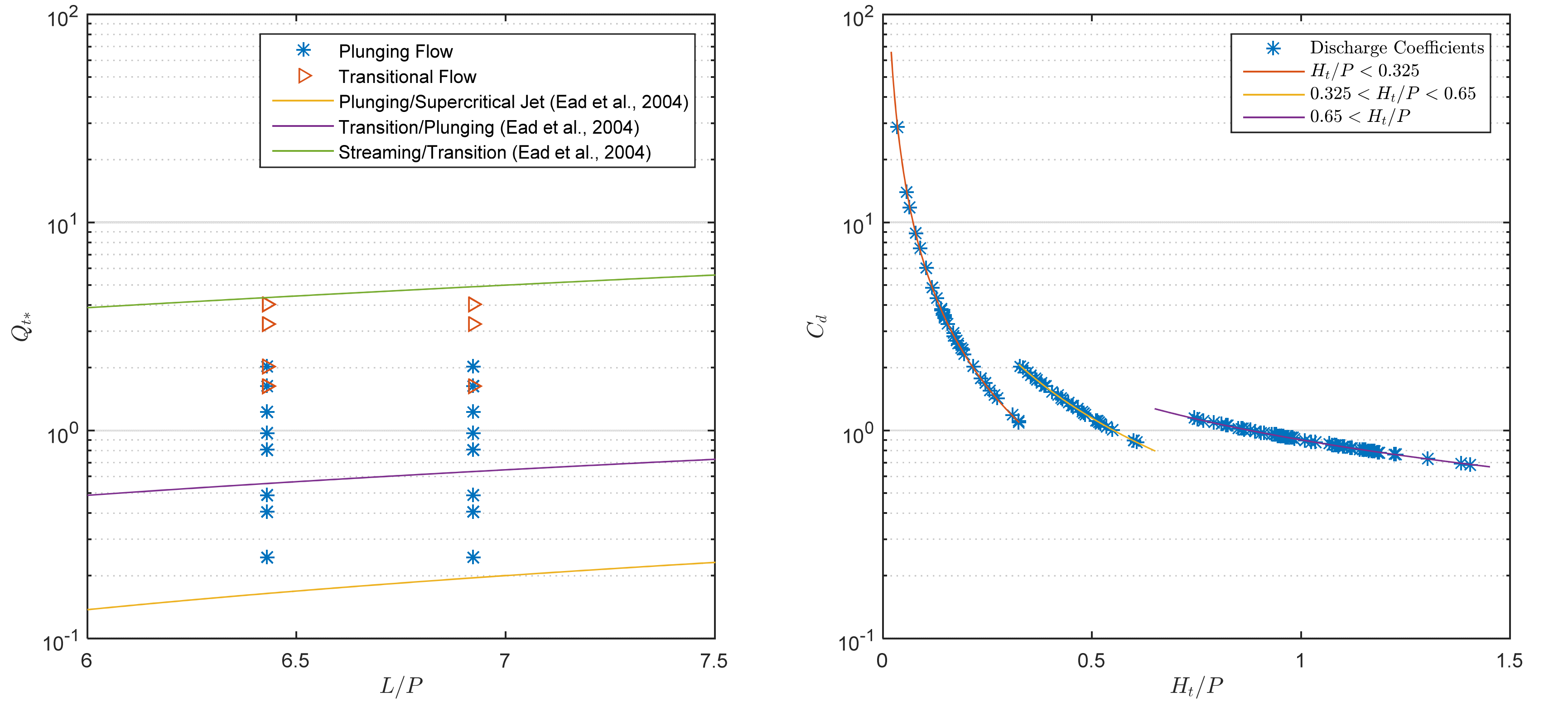

Figure 2.7. Flow regimes (left) based on dimensionless discharge and L/P shown with regimes from Ead et al. (2004). Discharge coefficient is shown as a function of total head divided by weir height (right).

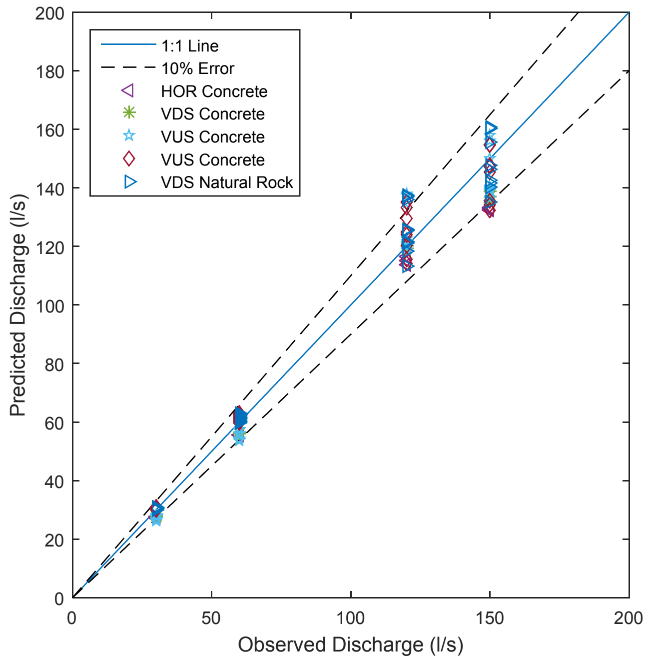

Figure 2.8. Observed discharge vs. predicted discharge for the proposed values of C_d. The proposed equation resulted in a mean error of 5.3% (SD = 3.8%).

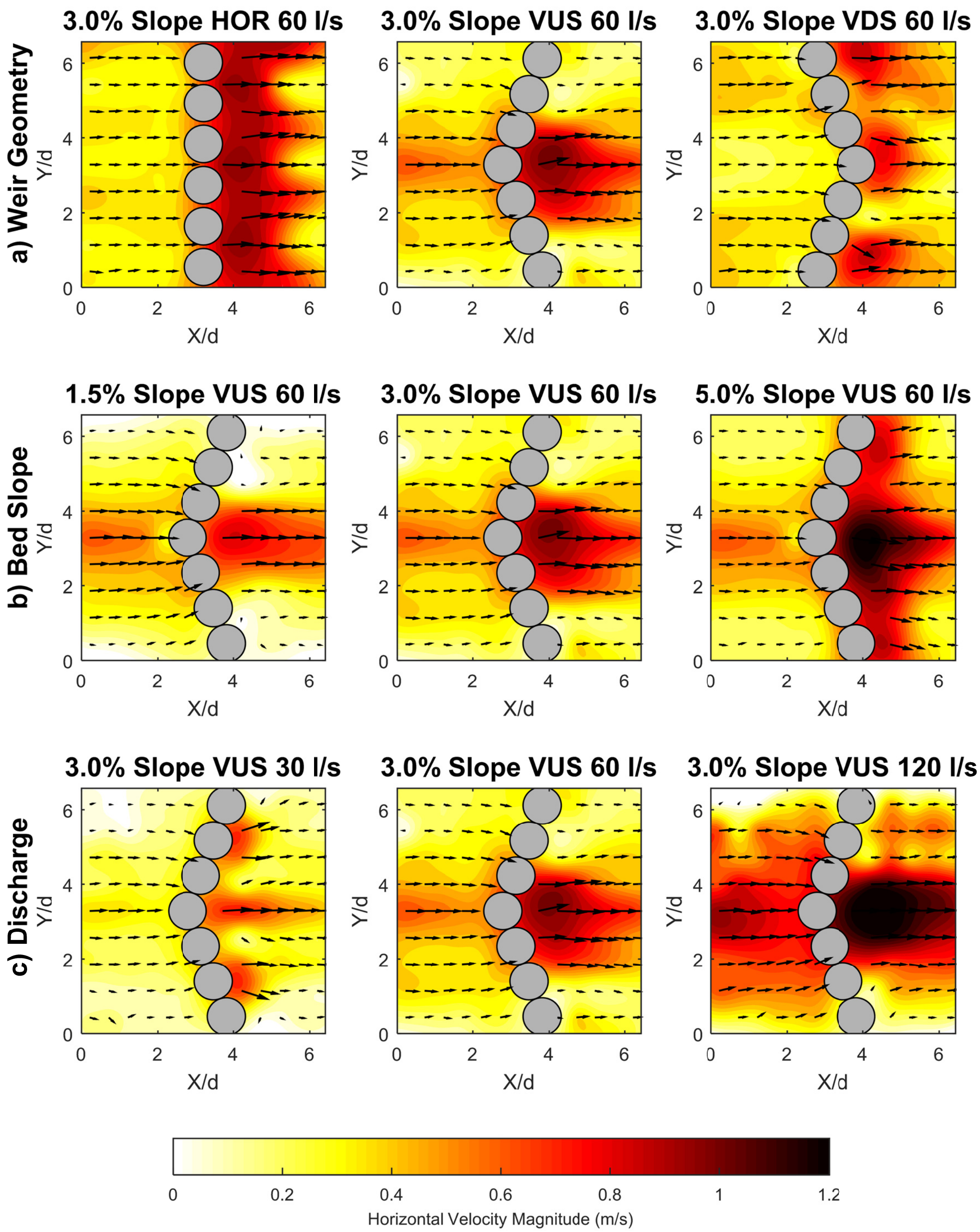

Figure 2.9. Influence of a) weir geometry, b) bed slope, and c) discharge on mean horizontal velocity magnitude $\sqrt{\overline{u^2}+\overline{v^2}}$ and velocity vectors in fishway. Note that all three plots in the centre column are identical. d = rock diameter (0.14 m).

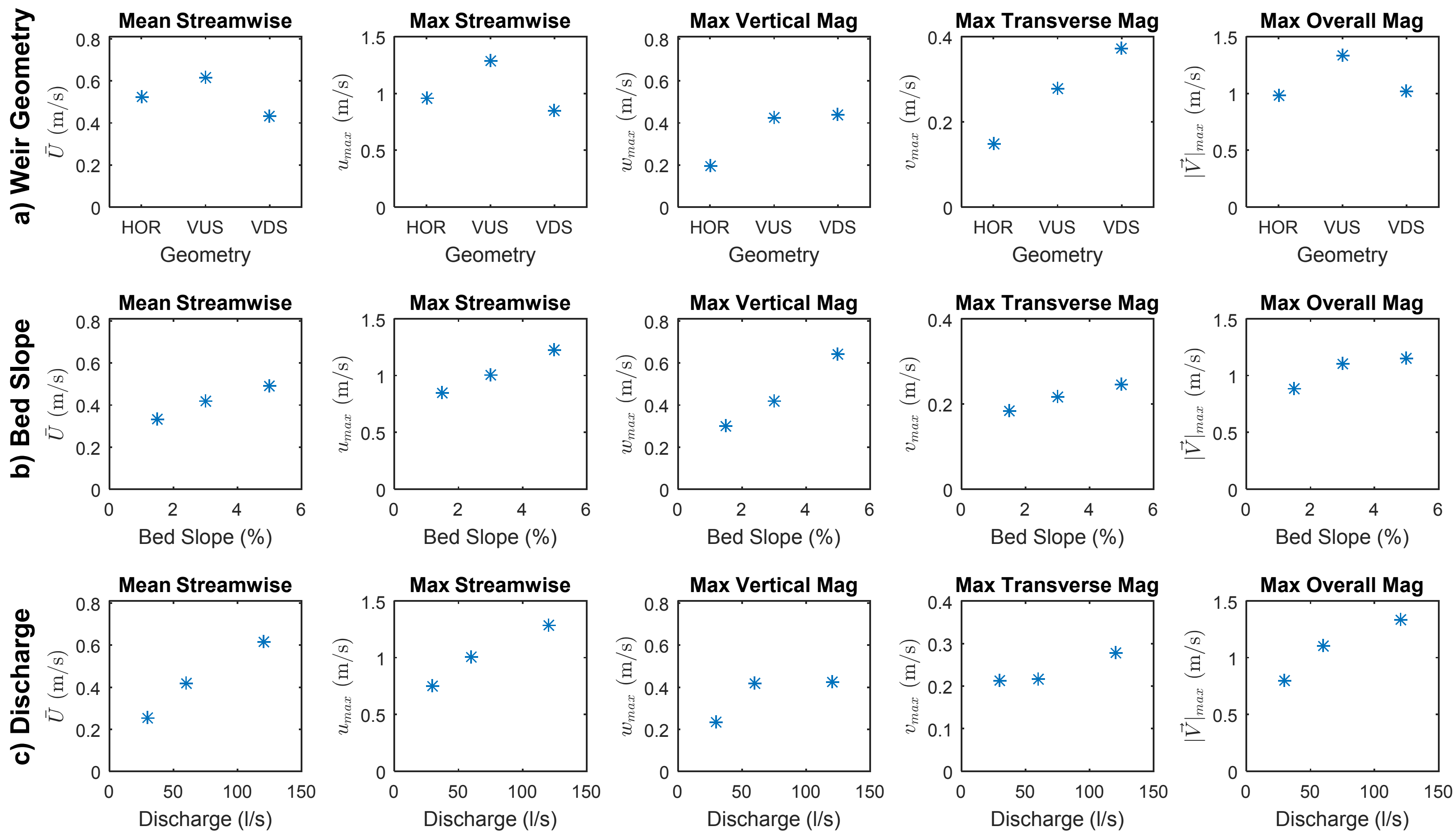

Figure 2.10. Influence of a) weir geometry, b) bed slope, and c) discharge on velocity. Row a) was run at 60 l/s and 3.0% bed slope, row b) at 60 l/s with VUS, and row c) at 3.0% bed slope with VUS. All results shown are for concrete spheres.

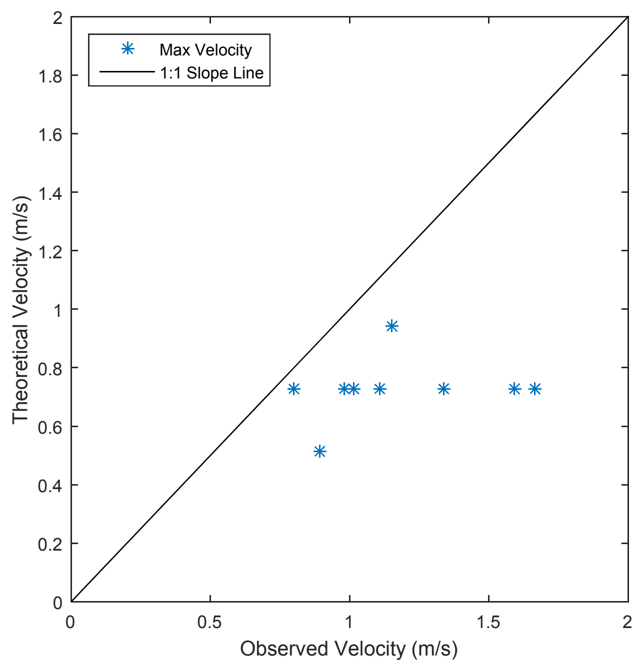

Figure 2.11. Observed maximum velocity magnitude vs. theoretical maximum velocity magnitude.

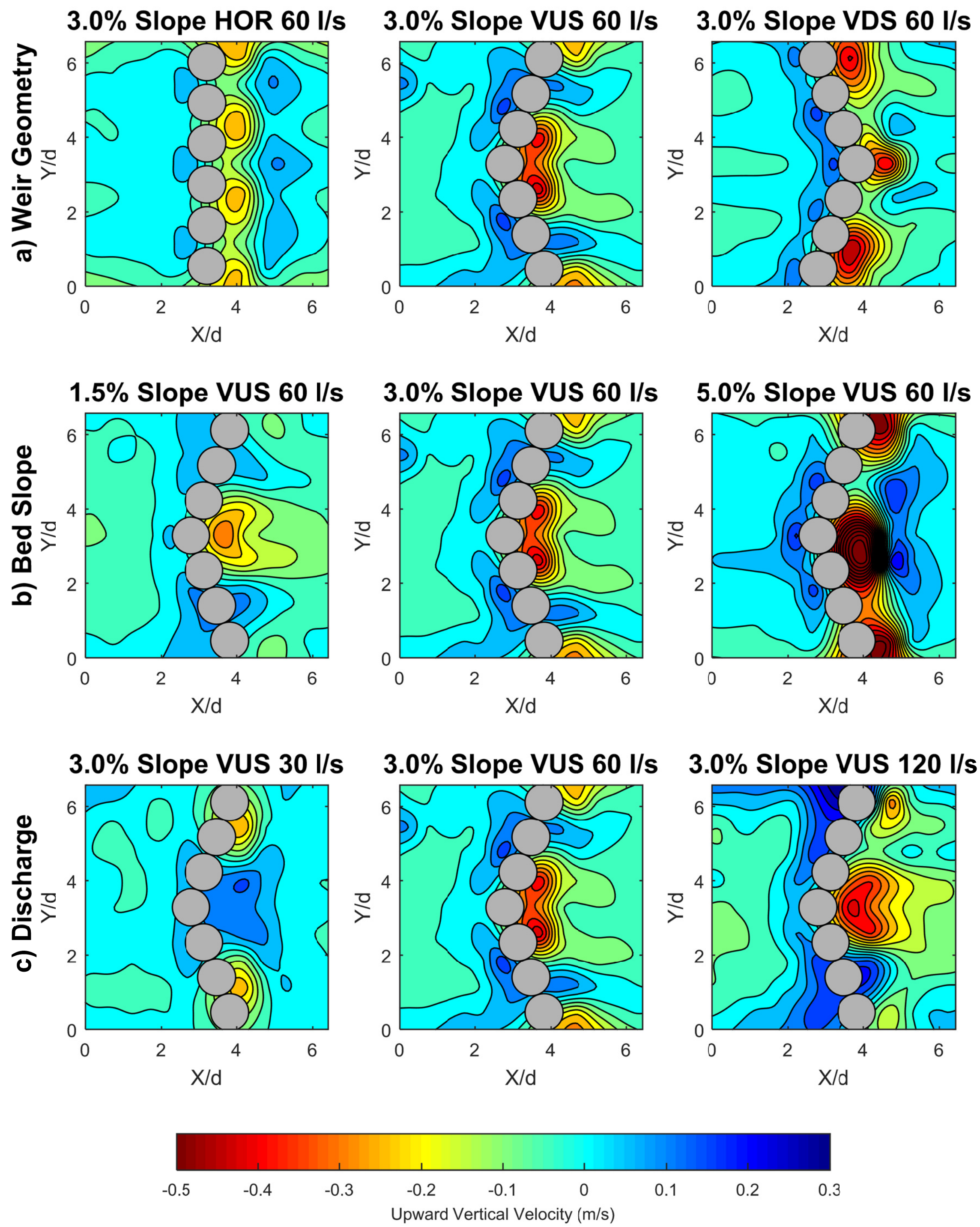

Figure 2.12. Influence of a) weir geometry, b) bed slope, and c) discharge on mean upward vertical velocity $\overline{w}$ in fishway. Note that all three plots in the centre column are identical.

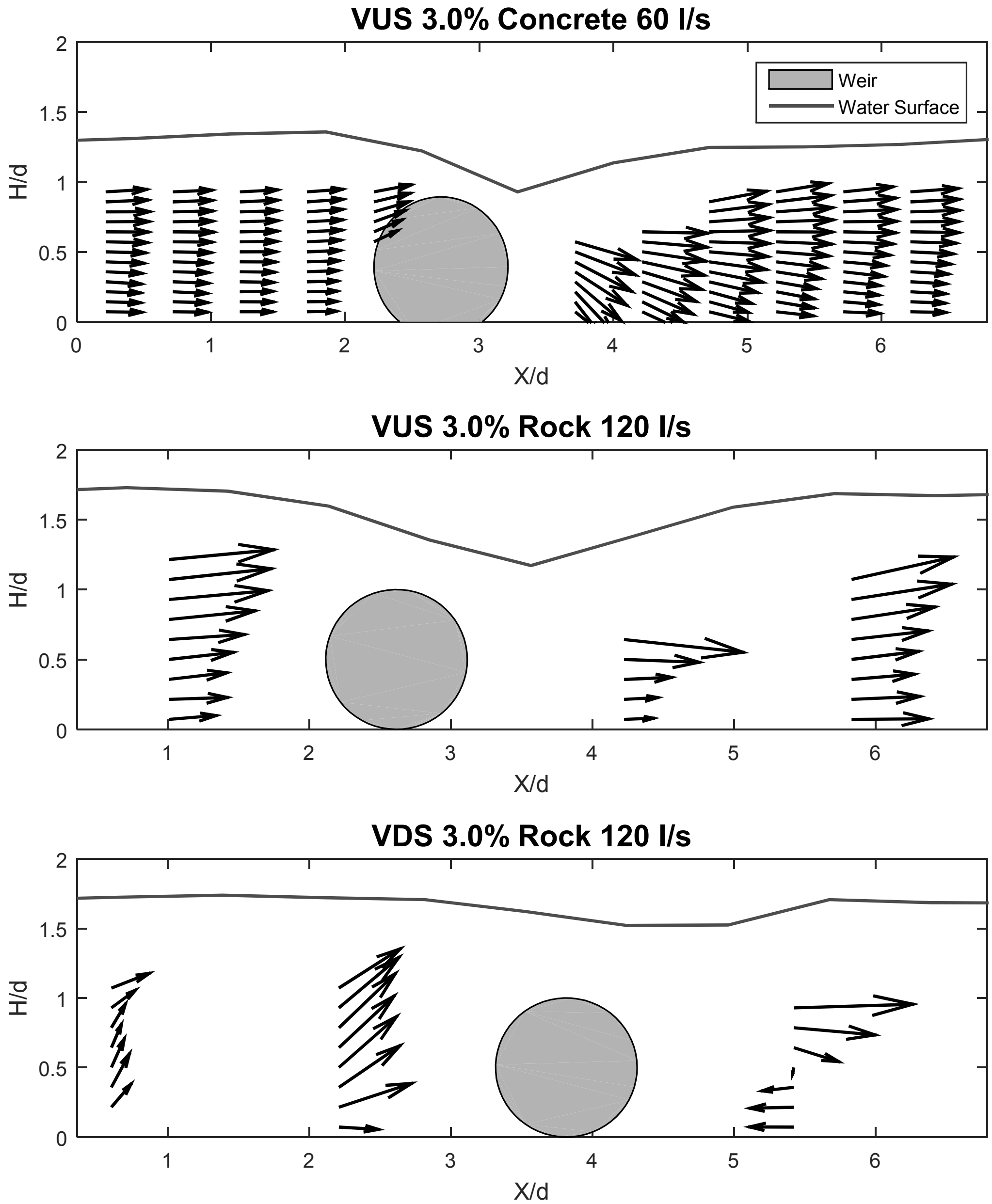

Figure 2.13. Vertical velocity profiles for VUS and VDS. The detailed velocity profile for VUS at 3.0% and 60 l/s shows relatively parallel streamlines, with a small region of downward flow on the downstream side of the weir. In comparison, lower detailed measurements at 120 l/s show the VUS weir still operating in a plunging flow regime while the VDS geometry switches to an oscillating flow regime with a recirculation zone on the downstream side of the weir.

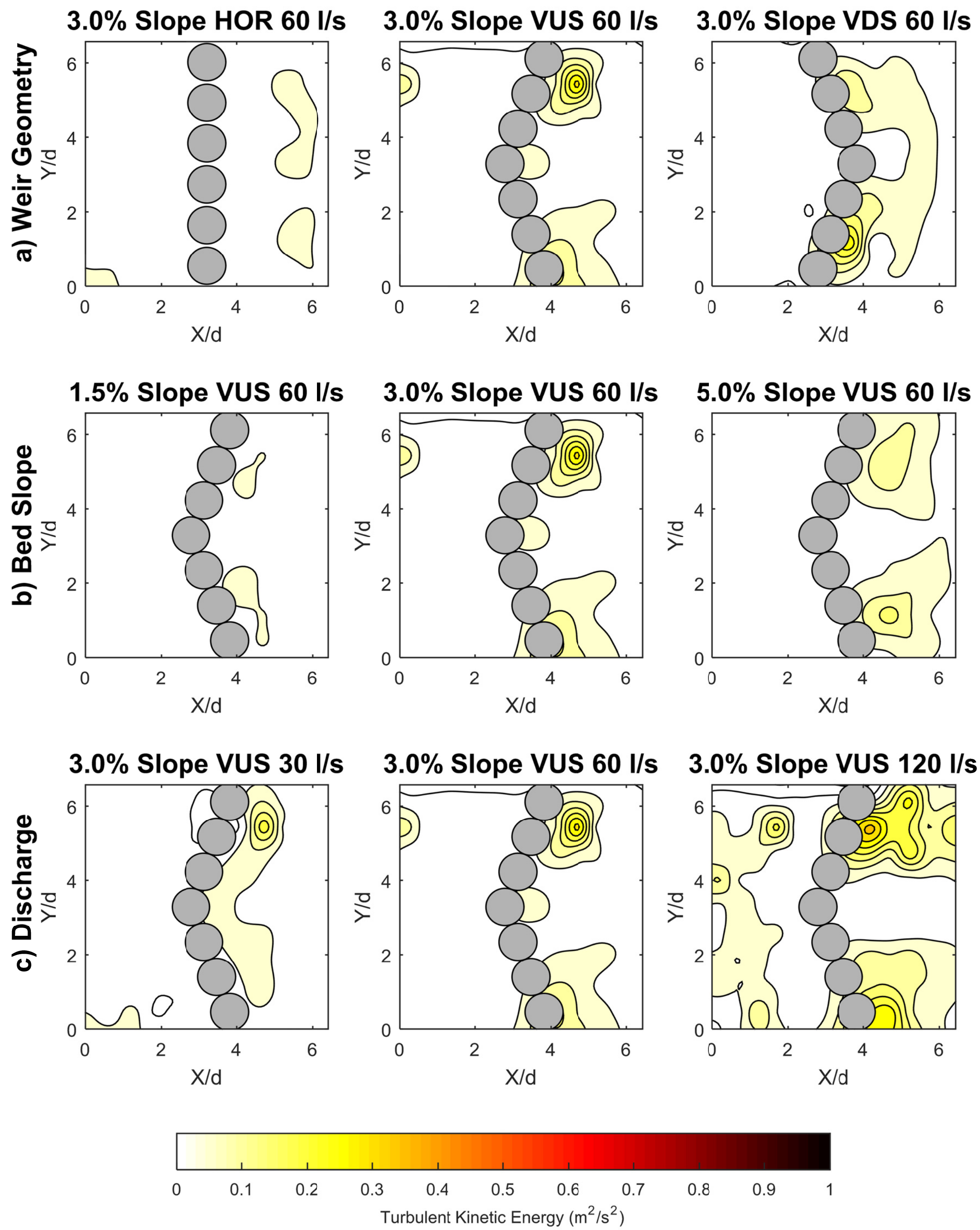

Figure 2.14. Influence of a) weir geometry, b) bed slope, and c) discharge on mean turbulent kinetic energy $\frac{1}{2}(\overline{u'^2}+\overline{v'^2}+\overline{w'^2})$ *in fishway. Note that all three plots in the centre column are identical.*

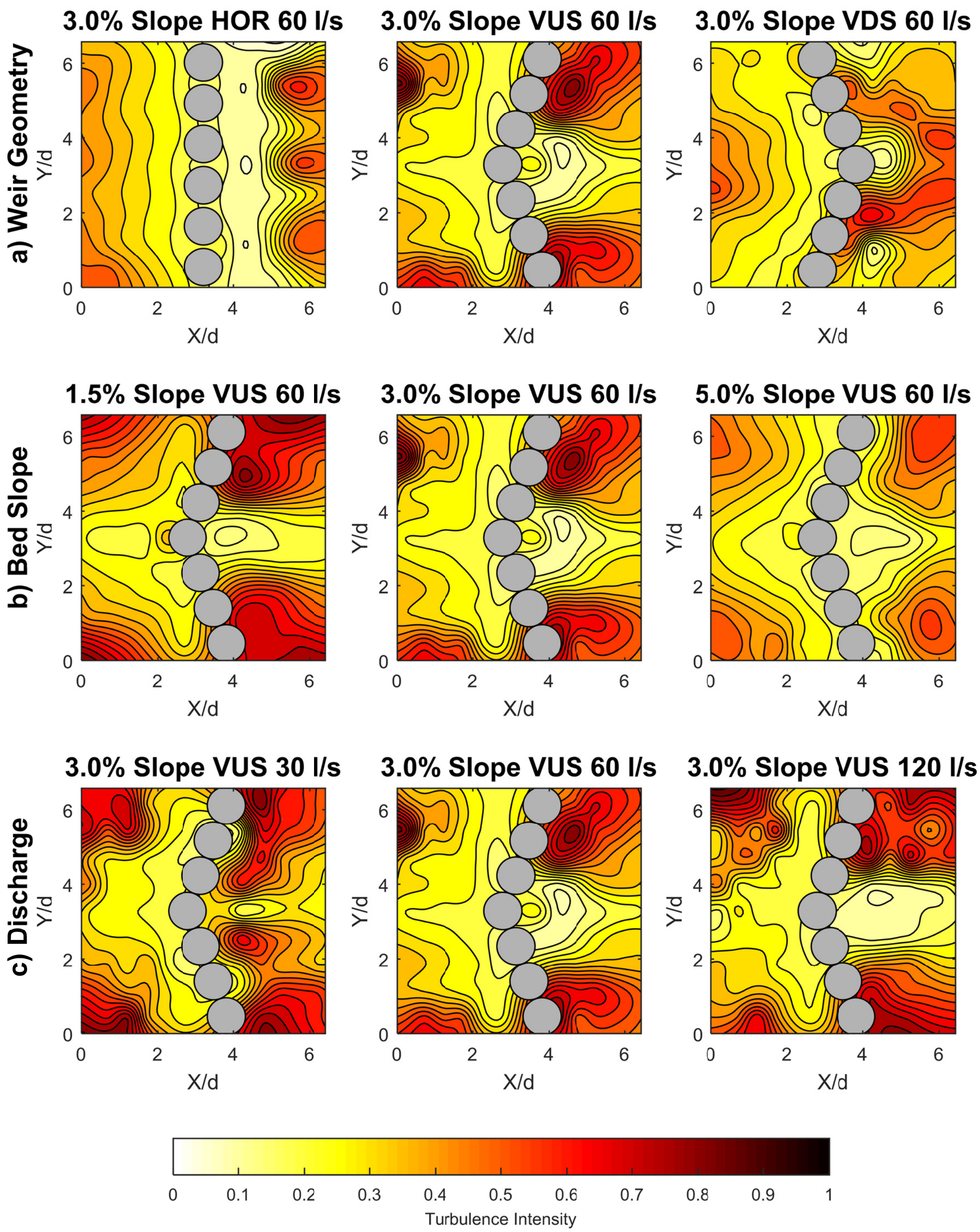

Figure 2.15. Influence of a) weir geometry, b) bed slope, and c) discharge on mean turbulence intensity $\sqrt{TKE}/\overline{u_{local}}$ in fishway. Note that all three plots in the centre column are identical.

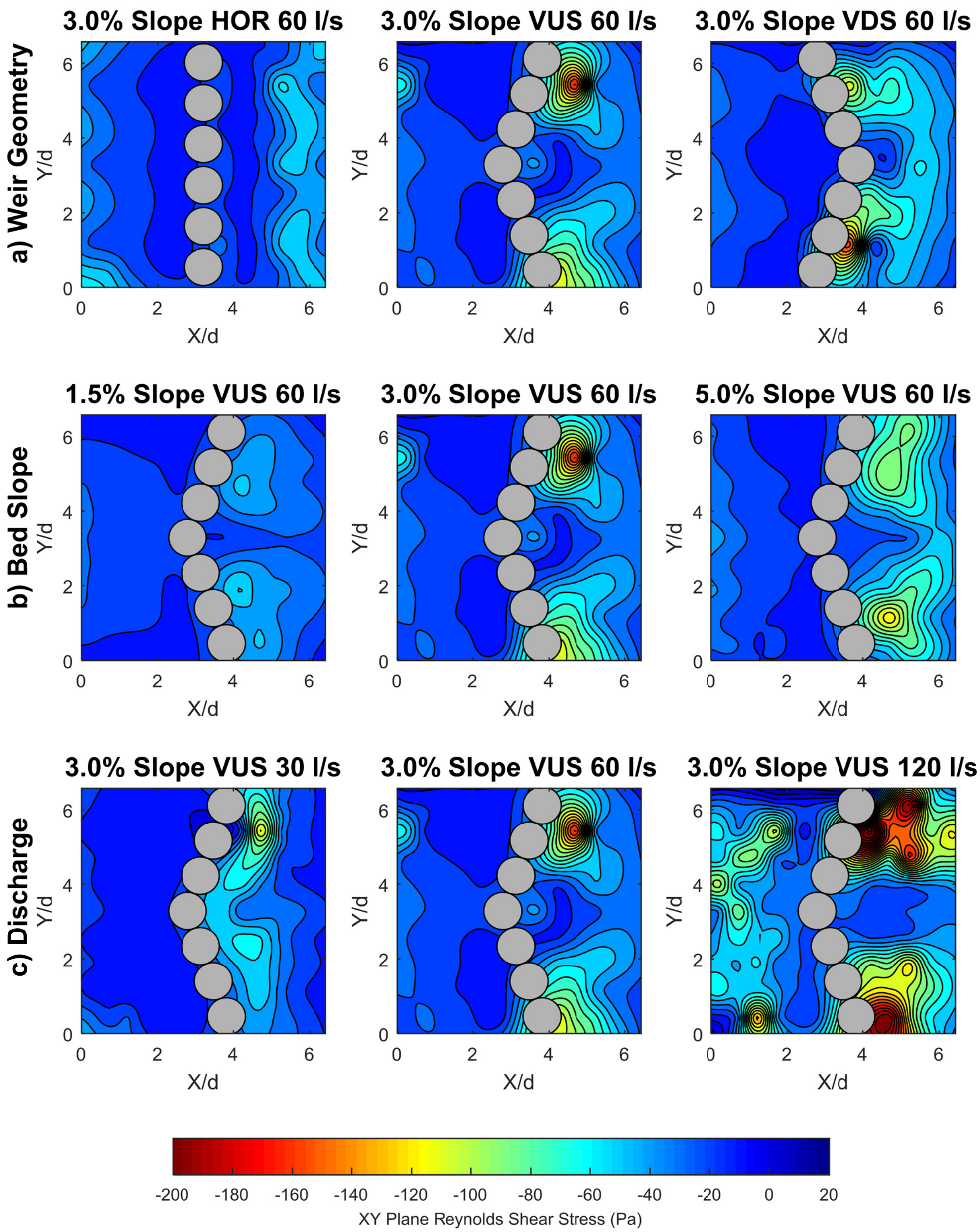

Figure 2.16. Influence of a) weir geometry, b) bed slope, and c) discharge on mean XY plane Reynolds shear stresses $-\rho\overline{u'v'}$ in fishway. Note that all three plots in the centre column are identical.

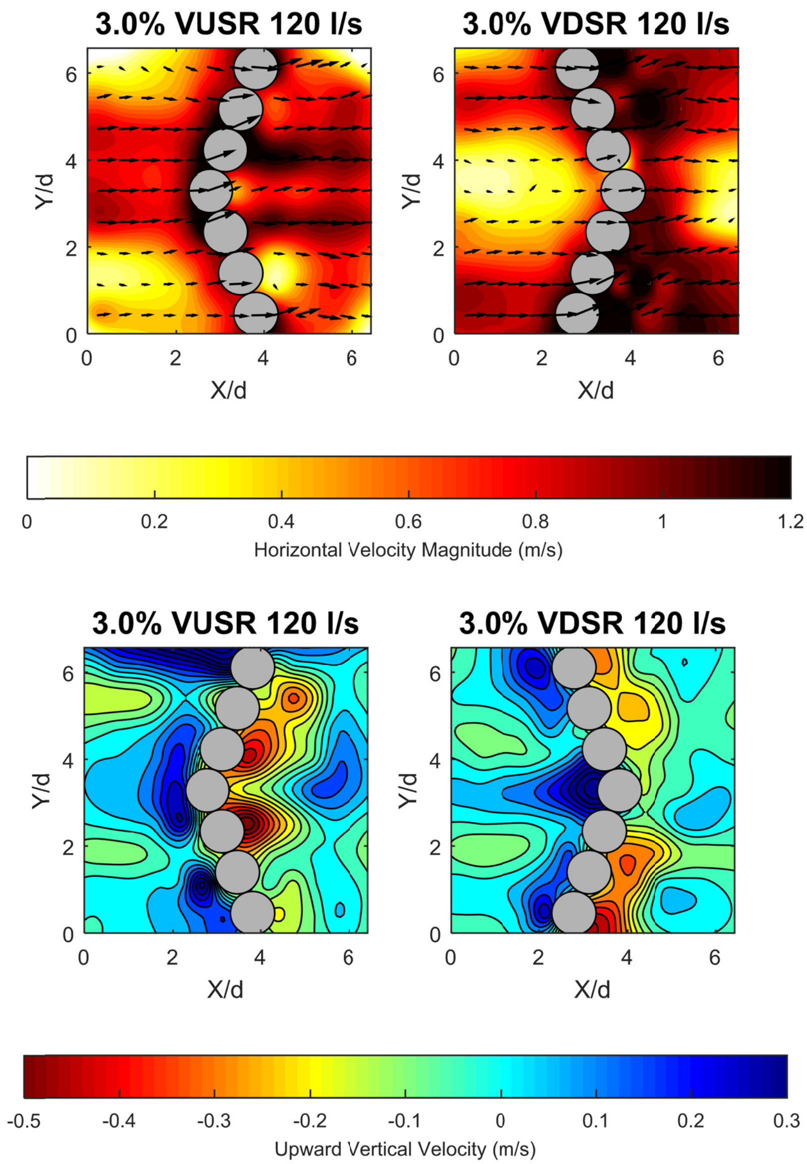

Figure 2.17. Horizontal velocity magnitude $\sqrt{\overline{u^2}+\overline{v^2}}$ with velocity vectors (top) and mean upward vertical velocity $\overline{w}$ (bottom) for weirs with natural rock construction. For the VDSR all points were sampled 0.13 m above the bed while for the VUSR weir some points immediately downstream of the weir were sampled at 0.08 m due to insufficient water depth.

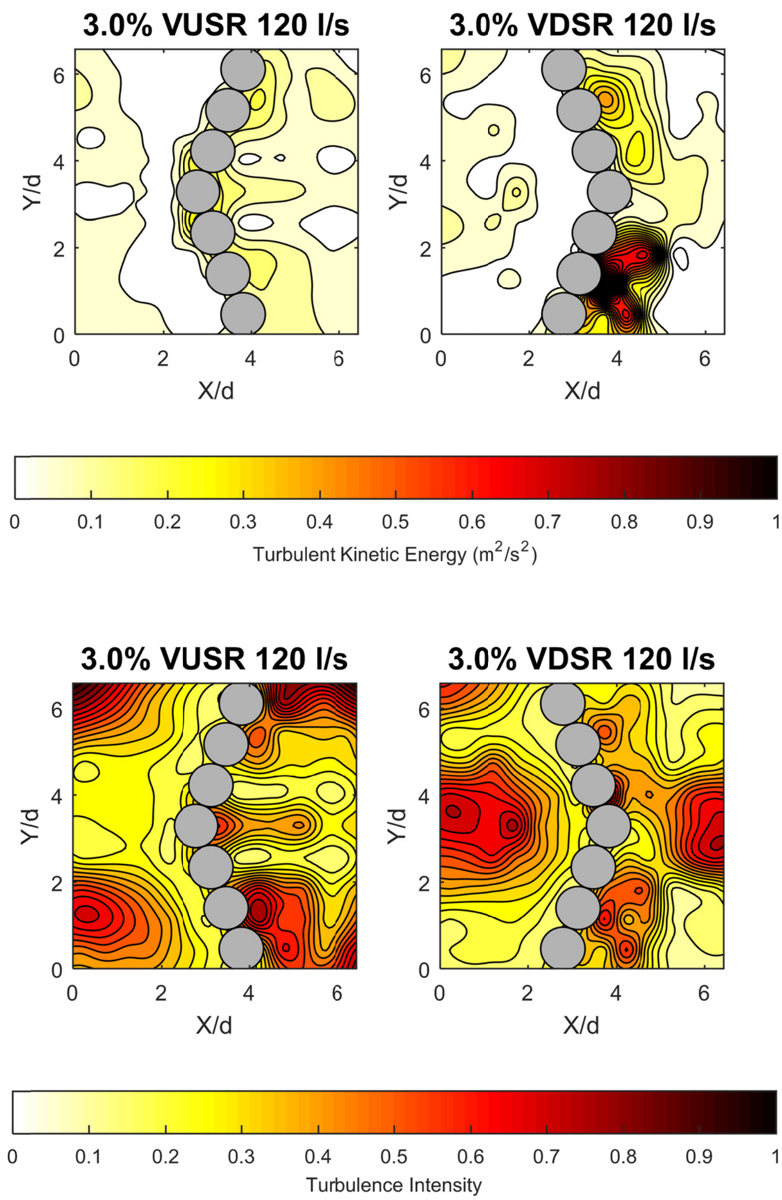

Figure 2.18. Mean turbulent kinetic energy $\frac{1}{2}(\overline{u'^2} + \overline{v'^2} + \overline{w'^2})$ *(top) and turbulence intensity* $\sqrt{TKE}/\overline{u_{local}}$ *(bottom) for weirs with natural rock construction. For the VDSR all points were sampled 0.13 m above the bed while for the VUSR weir some points immediately downstream of the weir were sampled at 0.08 m due to insufficient water depth.*

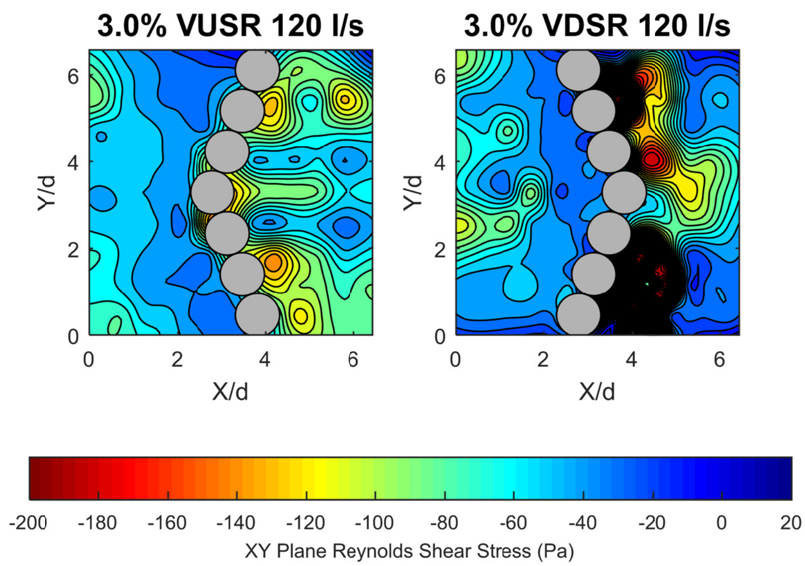

Figure 2.19. XY plane Reynolds shear stresses $-\rho\overline{u'v'}$ *for weirs with natural rock construction. For the VDSR all points were sampled 0.13 m above the bed while for the VUSR weir some points immediately downstream of the weir were sampled at 0.08 m due to insufficient water depth.*

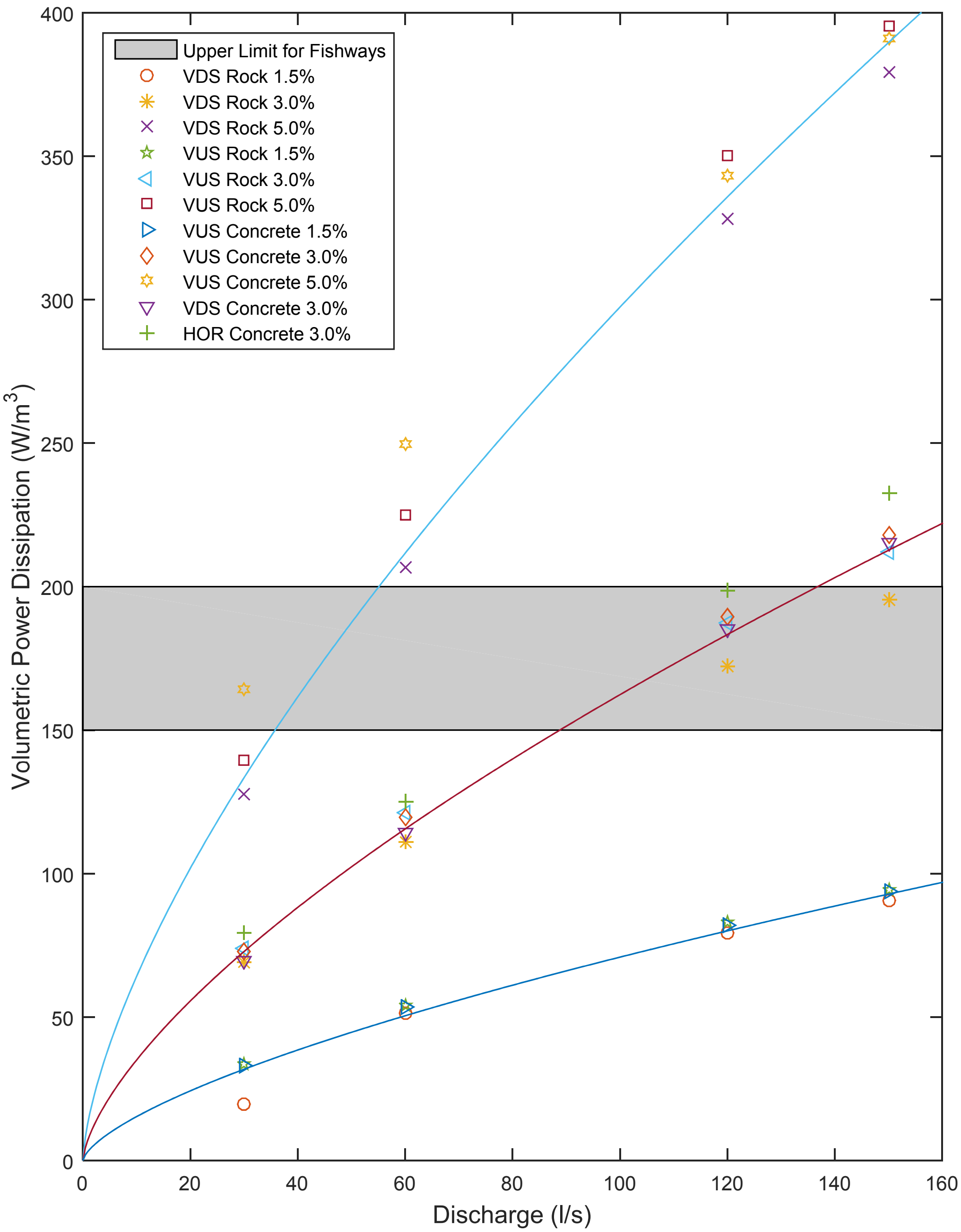

Figure 2.20. Volumetric power dissipation for a variety of design configurations and weir geometries. Power dissipation is shown with fitted curves for each bed slope based on a power function of a discharge coefficient multiplied by discharge to the exponent of 2/3.

Table 2.1. List of experiments. Continued on next page.

Weir Geometry	Bed Slope (%)	Discharge (l/s)	Weir Material	Water Surface Profile	ADV Horizontal	ADV Vertical
VUS	1.5	30	Concrete	X		
VUS	1.5	60	Concrete	X	X	
VUS	1.5	120	Concrete	X		
VUS	1.5	150	Concrete	X		
VUS	3.0	30	Concrete	X	X	
VUS	3.0	60	Concrete	X	X	X
VUS	3.0	120	Concrete	X	X	
VUS	3.0	150	Concrete	X		
VUS	5.0	30	Concrete	X		
VUS	5.0	60	Concrete	X	X	
VUS	5.0	120	Concrete	X		
VUS	5.0	150	Concrete	X		
VUS	1.5	30	Natural Rock	X		
VUS	1.5	60	Natural Rock	X		
VUS	1.5	120	Natural Rock	X		
VUS	1.5	150	Natural Rock	X		
VUS	3.0	30	Natural Rock	X		
VUS	3.0	60	Natural Rock	X		
VUS	3.0	120	Natural Rock	X	X	X
VUS	3.0	150	Natural Rock	X		
VUS	5.0	30	Natural Rock	X		
VUS	5.0	60	Natural Rock	X		
VUS	5.0	120	Natural Rock	X		
VUS	5.0	150	Natural Rock	X		
VDS	3.0	30	Concrete	X		
VDS	3.0	60	Concrete	X	X	
VDS	3.0	120	Concrete	X		
VDS	3.0	150	Concrete	X		
VDS	1.5	30	Natural Rock	X		
VDS	1.5	60	Natural Rock	X		
VDS	1.5	120	Natural Rock	X		
VDS	1.5	150	Natural Rock	X		
VDS	3.0	30	Natural Rock	X		
VDS	3.0	60	Natural Rock	X		
VDS	3.0	120	Natural Rock	X	X	X
VDS	3.0	150	Natural Rock	X		
VDS	5.0	30	Natural Rock	X		

Table 2.1. (continued)

Weir Geometry	Bed Slope (%)	Discharge (l/s)	Weir Material	Water Surface Profile	ADV Horizontal	ADV Vertical
VDS	5.0	60	Natural Rock	X		
VDS	5.0	120	Natural Rock	X		
VDS	5.0	150	Natural Rock	X		
HOR	3.0	30	Concrete	X		
HOR	3.0	60	Concrete	X	X	
HOR	3.0	120	Concrete	X		
HOR	3.0	150	Concrete	X		

Table 2.2. Mean and maximum velocities in the fishway under varying discharge and slope.

Weir Geometry	Slope (%)	Discharge (l/s)	Weir Material	Mean Streamwise Velocity (m/s)	Maximum Streamwise Velocity (m/s)	Maximum Vertical Velocity Mag (m/s)	Maximum Transverse Velocity Mag (m/s)	Maximum Velocity Magnitude (m/s)
VUS	1.5	60	Concrete	0.330	0.846	0.299	0.183	0.890
VUS	3	30	Concrete	0.254	0.756	0.232	0.213	0.798
VUS	3	60	Concrete	0.417	1.000	0.421	0.215	1.107
VUS	3	120	Concrete	0.614	1.291	0.422	0.279	1.335
VUS	5	60	Concrete	0.493	1.229	0.645	0.247	1.151
VDS	3	60	Concrete	0.430	0.853	0.436	0.373	1.015
HOR	3	60	Concrete	0.526	0.963	0.196	0.148	0.980
VUS	3	120	Natural Rock	0.721	1.370	0.536	0.620	1.593
VDS	3	120	Natural Rock	0.783	1.343	0.439	0.632	1.664

CHAPTER 3. Use of Resting Pools by Arctic Grayling (Thymallus arcticus) in a Nature-Like Fishway: Ecohydraulic Analysis and Implications for Fishway Design[2]

Introduction

On a global scale freshwater ecosystems are currently facing serious challenges. These ecosystems are one of the most affected by humans, and tend to have the highest number of species threated by extinction (MEA, 2005). In Canada freshwater ecosystems are protected under the Canadian Fisheries Act which states that, "No person shall carry on any work, undertaking or activity that results in serious harm to fish that are part of a commercial, recreational, or Aboriginal fishery, or to fish that support such a fishery," (2012). Historically in cases where harmful alteration, disruption or destruction (HADD) of fish habitat was unavoidable, compensation projects were required to achieve no net loss (NNL) with respect to the productive capacity of the ecosystem for fish (Fisheries and Oceans Canada (DFO), 1986). Since the 1950s, lake and stream destruction has been on the rise in northern Canada (Birtwell et al., 2005), triggering the need for an increasing number of fish habitat compensation projects and a corresponding need to evaluate these projects.

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The Arctic Grayling (*Thymallus arcticus*) is a freshwater fish species in the family Salmonidae native to the Canadian north (Northcote, 1995). This species is a relatively strong swimmer and typically spawns in streams during the spring and early summer over rocks and gravel (MacPhail and Lindsey, 1970). Although common in many parts of northern Canada, the slow growth of this species and ease of capture by angling make Arctic Grayling particularly susceptible to local extirpation (MacPhail and Lindsey, 1970), and many factors suggest that Arctic Grayling may be more susceptible to environmental and human impacts than the closely related European Grayling (*Thymallus thymallus*) (Northcote, 1995).

Resting areas are recognized as being important for Arctic Grayling, which have highly predictable foraging microhabitats based on minimizing net energy expenditure (Hughes and Dill, 1990; Hughes 1992a,b). In Alaska streams it was found that Arctic Grayling selected pool habitats with near-zero velocity and average depths of 0.8 m (Den Beste and McCart 1984). When constructing fishways to meet the ecohydraulic needs of grayling, challenges can arise since there are no clear guidelines for Arctic Grayling fishway design. In Europe, however, guidelines for European Grayling recommend that pools in pool-style fishways have a minimum length of 1.4 m, minimum width of 1.0 m, and a minimum depth of 0.6 m (FAO/DVWK, 2002).

In fall 2012 Diavik Diamond Mines Inc. (DDMI) completed the West Island Stream (WIS) habitat compensation project in the Barrenlands region of northern Canada. The goal of this project was to enhance fish spawning habitat and provide improved habitat connectivity for native fishes, particularly arctic grayling (Dillon, 2004; Courtice, 2014; Courtice et al., 2014). The habitat compensation project reduced the overall channel slope by increasing the stream length and used nature-like fishway structures to break up steep cascade sections into a series of smaller drops and pools.

This project provided the unique opportunity to perform a flow manipulation experiment and analysis on a full-stream scale. We used a diesel pump to manipulate the flow of WIS and artificially introduced fish to examine their behaviour in the steepest section of WIS. The objective of this research was to evaluate the behaviour of Arctic Grayling in resting pools under varied flow conditions. The evaluated resting pools were compared with the FAO/DVWK guidelines for European Grayling (2002) and the hydraulic and depth preferences of Arctic Grayling in the study pools were also determined with the goal of developing resting pools design guidelines for Arctic Grayling.

Methodology

Study Site

West Island Stream (WIS) is located in the Barrenlands, a region of northern Canada in the Southern Arctic Ecozone (Canadian Council on Ecological Areas, 2014) approximately 300 km northeast of Yellowknife and 100 km north of the tree line. The region is semi-arid receiving an average of 250 mm of precipitation annually, approximately half of which falls as snow (Environment Canada, 1991). Although daily highs in July average 15°C, the mean annual temperature is -12°C and the permafrost layer is continuous.

The ecological characteristics of the Barrenlands ecosystem are poorly studied, however, it is known that streams in the area are typically low sinuosity, braided or multichanneled, and are dominated by large boulders (Jones et al., 2003). Freshet usually arrives in early June with flow rapidly declining afterwards (Courtice, 2014). Many streams are seasonal, with flows diminishing to zero and pools becoming hydraulically separated during late summer (Jones et al., 2003). Most small streams freeze solid during the winter.

WIS is an ephemeral stream located at 64.527°N 110.436°W, approximately 8 km west of the DDMI mine site (Figure 3.1). It is the only outlet of West Island Lake (WIL), a 13.65 ha headwater lake with a direct catchment area of 30.08 ha (Baki, Zhu, and Courtice, 2012) and flows into the 577 km^2 Lac de Gras (Wedel et al., 1988). WIS was a pristine ecosystem prior to the habitat compensation project in 2012. A survey conducted in September 2011 indicated a stream length of 430 m with a gross overall slope of 1.8 percent (Golder Associates, 2012). The downstream-most 40 m section, however, had steep braided channels with cascading flow. The maximum slopes of individual channels in this steep section ranged from 9.1 to 12.8 percent, creating a barrier to fish passage.

In late summer 2012, construction works were performed on the downstream-most 310 m of WIS. The main channel was channelized, rock weir, choke-pool, and rock ramp structures were installed, and the steep lower section of WIS was rerouted. Based on an as-built survey conducted by Praetorian Construction Management in November 2012, the habitat compensation project increased the stream length by approximately 40 m (new total stream length of 470 m) and reduced the slope of the steep cascade section to 3.8 percent. Post-construction, it was deemed that the lower reach would still be the most challenging section for fish to pass, and as a result, our research focused primarily on the downstream-most 100 m section of WIS closest to the outlet into Lac de Gras.

Flow and Temperature Data

To obtain flow data, we used Diver pressure and temperature loggers (Schlumberger Water Services) to record hydrostatic pressure and water temperature in WIS. During summer 2014, loggers were placed at sites 12, 32, 74, 112, 249, and 345 m upstream of Lac de Gras to record pressure and temperature readings at 10 minute intervals. An additional pressure sensor placed above the water (WISAIR) was used to collect barometric pressure data.

Pressure data from the hydrostatic loggers were corrected for barometric changes by subtracting barometric pressure from the logger data. Barometric pressure data from the WISAIR sensor was used for loggers placed at WIS. A median filter (n=5) was then applied to remove noise and spikes from the data. Once the data was filtered, numerical differentiation was performed using MATLAB to identify any remaining discontinuities in the pressure data. During pressure data processing, spikes were flagged where the absolute value of the numerical derivative exceeded 1 mm/min.

Discharge data for WIS were collected using a FlowTracker (SonTek) acoustic doppler velocimeter (ADV), and efforts were made to begin data collection as close to the freshet date as logistically possible. To determine the discharge, we split the stream width into cells, and velocity data were collected at a sampling rate of 1 Hz for 40 s, measured at 60 percent of the sampling location water depth. The flow rate was then calculated using the area-velocity method. It should be noted that when using this method 25 to 30 sampling cells are typically recommended so that no more than 5% of the total discharge falls into any given cell (Harrelson et al. 1994). Due to the shallow depth and narrow width of WIS this was not possible. Instead, a minimum of 8 cells were used and we discarded any flow measurements where the discharge uncertainty exceeded 25%. Uncertainty was calculated using working versions of the ISO Standard 748 and United States Geological Survey (USGS) methods provided in the SonTek/YSI FlowTracker Technical Manual (2007).

To determine stream discharge from the water pressure data, we developed a stage (water depth) vs. discharge rating curve for each hydrostatic logger. We used this curve to convert hydrostatic pressure data into a flow data set with a resolution of 10 minutes. Limited historical flow data for the site pre and post construction were also available from Baki, Zhu, Hulsman et al. (2012) and G. Courtice (unpublished data), respectively.

Hydraulic Evaluation

To evaluate resting pool suitability for Arctic Grayling, we selected five pools in the downstream-most 100 m of WIS. Each pool was located immediately downstream of a nature-like fishway rock structure and was suspected to have high resting potential for Arctic Grayling. Pools were named after their upstream structure using the format "S-XX", where "S" stands for structure and "XX" corresponds to the stream thalweg distance (m) upstream from Lac de Gras (Figure 3.2). Pool S33 was downstream of a rock ramp, pool S38 was downstream of a choke structure, and pools S68, S72, and S85 were downstream of rock weirs. Under extreme low flow, the S68 and S85 structures could also operate as choke structures.

To evaluate the hydraulics of each pool, we specified sampling points on a 0.1 m by 0.1 m grid and collected 3-D velocity measurements at 60 percent depth for each sampling point using a FlowTracker ADV. We also measured the depth at each sampling point and recorded the bank locations of each cross-section for every pool. A bubble level was attached to the wading staff of the ADV to ensure that measurements were level and sampling occurred at the correct location.

Hydraulic measurements were taken at three different flow conditions: the natural background flow for early July and two enhanced flows. A diesel centrifugal pump (Gordan Rump 10 Series Model 14A2-TS2 S/G) and 90 m of 4 inch (10.2 cm) diameter lay-flat hosing was used to pump water from Lac de Gras into the lower 110 m reach of WIS (Figure 3.2).

Fish Monitoring

For each of the three flow conditions, 30 adult Arctic Grayling were captured and transported from the nearby M-Lakes to WIS via helicopter. Six fish were stocked in each of the study pools except for S68; instead, six fish were placed downstream of this site in pool S60 to provide an experimental control. Following a 1 hour acclimation period, fish were monitored for 48 hours.

To evaluate resting behaviour, fish surveys were conducted by an observer wearing polarized sunglasses, who recorded the position of all Arctic Grayling present in pool at a given time on a photo of the pool. Surveys were conducted at 30 to 60 minute intervals when it was logistically possible and safe to access the study site, typically between 8:00 and 18:00 hrs. To obtain higher resolution spatial data for fish location, GoPro cameras (HERO, HERO2, and HERO3) recorded videos of each pool under each flow conditions. Cameras were generally deployed when fish were present in a given pool, but were otherwise deployed in the early afternoon.

Initially, each camera was calibrated using the OpenCV image processing library and Python Version 2.7.5. The OpenCV function cv2.findChessboardCorners identified corners on video of a 10 x 7 checkerboard pattern and cv2.calibrateCamera calculated the intrinsic camera matrix and radial and tangential distortion coefficients. To correct for radial distortion, especially important with the GoPro cameras due to their use of fisheye lenses, we used the following equations, where (x,y) are the pixel coordinates measured from the optical centre, r is the radial distance from the optical centre, and k_1, k_2, and k_3 are the radial distortion coefficients.

$$r = \sqrt{x^2 + y^2} \qquad \textit{Equation 3.1}$$

$$x_{corrected} = x(1 + k_1 r^2 + k_2 r^4 + k_3 r^6) \qquad \textit{Equation 3.2}$$

$$y_{corrected} = y(1 + k_1 r^2 + k_2 r^4 + k_3 r^6) \qquad \textit{Equation 3.3}$$

To correct for tangential distortion, we used the following equations, where p_1, and p_2 are the tangential distortion coefficients.

$$x_{corrected} = x + [2p_1 xy + p_2(r^2 + 2x^2)] \qquad \textit{Equation 3.4}$$

$$y_{corrected} = y + [p_1(r^2 + 2y^2) + 2p_2 xy] \qquad \textit{Equation 3.5}$$

The resultant camera matrix was a 3x3 matrix containing the focal length in the x and y direction (f_x, f_y) and the optical centres in the x and y direction (c_x, c_y).

$$camera\ matrix = \begin{bmatrix} f_x & 0 & c_x \\ 0 & f_y & c_y \\ 0 & 0 & 1 \end{bmatrix}$$

Using the calibrated camera parameters, we then projected the 3-Dimensional, real-world sampling grid coordinates onto an image plane for the video of each of the pools using the OpenCV function cv2.projectPoints (Figure 3.3). For each video, the translation and rotation vectors were manually determined by fitting the sampled pool banks to the video pool banks.

For each pool and each flow condition, we sampled one frame per five seconds from 10 minutes of video data. For each video frame fish were represented as a line, identified manually by clicking the tip of their nose and the end of their tail (Figure 3.3). To determine the number of fish present in a cell for each frame, we quantified the intersection of each fish and sampling cell and then calculated the mean number of fish per sampling cell over the 10 minute interval.

To compare the available habitat with the habitat used by fish, we evaluated five parameters: x velocity, y velocity, z velocity, depth, and horizontal velocity magnitude ($\bar{V}$), calculated as $\bar{V} = \sqrt{u^2 + v^2}$, where u and v are the velocities at a given sampling point in the x and y directions, respectively.

To determine the habitat selected by grayling, we grouped the available and used habitat cells into histogram bins. Bin widths of 0.02 m/s, and 0.02 m were used for velocity parameters and depth, respectively. Habitat usage rate was then calculated by dividing the average cell usage by the number of cells available for each bin. Usage rate was not calculated for bins with five or less cells of available habitat.

Statistical Methods

To compare the number of fish resting in each pool during the visual fish surveys, we performed a one-way analysis of variance (ANOVA), combined with a Tukey honest significant difference (HSD) test for each pool under each flow condition. To see if fish selected for a specific type of habitat, we compared available vs. used habitat for each of the five evaluated parameters with the Z-test (Johnson, 2005) to evaluate the null hypothesis $\mu_1 = \mu_2$ where μ_1 and μ_2 are the means of the available and used habitat, respectively.

Results

Under the base flow condition, two fatalities occurred when fish became stranded between pools. During the manipulation 2 flow condition, one fish was predated by a red fox. No fatalities occurred during flow manipulation 1.

When comparing the resting pools in WIS with the recommended minimum dimensions for pool-weir fishways for European grayling from FAO/DVWK (2002), only S33 and S38 met the minimum surface area recommendation of 1.4 m^2 (1.4 m length x 1 m width) under all flow conditions. S85 met the surface area recommendation under manipulation 2 only. None of the pools meet the depth recommendation of 0.6 m under any flow condition.

The fish used in the base condition were 10% longer than those used in manipulation 1 or 2, while the stream temperatures during the two flow manipulations were 2.6 ^{o}C cooler due to the addition of water from Lac de Gras (Table 1). Compared to these small differences, however, mean flows were 10 and 22 times greater than the base flow during manipulations 1 and 2, respectively (Table 1).

At base flow, the number of fish resting differed among pools [$F(4,85)=644, p<0.001$](Table 2). There was no significant difference ($p=0.05$) between

S33 and S38 or S38 and S85, with these three pools all containing more fish than S72 ($p<0.01$). All stocked pools held more fish ($p<0.01$) than the unstocked pool (S68).

The number of resting fish again differed among pools under flow manipulation 1 [$F(4,105)=1318, p<0.001$](Table 2). Most fish were observed in S33, a small number rested in S38, and no fish were observed resting in and of the three upstream pools (Table 2). Under flow manipulation 2, there was also a difference in resting fish among pools [$F(4,95)=634, p<0.01$], with S33 holding a large number of fish, and very few fish observed in pools S38, S72, and S85. No fish were observed in the unstocked S68.

Under the base flow condition only pools S33 and S38 had large areas with water depths greater than 0.08 m and S33 was the only pool with large areas deeper than 0.2 m (Figure 3.4). When the flow was increased for manipulation 1 there was a large change in the amount of habitat deeper than 0.08 m in pools S38, S68, and S72 (Figure 3.4). Under flow manipulation 2 pools S72 and S85 both experienced large increases in areas with depth greater than 0.08 m, with no major changes in any of the other pools (Figure 3.4). In general, depth in pool S33 appeared to be least affected by changes in flow and offered the deepest habitat of all of the study pools.

Under the base flow condition horizontal velocity magnitudes remained near-zero for all five study pools (Figure 3.5). Under flow manipulation 1 the horizontal velocity magnitudes quickly increased in all pools with only S33, S38, and S85 offering any fish-size regions with near-zero horizontal velocities and pools S38, S68 and S72 all having regions with very high (>0.3 ms/s) horizontal velocities (Figure 3.5). Under flow manipulation 2 only pool S33 offered any large areas with near-zero horizontal velocities, with pools S38 having some small near-zero regions. Under this flow condition the maximum velocities in pools S38, S68 and S72 all increased to over 0.5 m/s (Figure 3.5).

Under the base flow condition vertical velocities remained near-zero in all of the study pools (Figure 3.6). Under flow manipulation 1 pool 72 contained a region with high upward vertical velocity (>0.3 m/s) and pool S38 contained a region with high downward vertical velocity (>0.2 m/s). Only pools S33 and S38 had large regions of near-zero vertical velocity (Figure 3.6). Under flow manipulation 2 regions of upward and downward both increased in pool S68 and S72. Pools S33 and S38 once again had large regions of near-zero vertical velocity with a small region of near-zero vertical velocity located at the downstream end of pool S72 (Figure 3.6).

Fish probability data obtained from processing the video data is shown in Figure 3.7. No video data was available for pool S68 under the manipulation 2 condition due to a camera failure. The highest usage rates occurred in pools S72 and S85 under the base flow condition (Figure 3.7). During these periods, fish use appeared to be highly concentrated in the deepest areas of pools. During the flow manipulation conditions, the high usage areas were located in pool S33, with minor usage areas in pool S38 (Figure 3.7). Fish use under the flow manipulation conditions appeared to be concentrated in deeper water with low horizontal and vertical velocities.

Under the base flow condition, mean available and used habitats differed for x velocity, depth ($p<0.05$) and y velocity ($p<0.01$), with fish selecting higher x velocities, deeper water, and lower y velocities (Z-test, Figure 3.8). In contrast, used and available habitats were similar for z velocity and horizontal velocity magnitude.

Under flow manipulation 1, mean available and used habitats differed for x velocity, z velocity, depth, and horizontal velocity magnitude ($p<0.01$), with fish selecting deeper water, lower x and z velocities, and deeper water (Figure 3.8). Used and available habitats did not differ ($p>0.05$) for y velocity.

At the highest flow (manipulation 2), used and available habitats differed for x velocity, z velocity, depth, horizontal velocity magnitude ($p<0.01$) and y velocity ($p<0.05$). Fish selected for deeper water, lower x and z velocities, lower horizontal velocity magnitude, and greater y velocity (Figure 3.8).

Discussion

Flow manipulation can be a useful tool for evaluating the hydraulic response of a modified stream and nature-like fishway structures. This technique allowed structures to be evaluated under a variety of flow conditions during a single site-visit, rather than requiring multiple visits to this site during different times of the year. Using a pump, we were able to obtain flows comparable to the estimated flows of 10 to 25 l/s in WIS during the Arctic Grayling spawning period. Although mean fish length varied between the base and manipulated flows, the maximum difference in mean length between trials (40 mm) was considered hydraulically negligible, as the difference in sustained swimming velocity for a 29 and 33 cm fish is less than 0.05 m/s (Jones et al., 1974).

Use of Resting Pools

Fish mobility, in particular upstream passage, appeared to be somewhat limited under the base flow condition. The relatively even distribution of fish among the stocked pools suggested that fish stayed in the pool in which they were stocked (particularly S33, S38, and S85), since low flow conditions made it difficult to move between resting pools. This was supported by visual observations of fish struggling to pass between pools and the deaths that occurred when two fish became stranded between pools. In particular, the steep rock-ramp structure between pool S33 and pool S38 appeared to act as a barrier to upstream passage under this flow condition. The visual surveys suggested some emigration out of S72, most of which was quite shallow (< 0.08 m) at base flow. Since this flow is lower than the flows expected during the spawning period, this general lack of movement does not indicate any issues with the fishway operation for adult grayling.

During flow manipulation 1 (9.9 l/s), it appeared that most fish moved out of the upstream pools and into downstream pools, particularly S33, which averaged 12 times as many fish as the second-best pool, S38, which still provided limited resting habitat for Arctic Grayling. S33 and S38 offered more deep water resting habitat than any of the other pools. These two downstream pools also offered regions of lower horizontal velocity, in particular when compared to S68 and S72. The higher horizontal velocities in S68 and S72 may have resulted in poor resting habitat. There did not appear to be any barriers to fish passage. Although S33 was the downstream-most of the study pools, there were two additional pools downstream of S33. We frequently observed fish travelling to the pools downstream of S33 and then returning to S33, likely due to the favourable resting conditions it offered.

Under the highest flow (21.9 l/s; manipulation 2), the only pool fish used on a regular basis was S33. It once again offered the greatest amount of deep water and had low horizontal velocity magnitude, including the largest regions with velocities below 0.2 m/s. There were again no evident barriers to fish passage, with both upstream and downstream passage frequently observed throughout the entire stream. There was less crowding in S33 than during flow manipulation 1 because many Arctic Grayling were found resting in the two pools downstream of S33. The backwater effect of the downstream block net appeared to create a large, deep, pool under this flow condition, with water depths similar to those found in S33.

Since flows during manipulation 1 and 2 were similar to the lower and upper end of the expected range of flows during spawning, respectively, it is likely that of the five study pools S33 and S38 would be the only ones to offer reasonable resting habitat during the spawning periods. If flow rates are towards the upper end of the estimated range, it is likely that only S33 would offer reasonable resting habitat.

Although both x velocity and y velocity were analyzed, the horizontal velocity magnitude results were used to determine horizontal velocity preferences. Although the ADV was equipped with a bubble level for z velocity measurements, the x and y velocities were based on aligning the sensor in the perceived upstream direction when taking a measurement. Although the alignment error for measurements in the x and y direction could not be quantified, this error is not present in the horizontal velocity magnitude. Under both flow manipulations, fish preferred horizontal velocities magnitudes of less than 0.2 m/s, with habitat use dropping off quickly above this value. Although maximum use occurred at 0.16 m/s for both flow manipulation conditions, there were two major peaks evident, with the second peak occurring at approximately 0.02 m/s. This suggests that Arctic Grayling select for two different velocities. It is likely that they use low velocity regions for resting and higher velocity regions for feeding, which grayling were regularly observed doing during the experiments. Similar observations were previously recorded by Den Beste and McCart (1984) who found that adult Arctic Grayling had a strong preference for pool habitat located adjacent to swift water (>0.5 m/s) that provided a steady supply of drift food.

For z velocity, there was no major change in usage between the different flow conditions. The usage rate suggested that fish selected near-zero vertical velocities and avoided areas with vertical velocities greater than about 0.05 m/s. During base flow and flow manipulation two, fish slightly favored upward vertical velocity compared with downward vertical velocity.

Under the base flow and manipulation 1 flow conditions, fish made use of the entire range of available depths, with maximum use occurring at 0.26 m. Under the highest flow condition, fish use was almost exclusively in water depths ranging from 0.2 to 0.3 m, with maximum use at 0.24 m. These values are much lower than the value of 0.8 m reported by Den Beste and McCart (1984) for adult grayling. Jones and Tonn (2004) evaluated resource selection for young of year (YOY) Arctic Grayling and found that small (15-21 mm fork length) and large (32-57 mm fork length) YOY had the highest selection indices for depths of 0.15 m and 0.55 m respectively, suggesting that Arctic Grayling select for deeper water as they grow. It is likely that the pool depths in WIS were less than ideal for adult Arctic Grayling, and that fish were making use of the deepest water available. During the highest flow condition, there was some water deeper than 0.3 m that was largely found in S33 and not used by fish. However, as shown in Figure 3.4 and Figure 3.5, much of this deep water had horizontal velocity magnitudes greater than 0.2 m/s, making it unfavourable for fish.

Implications for Fishway Design

Based on our findings, Arctic Grayling primarily rested in S33 and S38, which were the largest and deepest of the study pools and met the FAO/DVWK (2002) guidelines of 1.4 m^2. Other studies have found that during spawning males typically defend an area of 6 ft (1.83 m) wide by 12 ft (3.66 m) long (Bishop, 1971), and that in some mountain streams, total habitat use can be as small as 1.5 m^2 (Den Beste and McCart, 1984). Although a minimum surface area of 1.4 m^2 is likely sufficient for resting pools for Arctic Grayling, these studies suggest that larger surface areas should be used if spawning is intended to take place within the fishway.

The most used pool in our study had a maximum depth of 0.4 m, less than the 0.6 m recommended by FAO/DVWK (2002) and the preferred depth of 0.8 m documented by Den Beste and McCart (1984). Qualitative observations at other streams near the study site also showed adult Arctic Grayling resting in locations deeper than 0.4 m. Although deeper pools would likely be selected by fish, our study suggests that a depth of 0.4 m may provide sufficient resting habitat for Arctic Grayling. Until further studies can confirm this finding, we suggest that the FAO/DVWK (2002) recommendation of 0.6 m be used.

Fish avoided areas with horizontal velocity magnitudes greater than 0.2 m/s. This suggests that resting pools should contain large areas with horizontal velocity magnitudes less than this. Given that we found a bimodal use pattern, it may be necessary to provide regions with both near-zero and 0.16 m/s velocities. The pools should also provide near-zero vertical velocities. These guidelines should be met under all flows expected during the spawning period.

Conclusions and Recommendations

Our study showed that stream-scale flow manipulations can be an effective tool to evaluate fish habitat compensation projects. For the flows expected in WIS during spawning periods, S33 would provide acceptable resting habitat for Arctic Grayling, with S38 providing resting habitat when flows are in the lower end of the expected range. Our results also indicate that the FAO/DVWK (2002) guidelines for European grayling would likely be acceptable for Arctic Grayling. In WIS, pool S33 met the recommended guidelines for minimum surface area, but had a maximum depth of about 0.4 m, rather than the recommended 0.6 m. This suggests that depths of 0.4 m could be acceptable for Arctic Grayling. We recommend that until explicit guidelines for fishway design for Arctic Grayling are developed, resting pools should have a minimum length of 1.4 m, a minimum width of 1.0 m and a minimum depth of 0.6 m, with horizontal velocity magnitudes of less than 0.2 m/s and near-zero vertical velocities.

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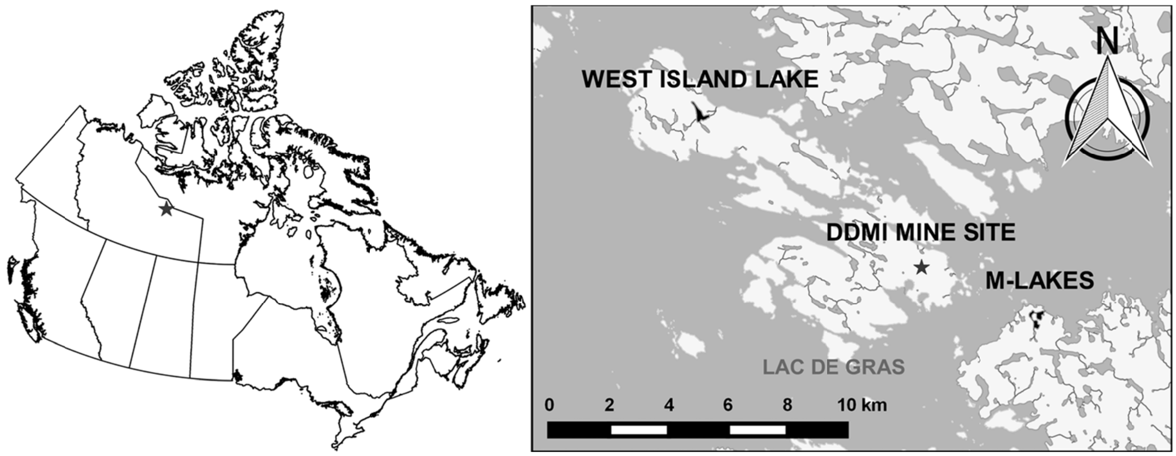

Figure 3.1 – Map showing location of study site in Canada (left) and the location of West Island Lake in relation to the Diavik Diamond Mine Inc. (DDMI) mine site (right). Arctic Grayling used in this study were captured at the nearby M-Lakes site and transport to the study site via helicopter. Map data from GeoBase (2014).

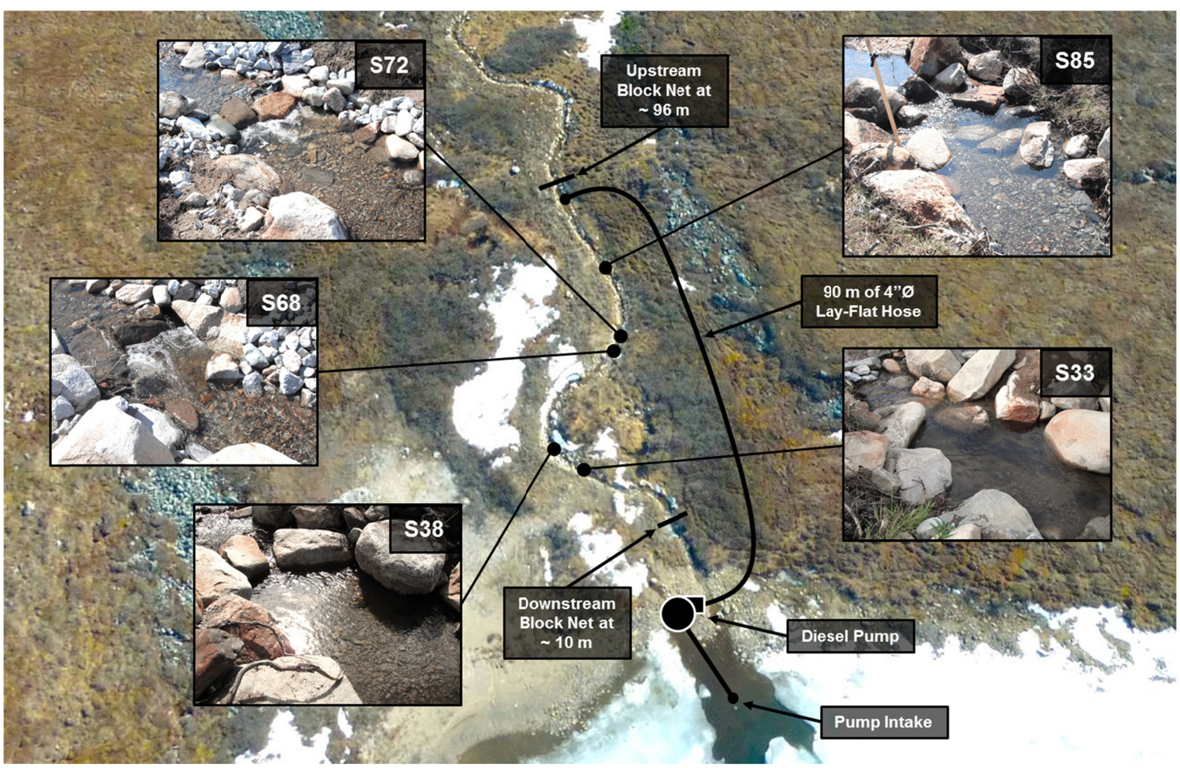

Figure 3.2 – Experiment setup for West Island Stream (WIS) flow manipulation experiment, including locations of the five study pools. Insets are photos of each study pool.

Figure 3.3 - Video frame shown with fish identified (top) and sampling grid projected on frame (bottom) using custom software. Banks are shown in blue, fish are shown in green, sampling cells are shown in red, and sampling cells with fish present are shown in white.

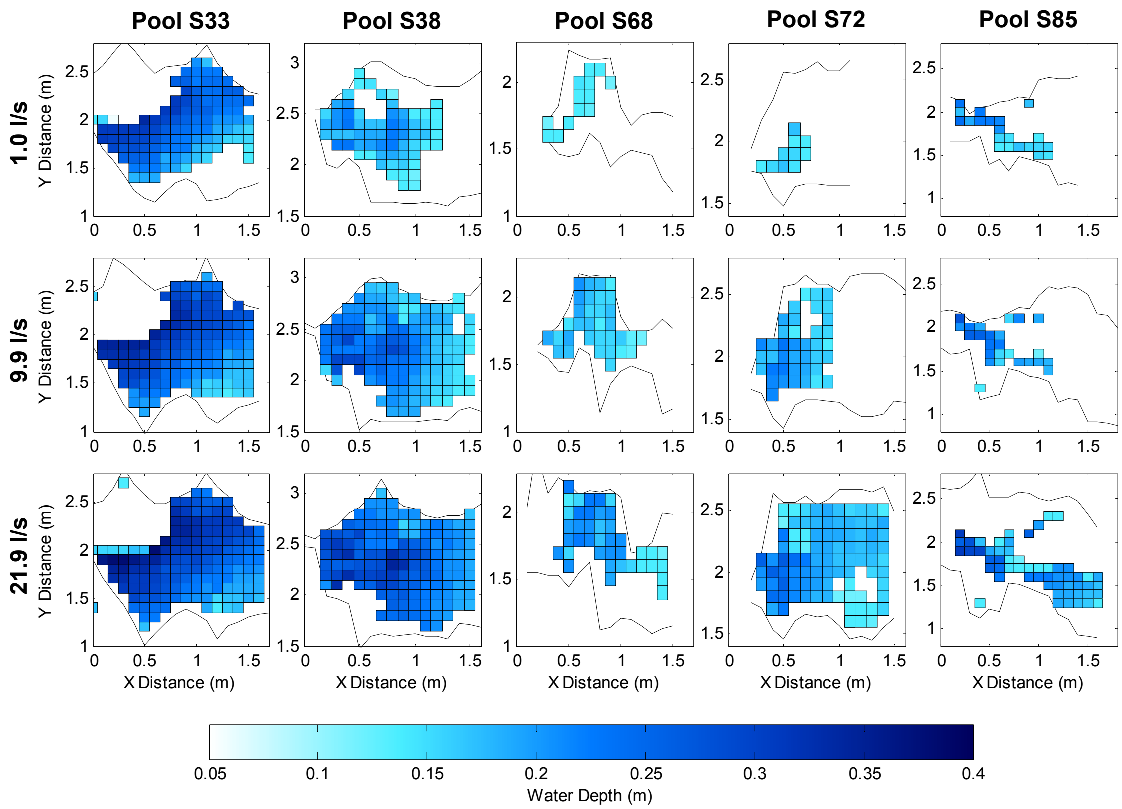

Figure 3.4 – Depth in the five study pools at the base and two manipulation flows. Black lines indicate pool banks. Data were only collected at locations with a minimum depth of 0.08 m.

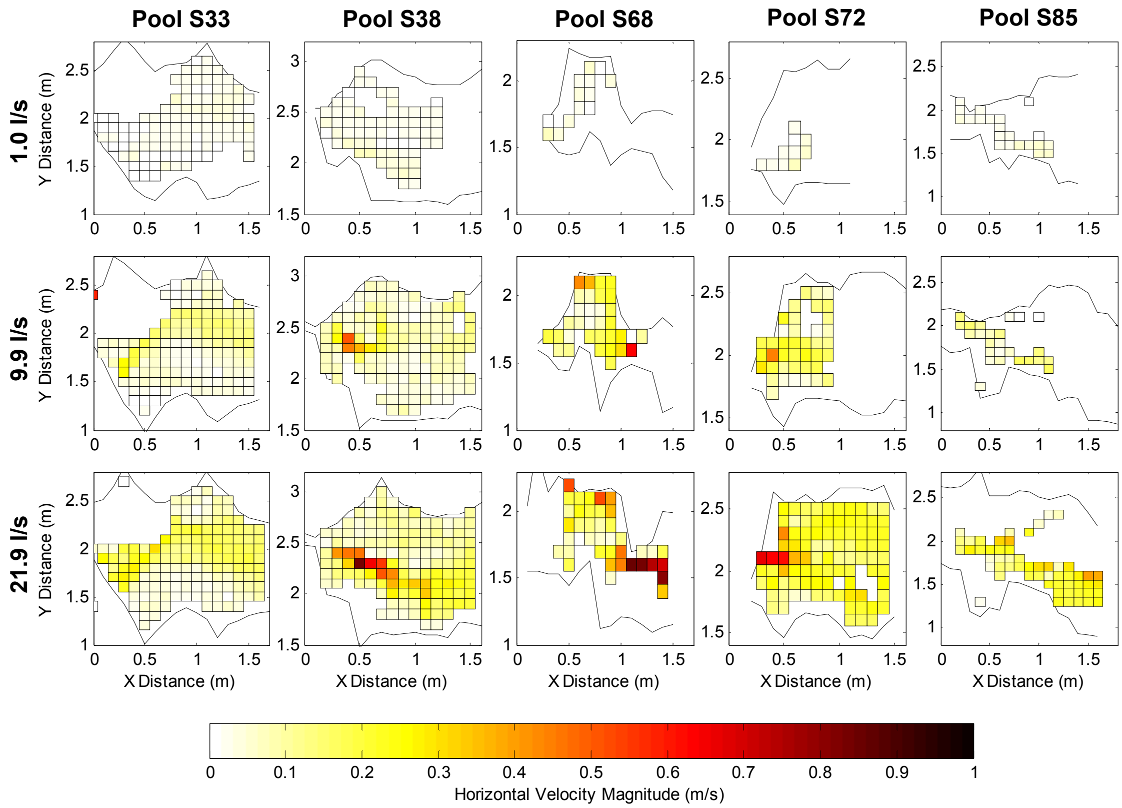

Figure 3.5 – Horizontal velocity magnitude in the five study pools at the base and two manipulation flows. Black lines indicate pool banks. Data were only collected at locations with a minimum depth of 0.08 m.

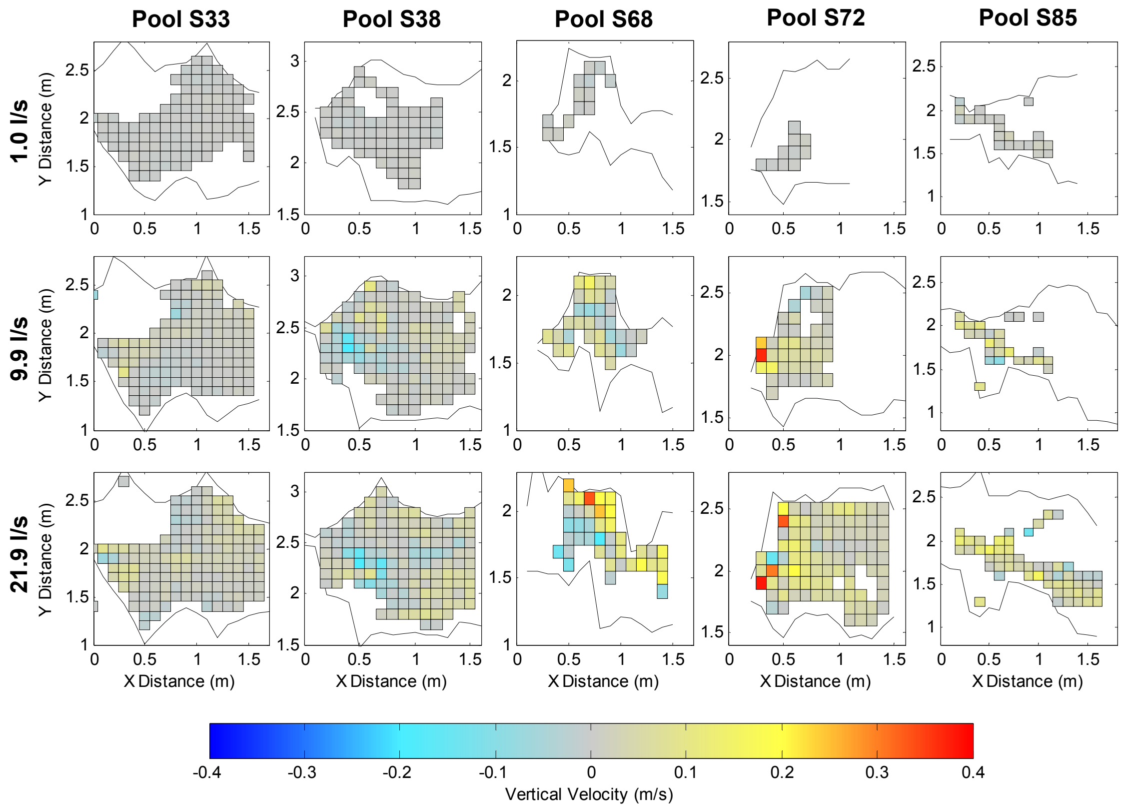

Figure 3.6 – Upward vertical in the five study pools at the base and two manipulation flows (positive values represent flow out of the page). Black lines indicate pool banks. Data were only collected at locations with a minimum depth of 0.08 m.

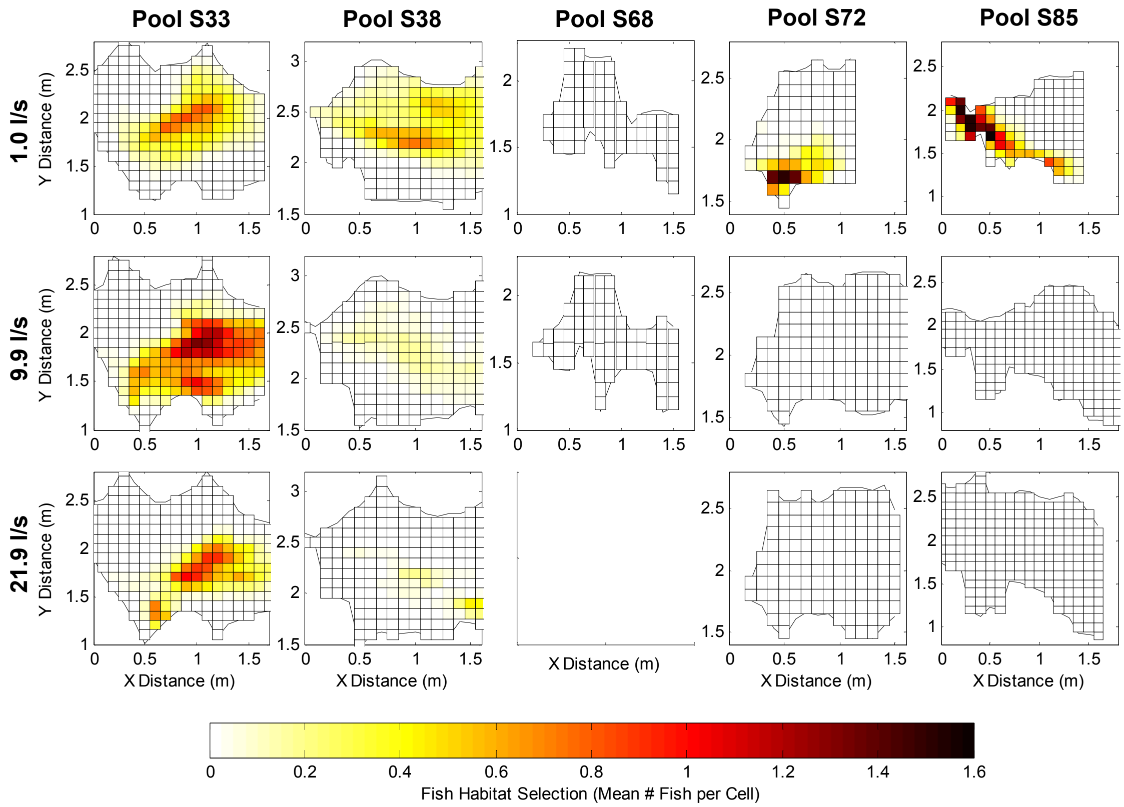

Figure 3.7 – Fish usage plots showing the mean number of fish per cell in the five study pools at the base and two manipulation flows. Black lines indicate pool banks.

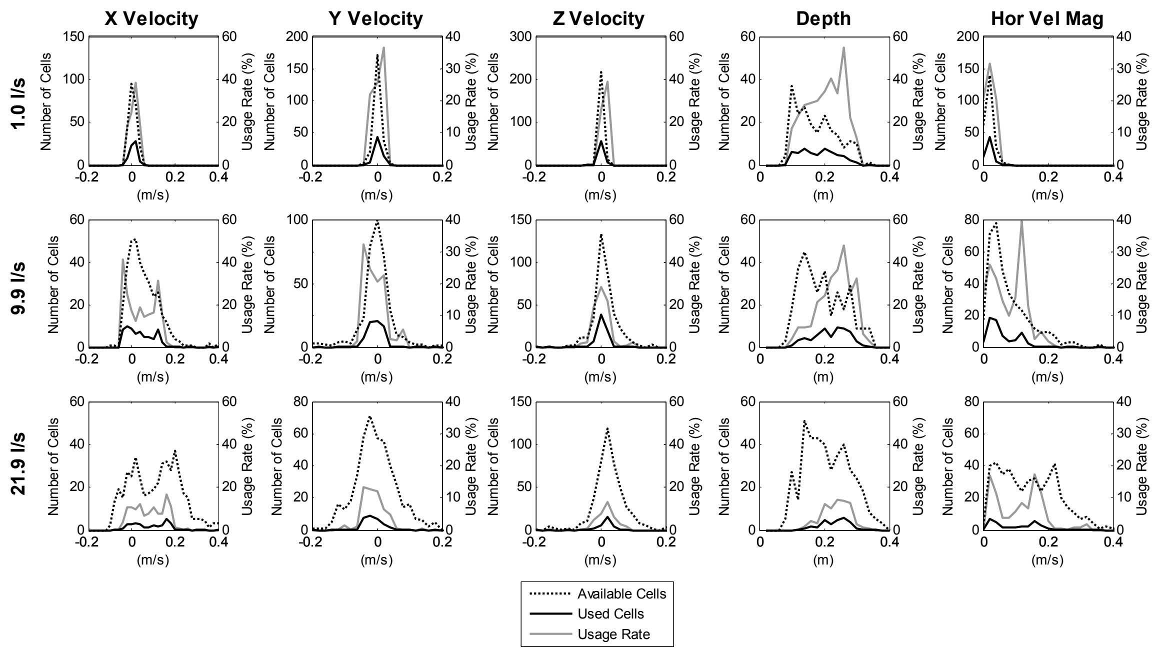

Figure 3.8 – Available habitat cells (dotted lines) and mean used habitat cells (black lines) for arctic grayling. Usage rate (gray lines) was calculated as the mean percentage of available habitat cells used.

Table 3.1 - Summary of conditions during the flow manipulation experiment. Each flow condition was run continuously for 48 hours, beginning at the start time.

Flow Condition	Start Time	Mean Flow (l/s)	Mean Water Temperature (°C)	Mean Fish Length (mm)
Base Condition	July 6, 2014 2:30 PM	1.0 (SD=0.1)	12.8 (SD=3.1)	330 (SD=32)
Manipulation 1	July 10, 2014 6:30 PM	9.9 (SD=1.5)	10.2 (SD=1.3)	300 (SD=32)
Manipulation 2	July 13, 2014 7:00 PM	21.9 (SD=2.3)	10.2 (SD=1.5)	290 (SD=39)

Table 3.2 - Average number of fish resting in each pool during visual fish surveys (n = number of visual fish surveys conducted under each flow condition).

Flow Condition	Pool S33	Pool S38	Pool S68	Pool S72	Pool S85
Base Condition (n=18)	5.3 (SD=0.8)	5.6 (SD=0.5)	0.0 (SD=0.0)	3.0 (SD=0.0)	5.9 (SD=0.2)
Manipulation 1 (n=22)	18.9 (SD=2.3)	1.5 (SD=0.8)	0.0 (SD=0.0)	0.0 (SD=0.0)	0.0 (SD=0.0)
Manipulation 2 (n=20)	11.1 (SD=1.8)	0.2 (SD=0.4)	0.0 (SD=0.0)	0.1 (SD=0.2)	0.2 (SD=0.5)

CHAPTER 4. General Conclusions and Recommendations

Conclusions

We conducted two experiments on the ecohydraulics of nature-like fishways, with one study taking place in the field and another taking place in the laboratory.

In Chapter 2 we presented a laboratory study on the potential use of a rock-weir pool-weir style fishway constructed with natural materials and a v-shaped weir. We were able to identify an acceptable operating zone of slope and discharge for this weir configuration, and developed a figure to aid designers in selecting an appropriate discharge and slope based on the criteria of volumetric power dissipation. We also discovered a-discharge relationship for the proposed weir design. In this experiment we also proposed a method of rock-weir construction to reduce installation time, cost, and improve design flexibility.

In Chapter 3 we examined a stream-scale flow manipulation using a diesel pump in the Canadian Barrenlands. This study identified one pool as having the best resting habitat for Arctic Grayling. In the study we determined that Arctic Grayling prefer near-zero horizontal velocities and select for deep water. Based on this study, we are proposing that until explicit guidelines for Arctic Grayling are developed, pool style fishways contain resting pools with a minimum length of 1.4 m, minimum width of 1.0 m, and a minimum depth of 0.6 m and contain regions with horizontal velocity magnitudes below 0.2 m/s and near-zero vertical velocities.

Recommendations

Despite current efforts, there is still a need to improve our understanding of nature-like fishways. In recent years, advances in technology such as PIV, acoustic methods, and numerical modeling have made it easier than ever to understand the hydraulics of nature-like fishways and to optimize designs. The use of these technologies will allow us to continue to improve our understanding and improve our designs in the future. Unfortunately, this hydraulic data is only as useful as the complementary data on the behaviour of fish within these structures. There is a dire need to perform comprehensive experiments that characterize the behaviour of fish based on shear stresses and the intensity, periodicity, orientation, and scale of turbulence. Only with this information will we be able to develop the most effective fishway designs.

With the current resource extraction development occurring in Northern Canada we must proceed with caution. We are encountering poorly-studied and fragile aquatic ecosystems. The existing concept of habitat compensation where an equivalent number of habitat units are created elsewhere to offset the impacts of develop should be carefully considered, particularly when those habitat units are being created by enhancing a nearby pristine ecosystem. The cost of working in Northern Canada can be incredible, and perhaps rather than providing habitat compensation projects in the north, money is better spent repairing damaged ecosystems in more developed areas where you can achieve more for the same cost. Faced with this current development, a dialogue should occur between first nations, governments, academia, and all other stakeholders to fully understand the impact of this development on the ecosystems of Northern Canada and the true value of any compensation that we are performing.